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The Rise of Health Expenditures

An analysis of the determinants and implications for the economy and welfare

DISSERTATION

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Kurzfassung

Im Laufe der letzten Jahrzehnte wurde das rasche Wirtschaftswachstum in den Industrieländern von einer erheblichen Verringerung der Sterblichkeit und einem starken Anstieg der Gesundheitsausgaben begleitet. Während eine umfassende Literatur zu den Determinanten des Gesundheitskostenanstiegs und der Rolle der medizinischen Versorgung bei der Senkung der Sterblichkeit entstanden ist, sind die Auswirkungen auf Volkswirtschaft und Wohlfahrt weniger bekannt. Diese Arbeit analysiert eine Reihe von Faktoren, von denen angenommen wird, dass sie eine Rolle bei der Erhöhung der Gesundheitsausgaben spielen. Dazu gehören der medizinische Fortschritt, die Ausweitung von Krankenversicherungen, das Einkommenswachstum und der Klimawandel. Darüber hinaus werden jedoch auch die Auswirkungen des Gesundheitskostenanstiegs auf die Wohlfahrt, die Bevölkerungsstruktur und die Wirtschaft sowie deren Rückkopplungen auf die Nachfrage und Bereitstellung von medizinischer Versorgung untersucht.

Die Analyse erfolgt innerhalb eines Lebenszyklusmodells mit endogener Gesundheitsnachfrage und Mortalität. Individuen wählen Konsum- und Gesundheitsausgaben über ihren Lebenszyklus, so dass ihr Gesamtnutzen maximiert wird. Der Erwerb von Gesundheitsleistungen erhöht die Überlebenswahrscheinlichkeit, während über den Konsum Nutzen generiert wird. Der individuelle Lebenszyklus ist eingebettet in ein Modell überlappender Generationen mit realistischer Bevölkerungsstruktur. Die Gesundheitsversorgung erfolgt durch einen medizinischen Sektor, der parallel zu einem Produktionssektor existiert und Kapital und Arbeitskraft der Bevölkerung nutzt. Dieser Modellrahmen ermöglicht es, die Rolle der oben genannten Determinanten von Gesundheitsausgaben zu beurteilen und gleichzeitig die Folgen für die Wirtschaft und eventuelle Rückkopplungen durch sektorale Reallokationen und Faktorpreisänderungen zu verfolgen. Darüber hinaus lassen sich Verschiebungen der Altersstruktur aufgrund von Mortalitätsreduktionen und die sich daraus resultierenden Implikationen für die gesamtwirtschaftliche Nachfrage darstellen und analysieren. Schließlich können auch die Auswirkungen der Ausweitung der Gesundheitsversorgung auf Konsum und Lebenserwartung und damit auf die Wohlfahrt untersucht werden.

Die Arbeit besteht aus drei Artikeln, die nicht nur thematisch verwandt sind, sondern auch im Hinblick auf die oben beschriebene Modellierung. Die ersten beiden Papiere befassen sich mit den USA und zeigen, dass das technologiebedingte Nachfragewachstum im Gesundheitswesen makroökonomische Rückkopplungen mit sich bringt, die eine Preiserhöhung für die medizinische Versorgung zur Folge hat. Darüber hinaus wird nachgewiesen, dass die Ausweitung der Krankenversicherung das Ausgabenwachstum erheblich beeinflusst, in besonderem Maße wenn Komplementaritäten mit Einkommenszuwächsen sowie induzierte Innovationen im medizinischen Bereich berücksichtigt werden. Das dritte Papier untersucht die Auswirkungen des

Klimawandels in einem allgemeineren Rahmen, in welchem eine uneindeutige Rolle von Umweltfaktoren für medizinische Ausgaben festgestellt wird. Die Wirkung des Klimawandels hängt dabei neben der Altersstruktur der Bevölkerung auch von der Art der Klimaeffekte auf die Wirtschaftskraft ab.

Abstract

Over the last decades, rapid economic growth came along with considerable reductions in mortality and large increases in health spending in developed countries. While a large literature has evolved that studies the determinants of the rise in health expenditure and the role of medical care in lowering mortality, few have studied the interrelationship with the economy and welfare in one comprehensive framework. This thesis explores a range of factors assumed to play a role in increasing health expenditures including medical progress, the expansion of health insurance, income growth and climate change but also studies the consequences of expanding health care on the population structure, on the welfare of individuals and on the economy as well as the feedbacks thereof on the demand and provision of health care.

The analysis is conducted within a life-cycle theory framework with endogenous health demand and mortality. Individuals choose consumption and health expenditures over their life-course, seeking to maximize life-time utility. The purchase of health care increases survival chances, while consumption provides a utility stream. The individual life-cycle is embedded into an overlapping generations model with realistic population structure. Health care is provided by a medical sector, existing alongside a production sector, using capital and labor provided by the population. This setup allows for assessing the role of aforementioned determinants of health care expenditures while keeping track of the implications for the economy and possible feedbacks through sectoral reallocations and shifts in prices for factors of production. Furthermore, changes in the age structure caused by mortality reductions and the resulting implications for aggregate health-demand can be traced and analyzed. Finally, the implications of the expansion of health care for consumption and longevity and thus for welfare can also be explored.

The thesis consists of three articles related to each other not only with respect to the focus on health expenditures, the economy and welfare, but also regarding the methodology involving the modeling described above. The first two papers are concerned with the US, showing that technology-driven health care demand growth induces macroeconomic feedbacks involving an increase in the price for medical care. Furthermore it is demonstrated that the expansion of insurance considerably shapes expenditure growth, particularly when complementarities with income as well as induced medical R&D effects are considered. The third paper studies the impact of climate change in a more general setting finding an ambiguous role of environmental factors on medical expenses depending on the age structure of the population and on the nature of climate change impacts on the economy.

Declaration

I hereby certify that no other than the sources and aids referred to were used in this thesis. All parts which have been adopted either literally or in a general manner from other sources have been indicated accordingly.

I certify that the main contribution of this thesis, the analysis of the determinants of rising health expenditures and its implications for the economy and welfare, is my own work.

Vienna, October 2017
Ivan Frankovic

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Contents

CHAPTER 1

Introduction

In developed countries, health expenditures have strongly increased over the last decades and even outpaced the growth of GDP as illustrated in Figure 1.1. Among the OECD countries, the share of GDP devoted to the health sector has risen from 3.8 % in 1960 to 9.5 % in 2009. This growing trend in health expenditure can be observed in all OECD countries, some of which are also depicted in the figure. While countries such as the United Kingdom and Japan exhibit a growth in health expenditures relatively close to the overall OECD trend, the US takes on a strong outlier role, which will further be discussed in section 1.2. Given that the GDP per capita has also increased quite considerably among OECD countries, real health expenditures as such have even expanded more rapidly than the trend for the health share suggests. During the same time period, life-expectancy in the OECD has risen by 11.2 years to 79.5 years, much of which has been attributed to the expansion of health care, see OECD (2011). This development, supported by falling fertility rates over the course of the 20th century, induced rapid population aging in the developed countries.

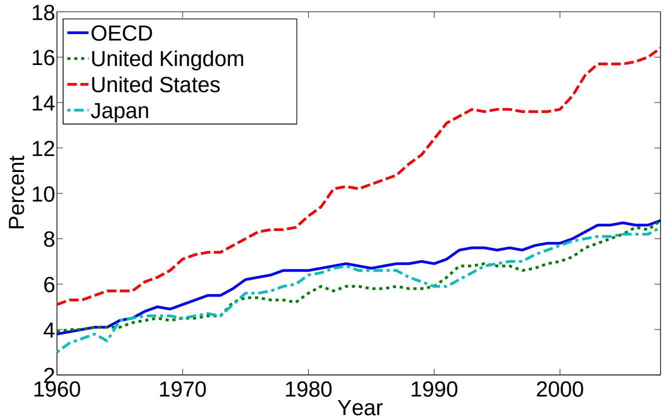


Figure 1.1: GDP health share in the OECD overall, UK, US and Japan - Source: OECD (2011)

Since decades, the reasons underlying this rapid and widespread expansion of medical expenditures have been subject to economic analysis. An important and related question pertains to the implications of health expenditure growth for the overall economic performance as well as for individual welfare. If the rise of the health care sector is detrimental to the economy or health expenditures as such are little effective in improving health and longevity, the observed pattern from figure 1.1 might be reason for concern and measures should be taken to contain this cost growth. If, on the other hand, the benefits associated with the expanding health spending share outweigh their opportunity costs, one can and should be much less critical about this development. That is why this thesis aims for not only shedding light on the role of various factors driving observed and possibly future increase in health expenditures, but also for assessing the interactions with the economy as a whole, the demographic structure of the population and its consequences for the welfare of individuals.

The thesis consists of three articles that are presented in chapters 2 to 4. The articles, which will be introduced in greater detail in the next section, are not only related to each other with respect to the research question, namely the assessment of various health cost drivers in a general economic and welfare context, but also methodologically. Underlying the analysis in each of the articles is a life-cycle model with endogenous health care demand embedded into an overlapping generation structure such that macroeconomic interactions can be studied as well.

1.1 Overview of the thesis

The first two articles focus on the determinants of health care expenditures in the United States, a country of particular interest in the context of health expenditure analysis as will be argued in subchapter 1.2. In particular, the first article discusses the impact of medical progress on the US economy and shows the importance of taking into account general equilibrium feedbacks of a health care demand expansion. These feedbacks involve adjustments in the capital market, namely a reduction in the market interest rate as a consequence of technology-induced population aging. Such a reduction of the price for capital favors the capital-intensive sectors, such that the price for health care, produced in a relatively labor-intensive sector, increases and as a consequence, dampens the rise in health demand initiated by medical progress.
The second article is concerned with the overall increase in medical expenditures in the US observed over the period 1965 to 2005. Building on the first article, it employs again a general-equilibrium approach and investigates in particular the role of insurance, medical progress and income, as well as their interactions in contributing to the growth of costs observed in the US during this time period. The article finds that the insurance expansion over the last decades has been a main driver of health expenses in the US. However, this effect on health expenditures is to some extent a consequence of increased incentives for medical R&D firms to develop new technology as well as for health care providers to adopt it. Furthermore, a complementarity between insurance and income in determining health expenditures plays quantitatively an important role. A welfare analysis reveals that while the moral hazard associated with the expansion of health insurance creates largely excessive health care expenditure as such, the gains in life expectancy brought about by induced medical progress more than compensate for this.

The third article presented in chapter 4 is not focused on the analysis of one particular country but investigates the role of climate change on health expenditures in a more general framework. While the impact of climate change on human health and consequently on health care expenditures is already present at the moment, the implications for health and medical care will intensify as climate change evolves over the course of the 21st century. The analysis is thus rather forward-looking than being concerned with past or current determinants of medical expenditures. The study shows that climate change can increase the demand for health care due to amplified mortality risks. However, income losses paired with mortality increases can result in an unfavorable complementarity reducing the willingness to pay for survival which overcompensates the direct effect of higher health demand. The impact of climate change on health expenditures is thus ambiguous and depends on the relative strength of climate change effects on economic performance, on the one hand, and on mortality, on the other.

In the remainder of the introduction we will set the stage for these three articles. First, we will discuss the outlier role of the United States in the context of health expenditures justifying the interest devoted to the US context in this thesis. Second we will provide a short literature review on the drivers of health care expenditures, again focusing mostly on the US situation. While certainly not being exhaustive, the factors discussed will provide a useful set of insights underlying the analysis of health expenditure growth in this thesis. Third, we will address another key feature common to all three articles (beside the topical focus on health expenditures) namely the underlying economic theory in which the analysis is conducted as well as the numerical simulation method by which we obtain most of our results. Finally, some information about the current state of dissemination of the research conducted within this thesis is presented.

1.2 The outlier role of the United States

In this thesis, two chapters are concerned with the US context. In this subsection we argue why the US are of particular interest in the analysis of health care expenditures.

First and foremost, the US is the largest consumer of medical care worldwide. Despite accounting for only about 24% of the World's GDP in 2012, its share in the health expenditure amounted to 48% in the same year, see Koijen et al. (2016). This US dominance in health expenditures is also visible in Figure 1.1. While in 2005, the US GDP health share amounted to about 15%, the GDP health share was only half of that in the overall OECD region. The outlier position of the US becomes even more visible when looking at the per-capita health expenditures because the share of GDP data mask the true difference due to the relatively high level of GDP per capita in the US. On average an US citizen spent USD 7960 on medical care in 2009, whereas the OECD per capita expenditures amounted to only USD 3233, see OECD (2011). Another important observation is, that the outlier position of the US has increased over time. In fact, according to OECD (2001), during the 20th century the average annual growth rate of health expenditures in the US was above the OECD average. Anderson et al. (2003) point out that a main reason for higher US health expenditures are the prices for medical services that strongly exceed the level in other developed countries. Several explanations for the relatively high medical prices in the US are brought forward in Anderson et al. (2003) as well as Reinhardt

(2012). First, relatively high salaries of medical personnel increase the cost of providing health care in the US relative to other countries. Second, the strong fragmentation of the US insurance system leads to a high burden with administrative costs as well as to low bargaining power on the demand-side of the health care market, leaving the providers of health care in powerful position to set high prices.

Second, the US health care market is the world's major driver of medical progress due to it being the greatest contributor to worldwide medical R&D. According to PWC (2017) the US accounts for approximately 50 % of all R&D expenditures related to health care. Furthermore, as Chandra and Skinner (2012) note, the reimbursement systems of public and private health insurances in the US encourage the diffusion of medical technology more than insurance systems do in other parts of the world. Consequently, US patients are often the first to utilize new technology whose usefulness is often unproven at first, while in other countries technology tends to be adopted only after its effectiveness and efficiency has been confirmed. Consequently, the pace at which the forefront of medical technology progresses is predominantly determined by the US health care market. Since medical technology presents a major health cost driver as will be shown in section 1.3, the US health care system is thus particularly interesting for the analysis conducted in this thesis.

Third, with the US being the largest economy in the world, its economic dynamics are predominantly shaped domestically whereas other, smaller countries might be to a much greater extent be shaped by international events. This observation is particularly important when it comes to modeling capital markets and the determination of the market interest rate. In contrast to small countries where the real interest rate is determined by foreign capital markets, population aging and the associated increase in savings depresses the domestic interest rate in the US, see Bloom et al. (2003), Aksoy et al. (2016) and De Nardi et al. (2010). This gives rise to possibly important economic feedbacks of expanding health care systems that effectively increase life-expectancy in a population. The general equilibrium approach pursued in the first two articles is well-suited to analyze these economic and demographic interactions with medical expenditures.

Hence, due to the relatively strong growth rate and high level of health expenditures, the particularly dominant role in medical technology development and diffusion as well as the relevance of macroeconomic and demographic feedbacks, the US health care system is well-worth studying, particularly using the comprehensive approach taken in this thesis.

1.3 Review of the drivers of health care expenditure increase

In the following we review shortly the determinants of health care expenditures most relevant for the analysis in the main part of the thesis. Many of the studies quoted refer specifically to the US situation, some other, however, consider international health care contexts such that insights can be viewed as of more general nature.

1.3.1 Population aging

The aging of societies has been a dominant characteristic of population dynamics for the last decades in developed countries around the globe. While population aging is often considered a burden on public finances and a threat to economic prosperity, it is partly the consequence of a quite favorable development, namely significant and continuing increases in life-expectancy, with the second force of this development being reductions in fertility.

One simple and intuitive measure of the population structure is the share of individuals aged 65 or higher. According to World Bank (2017), this share has increased from 8.5% in 1960 to 16.5% in 2016 in the OECD region, from 9% to 15% in the US and from 12% to 18% in the UK. As health care expenditures increase with age it is quite obvious to assume that aging of societies will increase health expenditures in a country, a claim first made by Fuchs (1984). However, if increases in longevity directly defer the onset of morbidity to older age groups, the rise in life-expectancy might not result in drastically increasing health costs as suggested by the so called "red herring" hypothesis. The issue boils down to the question whether health expenditures are a function of age or a function of remaining life-expectancy. In the former case, rises in longevity will increase the average age in a population and thus increase average health expenses while in the latter, costs might not increase as treatment is postponed to older ages.

Since the seminal work by Zweifel et al. (1999), there is ample evidence that age has little explanatory power in individual-level regressions on health expenditures once proximity of death is accounted for. In fact, a large share of life-time health care is purchased in the last months of an individual's life, see Breyer et al. (2010) for an overview. This is likely due to the compression of mortality and morbidity observed in many developed countries, i.e. the deferment of diseases, chronic illnesses and ultimately death to older age. Nevertheless, Breyer et al. (2010) point to some evidence for a modest role of population aging in the increase for health expenditures on region or country-level. This is likely due to the mutual reinforcement of population aging and public spending on elderly health care, caused by a shift in voting power towards the elderly as their numbers increase, see Zweifel et al. (2005). Another possible driver of aging-related health expenditure growth is the so-called Eubie-Blake effect, see Breyer et al. (2015). The Eubie-Blake effect implies that as the remaining life-expectancy for a given age increases, patients are treated more intensively as the positive results of the treatment can be enjoyed for a longer time-span. Hence higher life-expectancy would induce indirectly a higher demand for health care.

1.3.2 Income

Western countries have not only experienced an increase in health care expenditures and life-expectancy but also strong GDP growth, raising the income of their citizens. If health care is a normal good (a superior good) an increase in income necessarily results in higher health expenditures (higher health shares of GDP). Indeed there is ample evidence that the income elasticity of health care demand is positive. However, there is less consensus on the magnitude of the income effect. In an widely cited review paper, Getzen (2000) finds estimates for the income elasticity ranging from close to zero to as much as well above one. Studies investigating the income elasticity among insured individuals find estimates close to zero and those looking at uninsured individuals values well above zero but nevertheless below 1. On the regional and national level, estimates for the income elasticity are usually considerably higher and partly above one, implying that health care is even a superior good. Getzen argues that the inconsistencies in estimates are due to variations in the level of study. The effect of income on health expenditures is determined on the level where budget constraints are met. Insured individuals facing a marginal price for health care of zero are unlikely to adjust health expenditures according to their income. Only their health determines the demand for medical care. Among uninsured individuals, it can be expected that income will affect medical care expenses as budget constraints do play a role. The full extent of income effects is only active, however, on a macroeconomic scale as the average income of individuals in a region or country will determine the generosity of insurance programs as well as of national health programs. Getzen concludes, that health is neither a normal nor a superior good but indeed both, depending on the considered level of analysis.

In a seminal paper by Hall and Jones (2007), the role of income in determining health care expenditures was analyzed theoretically. The authors argue that as income rises, individuals shift expenditure shares towards consumption of medical care as opposed to non-medical consumption goods. This is a rational behavior if the marginal utility of non-medical consumption diminishes more rapidly than the marginal utility provided by medical goods through extension of life. Given estimates for the elasticity of consumption as well as the elasticity of medical care on mortality in the US over the second half of the 20th century, the authors find indeed empirical support for this channel.

For income alone to explain the increase in health care expenditures observed in the US, the income elasticity would have to be around 3 as Fonseca et al. (2013) note. Given the empirical estimates above, this seems rather unlikely and the direct role of income in the rise of medical expenditures is likely to be quite modest. However, Fonseca et al. (2013) as well as this thesis finds evidence that complementarities between income and other drives for health costs might exist, i.e. optimal medical spending might be more sensitive to income when the level of insurance coverage or medical technology is higher. Income is thus likely to be driving health care costs indirectly through the interaction with other factors. Interestingly, this complementarity might help explaining why health care expenditures have been rising more rapidly in the US than in other developed countries as Fonseca et al. (2013) point out: If complementarities exist, cost growth might be by far larger in those countries where income growth and insurance expansions are large even if medical technology progresses at the same rate internationally.

1.3.3 Baumol's cost disease

Complementary to the direct effect of income growth on health expenditures is the role of structural changes caused by productivity growth in the economy. Due to the nature of the work of health professionals, it is difficult to be substituted by new technologies whereas in other, particularly manufacturing sectors, labor can be more easily replaced or complemented by technology. Baumol (1967) hence concluded that faster productivity growth in the non-health sectors increases the wage rate even in the health sector because for the health sector to be able to keep its employees, wages of health professionals have to rise in the same way as they do in the rest of the economy. However, as productivity has not increased in the health care sector the cost of producing the same amount of health care rises, resulting in an expansion of the health care sector relative to the rest of the economy.

Hartwig (2011) finds indeed evidence in support of Baumol's prediction analyzing the health expenditure growth and the evolution of medical prices in a number of OECD countries. Bates and Santerre (2013) find that the Baumol phenomena played a statistically significant role in explaining the increase in health care expenditures in the US. It remains, however, unclear to what extent the Baumol cost disease has contributed to the overall increase in medical expenditures in the US.

Finally, it is important to add that macro-level estimates of the income elasticity, as presented in the previous section, not only measure the income effect working through the individual budget constraint but also, implicitly, the macroeconomic Baumol channel on health expenditures. This is likely an additional reason for higher macro than micro level estimates of the income elasticity.

1.3.4 Insurance

Particularly in the US context, the role of health insurances is strongly debated due to the relatively strong reduction in the share of health expenditures that are paid out-of-pocket (OOP) over the course of the last decades. If individuals pay a smaller share of the medical care they consume, the assumption that demand for health care will increase is not far-fetched. Indeed, it has long been empirically established that the price elasticity of health care demand is negative, i.e. a reduction in the consumer price of health care (e.g. through the reduction of the OOP share) induces individuals to consume more medical care.

Controversy only pertains to the question of the magnitude of this effect. The so called RAND health insurance experiment, see Manning et al. (1987), is considered the most prominent study on the price elasticity of health demand. It was conducted in the seventies as a controlled experiment in which the effect of varying degrees of insurance coverage were compared to a control group without any insurance coverage. The study yielded an estimate of the insurance elasticity of -0.2 to -0.3. This implies a rather weak role for the overall impact of the insurance expansion that we observed over the last decades. As Finkelstein (2007) argues, using the RAND estimate, only about 10-12.5% of the total health cost increase in the US can be attributed to the fall in out-of-pocket expenditures.

Subsequent studies have only partly confirmed the RAND result. The range of estimates has increased quite enormously and considerable uncertainty remains about the true magnitude. McGuire and Newhouse (2012) finds estimates of -0.1 to -0.8 in a review on various empirical price elasticity studies. However, more recently Kowalski (2016) finds much larger elasticities ranging from -0.8 to -1.5. Kowalski reaches this result using a novel empirical method taking account of the skewness of health expenditures across the population as well as of a potential bias of stoploss mechanisms in health insurance programs: Individuals insured with a high marginal price of health care (low insurance coverage) might not strongly differ in demand from those with a low marginal price if they expect to reach the stoploss, after which the marginal price of every additional unit of health care permanently drops to zero. Hence, the differences between insurance programs of varying marginal price of health care might be smaller than in the absence of a stoploss mechanism, biasing estimates downwards. In the RAND study, this bias is dealt with by constructing a measure of expected health care expenditures in the absence of stoploss. This measure is based on myopic foresight, implying the assumption that individuals do not expect to reach the stoploss threshold when making health investment decisions. Kowalski presents some evidence that individuals are indeed forward-looking when making health investments for a given insurance period confirming that the bias is present in the RAND estimate. When introducing a similar measure of expected health expenditures in absence of stoploss (assuming myopic behavior), Kowalski also obtains estimates in the range of the RAND study. She concludes that the differences to the RAND estimate are likely due to the different treatment of myopia and foresight. Other recent estimates on the price elasticities that take measures against the stoploss bias find larger values than the RAND estimate, including Ellis et al. (2017) with -0.44 and Fonseca et al. (2013) with -0.6. Hence, considerable uncertainty still pertains to the real magnitude of the price elasticity of health demand and thus also to the impact of insurance expansions on health care expenditures.

Related to the issue of the role of insurance is the role of reimbursement schemes used by insurers to pay health care providers. Payments from the public or private insurers to health care providers can be organized as fee-for-service reimbursements, implying that health care providers are paid retrospectively for each medical service, or as per-person payments, paid prospectively for providing health care to a group of people covered collectively by a so called health maintenance organization (HMO). While the former approach can lead to excessive health expenditures due to the missing incentive for cost-saving at the supplier side, the latter scheme might successfully control health expenditures (possibly at the cost of lower quality of service), see McClellan (2011). However, reviewing the relevant literature, Chernew and Newhouse (2012) find that moving from a fee-for-service system to prospective payment does not lead to a permanent reduction of the growth rate of health expenditures even though it has contributed to a temporary slowdown in expenditure growth during 1990s in the US. Some of these expenditure savings might have been achieved through the delay of technology adoption. This is implied by evidence that the increasing market penetration of HMOs in the late 20th century led to a slower diffusion of cost-intensive magnetic resonance imaging and neonatal intensive care units, see Baker (2001) and Baker and Phibbs (2002).

1.3.5 Medical technology

One of the first papers pointing to the important role of medical progress as a driver of health care expenditures is Newhouse (1992). The author argues that most of the observed expenditure increase in the US was due to medical progress, reaching this conclusion using a residual approach. This implies that first all other relevant cost drivers in the health care sector are identified, e.g. aging, income growth, insurance expansion and differential productivity growth (Baumol), then their individual contribution to cost growth is estimated and ultimately the unexplained residual of cost growth is attributed to technological progress. Newhouse concludes that as only 25-50% of health expenditure growth can be attributed to other factors, technological progress must be the dominant driver.

Cutler and McClellan (2001) follow a different approach by investigating the health care costs associated with several diseases that were subject to strong technological change. They find, in line with Newhouse (1992), that close to a half of health cost growth was the consequence of the use of better medical technology. The authors also perform a welfare analysis showing that despite the increased health spending, medical progress is nevertheless welfare improving given the associated reductions in mortality. The monetary value of such mortality reductions is derived from empirical estimates for the value of life, capturing the relative importance of foregone consumption and gains in health and longevity that individuals reveal in market decisions.

In a more recent and nuanced contribution, Chandra and Skinner (2012) show that the consequences of medical progress depend on the nature of the innovation. Low cost technology such as antibiotics or beta-blockers tend to have the largest effects on mortality and do not strongly impact health care expenditures. Other technologies may have positive impacts on mortality for a small subset of the population or are overall small, but nevertheless are employed in a widespread fashion in the health care system. Overall, the technology might then have negative effects on welfare as the associated benefits fall short of the induced medical costs. According to the authors, innovations falling in the latter category were more likely to be adopted in the United States compared to other developed countries, due to relatively generous reimbursement schemes in the US, which can contribute to explaining the higher level of health care expenditures in the US.

Fonseca et al. (2013) estimate the impact of medical progress using a calibrated life-cycle model. Individuals maximize lifetime utility while mortality depends on health that is produced using medical care. In their model, calibrated to US data from 1965-2005, medical progress accounts for about 30% of the total increase in health care expenditures. Importantly, and as already mentioned, the authors point to a strong role of complementarities between income, insurance and medical technology. These effects might be misidentified by residual-approach studies attributing complementarities to medical progress only.

Finally, many have argued that medical progress itself is merely a consequence of other health cost drivers and should be viewed as an indirect channel through which these other drivers operate. For example, Weisbrod (1991) argues that insurance expansions might induce increased medical development and adoption among health care providers as insurances provide the respective financial incentives to do so. In fact, Finkelstein (2007) and Clemens (2013) confirm Weisbrod's hypothesis empirically showing that the introduction of Medicare and Medicaid in the US lead to faster technological progress and diffusion among care providers. Jones (2016) points out that income growth can also induce an economy to invest more and more resources into the development of medical technology because the value of life is likely to rise faster than consumption, see also Hall and Jones (2007).

1.3.6 Climate change

There is a well-established link between human health and changes in the environment induced by a warming climate. Worsening climates can have effects through various channels, including an increasing number and intensity of extreme weather, such as heat waves, rain falls, storms, droughts but also more indirect effects such as air pollution, food insecurity and spread of disease vectors, see Watts et al. (2015) for an overview. The adverse effects on mortality are already present but likely to intensify over the course of the 21st century. The World Health Organization, see WHO (2014), estimates some additional 250,000 annual deaths related to climate change by 2030. Developing countries are expected to suffer the largest part of adverse impacts on health; nonetheless, the developed world is also likely to be affected.

Nevertheless, a reduction in mortality and morbidity risk can result from climate change, namely for diseases related to cold weather. The effect will depend on climatic conditions of a given region, with cold regions possibly benefiting from warmer temperatures in the short and medium run, see Bosello et al. (2006) and Watkiss et al. (2009). However, moderate and hot regions are already suffering from global warming and the impact is a growing concern for health care systems worldwide, see Watts et al. (2015).

The effect of heat waves is the most studied channel through which climate change acts on mortality and health care utilization. There is evidence, both for the US, see Anderson et al. (2013) and for Europe, see Åström et al. (2013), that heat waves result in higher rates of hospitalization. Given that both the number of people living in urban regions particularly vulnerable to heat and the number and duration of heat waves and will rise as climate change unfolds, heat waves will become a growing health concern. Several studies have also shown that heat waves increase mortality; an effect going beyond the so-called harvest effect, i.e. the temporary displacement of mortality towards the period of a heat wave. Deschenes and Greenstone (2011) estimate that the age-adjusted mortality in the US will increase by 3 percent in the business-as-usual climate scenario as a result of more intensive and frequent heat waves. However, adaptation might strongly mitigate these negative effects. Barreca et al. (2016) shows that the impact of hot days on mortality has declined over the 20th century in the US with the adoption of residential air conditioning explaining almost the entire decline in this relationship. Defining the category of medical expenditures more broadly such that the purchase of air conditioning and the associated energy expenses are included, this further suggests that health care demand and expenditure is shaped by climate change.

1.4 Underlying economic theory and simulation method

In this thesis, the role of the various determining factors of health expenditures discussed in section 1.3 as well as their effects on economic performance and welfare will be analyzed in one common theoretical framework, illustrated in figure 1.2. At the center of the economic theory stands a representative agent choosing consumption and health expenditures over the course of her life, while facing an increasing mortality risk with age. The agent can increase her survival chance by purchasing medical care, while deriving utility from consumption expenditures. Overall, the agent seeks to maximize the lifetime utility, consisting of the utility stream of consumption over the life weighted by the survival likelihood of reaching a particular age. In doing so, a life-time budget constraints holds: Agents begin their economic life with zero assets and accumulate savings by supplying labor to the economy and earning interest on capital loaned to firms. Drawing on these financial resources, consumption and medical expenses are paid for, where medical expenses are subsidized by public or private health insurance programs. After reaching retirement age, agents may receive pension benefits. Taxes or insurance premiums are levied to finance health insurance programs as well as the pension system. Finally, the risk of mortality and the effectiveness of medical care can be influenced by factors beyond the control of individuals, such as the state of medical technology or the adverse effects of climate change.

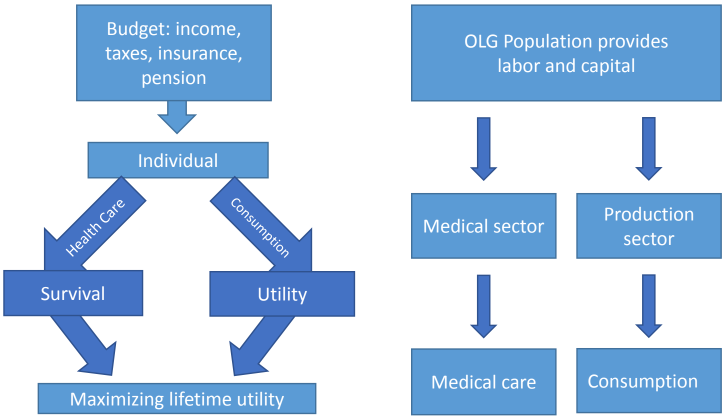


Figure 1.2: Model structure underlying the analysis in this thesis

In order to analyze macroeconomic dynamics, the model is extended to an overlapping generation (OLG) structure, such that individuals that differ in age and time of birth populate the economy. The OLG framework allows for an in-depth analysis of population dynamics in the context of health care. In particular the analysis will pay attention to cross-sectional life-expectancy and the population share of the elderly over time.

The population, as an aggregate, provides labor and capital to several sectors in the economy, the number of which varies in the following chapters. In general, the existence of at least two sectors is assumed, namely a production sector, providing the consumption good, and a health care sector, generating medical services for the population. The allocation of labor, capital and ultimately value-added across the sectors is determined by profit maximization in each sector and by the clearing of all markets. Unless not otherwise stated, this includes the clearing of the capital markets, where we assume the existence of a closed economy. While the modeling distinction to related literature will be discussed in great detail for each article independently, it should be highlighted that the general-equilibrium perspective is an important contribution of this thesis to the literature. While rendering the analytical and numerical analysis considerably more involved, it allows for an comprehensive study of health care expenditure in the greater context of economic dynamics that, as will be argued, are considerably shaped by structural re-allocation and population aging caused through the expansion of health care.

While this modeling approach yields a number of analytical insights that will be discussed in great detail in the following chapters, the bulk of results is derived from a numerical solution using the software MATLAB. The reason for resorting to a numerical solution is the lack of analytical tractability of the highly-complex model, featuring not only life-cycle decision making at the level of the representative agent but also a multi-sectoral economy with endogenous prices in general equilibrium. The algorithm employed for the solution in each of the three articles of this thesis is based on the age-structured maximum principle developed by Veliov (2003) but has been extended considerably, in particular with respect to the modeling of the macro economy.

1.5 Dissemination of research

A previous version of chapter 2 has been published as a working paper together with the co-authors Michael Kuhn and Stefan Wrzaczek, see Frankovic et al. (2016). The paper has also been submitted to the Journal of Health Economics. The article presented in chapter 3 will be submitted within this year. The article in chapter 4 is currently under peer-review with the Journal of Environmental Economics and Management and has been published as a working paper, see Frankovic (2017). All three articles have been presented by the author of this thesis at multiple conferences, including at the Congress of the European Economic Association (EEA) 2016, the European Health Economics Association (EuHEA) 2016, the European Association of Environmental and Resource Economists (EEARE) conference 2017 and the international Health Economics Association (iHEA) conference 2017.

CHAPTER 2

Medical Progress, Demand for Health Care, and Economic Performance

In this first article, which is joint work with Michael Kuhn and Stefan Wrzaczek from the Vienna Institute of Demography, we study the role of medical technology within an economy of overlapping generations subject to endogenous mortality. We establish the model framework outlined in the introductory section 1.4 in great detail and characterize the individual optimum and the general equilibrium of the economy and study the impact of improvements in effectiveness of health care. We find that general equilibrium effects dampen strongly the increase in health care usage following medical innovation. Moreover, an increase in savings offsets the negative impact on GDP per capita induced by a decline in the support ratio.

2.1 Introduction

The impact of demographic and medical change on the sustainability of health care systems and the resulting need for reform have been the subject of empirical analyses for considerable time.[1] By now, a consensus has emerged that medical progress is driving both the increase in health care spending per capita or per unit GDP and the increase in longevity, e.g. Cutler (2004), Chandra and Skinner (2012) and Chernew and Newhouse (2012).[2] Recent analysis by Fonseca et al. (2013) shows that about 30 percent of health care spending growth in the US over the period 1965-2005 can be explained by medical progress, with improved health insurance cover-

[1] See e.g. Breyer and Felder (2006) and Breyer et al. (2015) for Germany; Dormont et al. (2006) for France; Meara et al. (2004) and Shang and Goldman (2007) for the US; Karlsson and Klohn (2014) for Sweden; Zweifel et al. (1999) for a set of OECD countries; and European Commission (2015) for the then EU27. For an overview see Breyer et al. (2010).

[2] Other important drivers include income, see Hall and Jones (2007), and the presence of social security, see Zhao (2014).

age explaining 6 percent and income growth explaining 4 percent.[3] At the same time, medical progress explains most of the increase in life expectancy over the period of observation, which in welfare terms more than offsets the greater spending. These findings echo, at aggregate level, earlier results by Cutler and Huckman (2003) and Cutler (2007) who find that the technological improvements in the treatment of heart disease over the 1980s and 1990s were generating benefits from increased survival, the value of which was more than compensating the boost to health care costs.[4]

Although explaining the macro-economic implications of medical progress, the current line of inquiry remains to a large extent silent about the general equilibrium effects of this very medical progress. Indeed, there is strong evidence that medical innovations tend to boost the utilization of health care, see for example Baker et al. (2003), Cutler and Huckman (2003), Wong et al. (2012), andRoham et al. (2014). Given that the main concern about the expanding health share in the economy lies with its absorption of resources that may be employed more productively in other sectors of the economy (Kuhn and Prettner 2016, Pauly and Saxena 2012) it is then surprising that the role of medical progress in this has not yet received more attention. An examination of this concern warrants a general equilibrium analysis that keeps track of the way in which the increase in the demand for health care that is induced by medical change leads to changes in the sectoral structure of the economy and of the way in which the induced price changes feed back again into the pattern of individual demand.

In this article, we examine the impact of medical progress on individual life-cycle outcomes as well as on economic performance by analyzing an OLG model, involving an endogenous demand for and supply of health care. The demand for health and health care is derived from utility maximization within a life-cycle model with a realistic mortality pattern. Health care is provided within a medical sector, employing capital and labor, competing for resources with a final goods production sector. We characterize the optimal life-cycle allocation in terms of consumption and health care and show how it evolves with age, depending on the various prices and on the state of medical technology. As one important determinant of the demand for health care, we characterize the value individuals attach to their survival, which will prove to be an important link between macro-economic changes and their impact on the micro-decisions. Solving the profit maximization problem of perfectly competitive providers within the final goods and health care sectors, we can characterize the optimal structure of supply and factor demand as well as the aggregate dynamics.

We then employ our model to analyze numerically the impact of medical progress on the provision of health care. Based on a steady-state benchmark scenario that is calibrated to represent the US economy in the year 2003, we illustrate the importance of the micro-macro feedback by studying the impact of a medical innovation which is either (i) unanticipated or (ii) anticipated.

In contrast to Hall and Jones (2007), Fonseca et al. (2013), Zhao (2014) and Koijen et al. (2016), we do not focus so much on characterizing the contribution of different factors to health care expenditure growth. We rather seek to identify and characterize in detail the mechanisms

[3] The analysis also reveals an important complementarity between medical progress and income, which explains 57 percent of the increase in spending.

[4] Skinner et al. (2006) and Chandra and Skinner (2012) take a more nuanced view, showing that whether or not welfare gains arise from the adoption of new medical technologies depends both on the nature of technology as well as on the organization of the health care system into which it is adopted.

that govern the impact of medical innovations on the economy. In so doing, we adopt a quasi-experimental approach by which we study the impact of a "stylized" medical innovation on a steady state economy, tracing out the adjustment processes at micro- and macro-level that lead the economy into a new steady state. This distinguishes our model from the steady state comparisons in Fonseca et al. (2013) and Zhao (2014) and balanced growth representations in Hall and Jones (2007) and Koijen et al. (2016). Here, the abstraction from interfering macroeconomic time trends allows a much clearer analytical and numerical identification of the impact of medical innovation.

Considering a medical innovation that improves the effectiveness of health care and raises life expectancy by a little more than 1 year, which is broadly consistent with the increase in life expectancy brought about by the US cardiac revolution during the 80s and 90s (Cutler 2007), our key findings include the following. Health expenditure per capita increases by some 12.2%, about 0.9 percentage point of which owing to an increase in the price for medical care, about 1.8 percentage points owing to the aging of the population that is induced by the medical innovation, and the remaining 9.5 percentage points owing to an increase in individual demand. Although this is a substantive impact, we find that more than half of the increase in individual demand that would be obtained under a constant set of prices is absorbed by the general equilibrium increase in the price for health care. This suggests that estimations or projections of the impact of medical innovation on health care spending need to keep close track of possible general equilibrium repercussions in order to avoid strong biases. With the health expenditure share in GDP increasing by some 1.6 percentage points, it may come as a surprise perhaps, that the level of GDP per capita itself remains unaffected. This is because the drop in the employment rate that comes with a disproportionate increase in survival amongst the retired population is neutralized by the accumulation of additional wealth that is induced by the increase in longevity and the prospect for individuals to purchase more effective health care in their old age.[5] Indeed, if a medical innovation is fully anticipated, individuals increase their savings prior to the innovation, triggering a temporary economic boom.[6] Finally, mortality reducing medical innovations tend to come with a reduction in the value of survival over large parts of the life-course. On the one hand, this reflects a reduction in consumption levels; on the other hand, it implies that the price of medical care per life-year gained has fallen, a result that is in line with empirical evidence (Cutler et al. 1998).

This work ties in with two lines of literatures. First, a long-standing literature on the individual demand for health and health care over the life-course (e.g. Dalgaard and Strulik 2014, Ehrlich 2000, Ehrlich and Chuma 1990, Fonseca et al. 2013, Grossman 1972, Hall and Jones 2007, Kuhn et al. 2011, 2015). While these works are providing important insights into the determinants of the demand for health and health care at the individual level, they take a partial equilibrium stance by assuming an exogenous set of prices. As we will see, however, a neglect of general equilibrium effects may lead to a rather exaggerated assessment of the boost to the demand for health care following an innovation.

[5] This is consistent with empirical evidence provided by De Nardi et al. (2010).

[6] While a number of recent studies have empirically examined the anticipation effects related to Medicare Part D reform at microeconomic level (Alpert 2016, Hu et al. 2014, Kaplan and Zhang 2017), we are unaware of a theoretical analysis of the macroeconomic impacts of anticipated medical innovation. See Mertens and Ravn (2011) for a theoretical treatment of anticipation effects in the context of tax reform.

Second, this article adds to an emerging literature that considers the role of a health care sector within a general equilibrium context. Zhao (2014) analyses the impact of social security on health care spending, when the latter enhances survival and finds by way of a numerical calibration for the US economy a substantial positive impact. Jung and Tran (2016) model the general impact of the US 2010 health care reform but do not consider the role of medical progress. Koijen et al. (2016) study the interaction between financial and real health care markets and find that the premium associated with regulatory risk for e.g. pharmaceutical companies lowers research and development (R&D) investments by more than a half and thereby contains growth of health care expenditure by more than 3 percent. Kuhn and Prettner (2016) examine the impact of exogenous variations to the size of the health care sector within an R&D-driven growth economy, where health care enhances the survival and labor market participation of overlapping generations of individuals. They conclude that while Euro area health care systems impose a drag on economic growth, they are typically nevertheless favorable on welfare grounds. Schneider and Winkler (2016) study an endogenous growth economy in which overlapping cohorts of individuals invest in health care in order to lower mortality. Comparing the balanced growth paths associated with different states of medical technology, they find that the technology leading to a higher life expectancy imposes a drag on economic growth but leads to a welfare gain. Finally, Kelly (2017) studies the response of a neoclassical economy with a medical sector to changes in total factor productivity and in the productivity of health care.[7] The present work differs by the more realistic modeling of the individual life-cycle from Koijen et al. (2016) and Kelly (2017) who consider an infinitely lived representative individual; from Jung and Tran (2016) who consider overlapping generations subject to exogenous mortality; as well as from Kuhn and Prettner (2016) and Schneider and Winkler (2016) who consider Blanchard-Yaari type models with endogenous but age-unspecific mortality and perfect annuitisation. The realistic demographic modeling is important in as far as the economic impact of medical progress hinges on its impact on the age distribution of the population.[8] While Zhao (2014) also considers a realistic life-cycle pattern and an endogenous choice of health care, he does not touch on the role of medical progress.[9] Finally, Jones (2016) studies the interaction of conventional and life-saving R&D but does so within a social planner context.

The remainder of the article is structured as follows: The following section is devoted to a presentation of the model; Sections 2.3 and 2.4 solve for and characterize the individual life-cycle allocation and the general equilibrium of the economy, respectively; Section 2.5 provides an analytical assessment of the impact of medical progress; Section 2.6 presents the numerical analysis before Section 2.7 wraps up. Some of the proofs have been relegated to an Appendix.

[7] In contrast to the other approaches, the health care sector modeled in Kelly (2017) is not employing domestic production factors. Changes to the provision of health care are therefore unrelated to factor prices and final goods production.

[8] In particular, those models that assume infinitely-lived agents or an exogenous profile of mortality are abstracting altogether from a saving response to health-induced changes in longevity. As e.g. Bloom et al. (2003) and De Nardi et al. (2010) show, however, such a response is empirically relevant.

[9] OLG models with rich demography have been developed in other contexts (e.g. Boucekkine et al. 2002, D'Albis 2007, Heijdra and Mierau 2012, Heijdra and Romp 2009a,b). These models do not involve endogenous health and survival.

2.2 The Model

We consider an OLG model in which individuals choose consumption and health care over their life-course. Individuals are indexed by their age a at time t, with $t_0 = t - a$ denoting the birth year of an individual aged a at time t. At each age, individuals are subject to a mortality risk, where $S(a,t) = \exp\left[-\int_0^a \mu(\widehat{a}, h(\widehat{a},\widehat{t}), M(\widehat{t}))d\widehat{a}\right]$ is the survival function at (a,t), with $\mu(a, h(a,t), M(t))$ denoting the force of mortality. Following Kuhn et al. (2010, 2011, 2015) we assume that mortality can be lowered by the consumption of a quantity $h(a,t)$ of health care. In addition, we assume that mortality depends on the state of the medical technology $M(t)$ at time t. More specifically, we assume that the mortality rate $\mu(a, h(a,t), M(t))$ satisfies

$$\begin{aligned}\mu(a,h(a,t),M(t)) &\in (0,\tilde{\mu}(a,t)] \quad \forall\,(a,t)\,;\\ \mu_h(\cdot) &< 0,\ \mu_{hh}(\cdot) > 0;\\ \mu_h(a,0,M(t)) &= -\infty,\ \mu_h(a,\infty,M(t)) = 0 \quad \forall\,(a,t)\,;\end{aligned}$$

where $\tilde{\mu}(a,t) = \mu(a,0,M(t))$ is the "natural "mortality rate for an individual aged a at time t when no health care is consumed. By purchasing health care, an individual can lower the instantaneous mortality rate, and can thereby improve survival prospects, but can only do so with diminishing returns.[10]

In regard to medical technology, we assume the following properties

$$\mu_M(\cdot) < 0,\ \mu_{MM}(\cdot) \geq 0,\ \mu_{hM}(\cdot) \gtreqless 0 \quad \forall\,(a,t)\,.$$

Hence, medical technology contributes toward reductions in mortality ($\mu_M(\cdot) < 0$) with (weakly) decreasing returns. We leave it open, however, whether for any given positive level of health care, $h(a,t) > 0$, medical technology is complementing the consumption of health care ($\mu_{hM}(a,h(a,t),M(t)) \leq 0$) or substituting it ($\mu_{hM}(a,h(a,t),M(t)) > 0$).

Individuals enjoy period utility $u(c(a,t))$ from consumption $c(a,t)$. Period utility is increasing and concave: $u_c(\cdot) > 0$, $u_{cc}(\cdot) \leq 0$. In addition, we assume the Inada condition $u_c(c_0) = +\infty$ with $c_0 \geq 0$ denoting a level of subsistence consumption. Individuals maximize the present value of their expected life-cycle utility

$$\max_{c(a,t),h(a,t)} \int_0^\omega e^{-\rho a} u(c(a,t))S(a,t)da \tag{2.1}$$

by choosing a stream of consumption and health care on the interval $[0,\omega]$, with ω denoting the maximal possible age, with $\rho \geq 0$ denoting the rate of time preference, and with $S(a,t)$, defined above, denoting the survival function.[11],[12] The individual faces as constraints the dynamics of

[10] Zweifel et al. (2005) provide empirical evidence of decreasing returns to health expenditure in the reduction of mortality. The decreasing returns assumption is also reflected in other empirical work on the relationship between health care and mortality (e.g. Baltagi et al. 2012, Cremieux et al. 1999, Hall and Jones 2007, Lichtenberg 2004).

[11] While we are subsequently interpreting $S(a,t)$ as survival alone, the function may, in fact, be interpreted as a more general measure of health that is subject to depreciation over the life-course (see e.g. Chandra and Skinner 2012, Kuhn et al. 2015). Assuming that utility from consumption and utility from good health are multiplicatively separable, one could generalize the interpretation of (2.1) to include not only health-dependent duration of life but also health-dependent quality of life.

[12] Note that from the individual's perspective age and time progress simultaneously, following the identity $a \equiv$

survival and the dynamics of individual assets $k(a,t)$, as described by the system[13]

$$\begin{aligned} \dot{S}(a,t) &= -\mu(a,h(a,t),M(t))S(a,t), && (2.2)\\ \dot{k}(a,t) &= r(t)\,k(a,t)+l(a)w(t)-c(a,t) \\ &\quad -\phi(a,t)\,p_H(t)h(a,t)-\tau(a,t)+\pi(a,t)+s(t), && (2.3) \end{aligned}$$

with the boundary conditions

$$\begin{aligned} S(0,t_0) &= 1, \quad S(\omega,t_0+\omega)=0 && (2.4)\\ k(0,t_0) &= k(\omega,t_0+\omega)=0. && (2.5) \end{aligned}$$

Here, (2.2) describes the reduction of survival according to the force of mortality. According to (2.3) an individual's stock of assets $k(a,t)$ (i) increases with the return on the current stock, where $r(t)$ denotes the interest rate at time t; (ii) increases with earnings $l(a)w(t)$, where $w(t)$ denotes the wage rate at time t, and where $l(a)$ denotes an individual's effective age-dependent labor supply; (iii) decreases with consumption, the price of consumption goods being normalized to one; (iv) decreases with private health expenditure, $\phi(a,t)\,p_H(t)h(a,t)$, where $p_H(t)$ denotes the price for health care, and where $\phi(a,t)$ denotes an (a,t)-specific rate of coinsurance; (v) decreases with an (a,t)-specific tax, $\tau(a,t)$; (vi) increases with (a,t)-specific benefits $\pi(a,t)$; and (vii) increases with a transfer $s(t)$ by which the government redistributes accidental bequests in a lump-sum fashion. Here, we follow Ludwig et al. (2012) and Zhao (2014) by considering a setting without an annuity market.[14],[15] We assume that the survival function is bounded between 1 at birth and 0 at the maximum feasible age ω [see (2.4)], and that individuals enter and leave the life-cycle without assets [see (2.5)].

Denoting by $B(t-a)$ the size of the birth cohort at $t_0=t-a$, the cohort aged a at time t has the size

$$N(a,t)=S(a,t)B(t-a).$$

By aggregating over the age-groups who are alive at time t we obtain the following expressions for the population size,[16] aggregate capital stock, aggregate effective labor supply, aggregate

$t-t_0\in[0,\omega]$ for $t\in[t_0,t_0+\omega]$. Thus, we have $\int_0^\omega e^{-\rho a}u(c(a,t))S(a,t)da=\int_0^\omega e^{-\rho a}u(c(a,t_0+a))S(a,t_0+a)da=\int_{t_0}^{t_0+\omega}e^{-\rho t}u(c(t-t_0,t))S(t-t_0,t)dt$.

[13] In the following, we will use the $\dot{()}$ notation to indicate both the derivative $\dot{x}(a,t):=x_a+x_t$ for life-cycle variables and the derivative $\dot{X}(t):=X_t$ for aggregate variables. Drawing again on the identity $t\equiv t_0+a$ from the individual's perspective, it follows that $\dot{x}(a,t)$ collapses into a single dimension.

[14] This is well in line with evidence that few individuals annuitize their wealth (e.g. Reichling and Smetters 2015, Warshawsky 1988). Hansen and Imrohoroglu (2008) show that the empirically relevant hump-shaped life-cycle profiles of consumption can be consistently explained within a life-cycle model only when assuming that annuity markets are assumed to be absent (or severely imperfect).

[15] We have also considered a specification with imperfect annuities yielding a return $r(t)+\theta\overline{\mu}(a,t)$, where $\theta\in[0,1]$ and where $\overline{\mu}(a,t)=\mu(a,h^*(a,t),M(t))$ is the expected mortality, given the equilibrium level of health care $h^*(a,t)$. Following Heijdra and Mierau (2012) in considering a scenario with $\theta=0.7$, we obtain qualitatively similar results to those reported here.

[16] In a slight abuse of notation, $N(t)$ denotes the population size at time t, whereas $N(a,t)$ represents the size of the cohort aged a at time t.

consumption, aggregate demand for health care, aggregate fiscal income from taxation, and aggregate transfer payments, each at time t:

$$
\begin{aligned}
N(t) &= \int_0^\omega N(a,t)da, \\
K(t) &= \int_0^\omega k(a,t)N(a,t)da, \\
L(t) &= \int_0^\omega l\,(a)\,N(a,t)da, \\
C(t) &= \int_0^\omega c(a,t)N(a,t)da, \qquad (2.6) \\
H(t) &= \int_0^\omega h(a,t)N(a,t)da, \qquad (2.7) \\
\Upsilon\,(t) &= \int_0^\omega \tau\,(a,t)\,N(a,t)da, \\
\Pi\,(t) &= \int_0^\omega \pi\,(a,t)\,N(a,t)da.
\end{aligned}
$$

The economy consists of a manufacturing sector and a health care sector. In the manufacturing sector a final good is produced by employment of capital $K_Y(t)$ and labor $L_Y(t)$ according to a neoclassical production function $Y(K_Y(t), A\,(t)\,L_Y(t))$, with $A\,(t)$ measuring the state of labor augmenting technology. A manufacturer's profit can then be written as

$$V_Y(t) = Y(K_Y(t), A\,(t)\,L_Y(t)) - w(t)L_Y(t) - [\delta + r\,(t)]\,K_Y(t), \qquad (2.8)$$

where δ denotes the depreciation rate of capital.

Health care goods and services are produced by employment of labor $L_H(t)$, and capital $K_H(t)$ according to the neoclassical production function $F(K_H(t), L_H(t))$. Recalling the price for health care $p_H\,(t)$, the profit of a health care provider is then given by

$$
\begin{aligned}
V_H(t) &= p_H\,(t)\,F(K_H(t), L_H(t)) - w(t)L_H(t) \\
&\quad - [\delta + r\,(t)]\,K_H(t), \qquad (2.9)
\end{aligned}
$$

where we assume that capital depreciates at the same rate across both sectors. Note that the presence of perfect competition together with a neoclassical production function in the two sectors implies $V_Y(t) = V_H(t) = 0$ in equilibrium.

The government and/or a third-party payer (e.g. a health insurer) raise taxes (or contribution rates, e.g. insurance premiums) for the purpose of co-financing health care at the rate $1-\phi\,(a,t)$ and of paying out transfer payments $\pi\,(a,t)$. More specifically, $\pi\,(a,t)$ may refer to pension benefits, implying that

$$\pi\,(a,t) = \begin{cases} 0 \Leftrightarrow a < a_R \\ \pi \geq 0 \Leftrightarrow a \geq a_R \end{cases}$$

with π a uniform pension benefit and a_R the retirement age. In such a setting we would also have

$$l\,(a) = \begin{cases} \widehat{l}\,(a) \geq 0 \Leftrightarrow a < a_R \\ 0 \Leftrightarrow a \geq a_R \end{cases} .$$

Likewise, $\tau(a,t)$ are age-specific taxes. We could distinguish these into taxes used to finance health care payments (or health insurance premiums), $\tau_H(a,t)$, and social security contributions, $\tau_\Pi(a,t)$, where $\tau(a,t)=\tau_H(a,t)+\tau_\Pi(a,t)$. Furthermore, we could, in principle distinguish between lump-sum and labor income taxes, $\tau_j(a,t)=\widehat{\tau}_j(a,t)\,l(a)\,w(t)$, with $j=H,\Pi$. As long as we assume a unified government budget and an exogenous labor supply, it is sufficient to consider $\tau(a,t)$.

Assuming that the government budget must be balanced within each period t we obtain the constraint

$$\int_0^\omega \left\{ \begin{array}{c} [1-\phi(a,t)]\,p_H(t)\,h(a,t) \\ +\pi(a,t)-\tau(a,t) \end{array} \right\} S(a,t)B(t-a)da=0. \tag{2.10}$$

Finally, we assume that

$$s(t)=\frac{\Upsilon_B(t)}{N(t)}, \tag{2.11}$$

where

$$\Upsilon_B(t)=\int_0^\omega \mu(a,t)k(a,t)N(a,t)da \tag{2.12}$$

are total accidental bequests.[17]

2.3 Individual Life-Cycle Optimum

In Appendix 2.8.1 we show that the solution to the individual life-cycle problem is described by the following two sets of conditions

$$\begin{aligned} & \frac{u_c(c(a,t))}{\exp\left\{-\int_a^{\widehat{a}}\left[\rho+\mu\left(\widehat{\widehat{a}},t+\widehat{\widehat{a}}-a\right)\right]d\widehat{\widehat{a}}\right\}u_c(c(\widehat{a},t+\widehat{a}-a))} \\ = & \exp\left[\int_a^{\widehat{a}} r\left(t+\widehat{\widehat{a}}-a\right)d\widehat{\widehat{a}}\right], \end{aligned} \tag{2.13}$$

$$-\mu_h(a,t)\,\psi(a,t) = \phi(a,t)\,p_H(t) \quad \forall(a,t), \tag{2.14}$$

describing the optimal pattern of consumption $c(a,t)$ and the demand for health care $h(a,t)$, respectively, of an individual aged a at time t. Condition (2.13) is the well-known Euler equation, requiring that the marginal rate of intertemporal substitution between consumption at any two ages/years (a,t) and $(\widehat{a},t+\widehat{a}-a)$ equals the compound interest. Note that in the absence of annuity markets, the uninsured mortality risk can be interpreted as an additional factor of discounting, implying an effective discount rate $\rho+\mu(a,t)$ at any (a,t).

Condition (2.14) requires that at each (a,t) the marginal value of health care, $-\mu_h(a,t)\,\psi(a,t)$, equals its effective price, $\phi(a,t)\,p_H(t)$. The marginal value of health care

[17] In order to ease on notation, we will subsequently refer to the shortcut $\mu(a,t)$ for $\mu(a,h(a,t),M(t))$.

is given by the marginal effect of health care on mortality, $-\mu_h(a,t)$, weighted with the private value of life (VOL). The private VOL is defined by

$$\psi(a,t) := \int_a^{\omega} v(\widehat{a}, t+\widehat{a}-a)\, R(\widehat{a},a)\, d\widehat{a}, \tag{2.15}$$

with

$$v(a,t) := \frac{u(c(a,t))}{u_c(\cdot)}, \tag{2.16}$$

and

$$R(\widehat{a},a) := \exp\left[-\int_a^{\widehat{a}} r\left(t+\widehat{\widehat{a}}-a\right) d\widehat{\widehat{a}}\right], \tag{2.17}$$

and amounts to the discounted stream of consumer surplus, $v = u(\cdot)/u_c(\cdot)$ taken over the expected remaining life-course $[a,\omega]$.[18]

For a given set of prices, the evolution of consumption with age is described by (for a derivation see Appendix 2.8.1)

$$\dot{c} = \frac{u_c}{u_{cc}}(\rho - r + \mu). \tag{2.18}$$

Noting that $u_{cc} < 0$, it is readily seen that consumption tends to increase over the life-cycle if and only if $r - \rho > \mu$. In the absence of an annuity market, the uninsured mortality risk imposes a downward drag on consumption over the life-cycle and implies that consumption will eventually decrease with age when mortality μ grows sufficiently high.

For a given set of prices and a given state of the medical technology, the demand for health care evolves with age as described by (for a derivation see Appendix 2.8.1)

$$\dot{h} = \frac{-1}{\mu_{hh}}\left[\mu_{ha} + \mu_h\left(\frac{\dot{\psi}}{\psi} - \frac{\dot{\phi}}{\phi}\right)\right]. \tag{2.19}$$

Noting that $\mu_{hh} > 0$, the impact of age on the consumption of health care involves three forces: (i) the changing effectiveness of health care with age μ_{ha}, a stronger (weaker) effectiveness with age, $\mu_{ha} < 0\ (> 0)$ implying an increase (decrease) in health care; (ii) the rate at which the VOL changes with age, a decrease implying a reduction in health care; and (iii) changes with age in the co-insurance rate, ϕ, as e.g. during a transition from private to public health insurance at the onset of retirement.

Differentiating (2.15) with respect to age, we obtain the dynamics of the private VOL as

$$\dot{\psi}(a,t) = r(t)\,\psi(a,t) - \frac{u(c(a,t))}{u_c(c(a,t))}. \tag{2.20}$$

Thus, the private VOL increases with the interest rate and declines over time as the consumer surplus from a life-year lived is written off.

[18]The VOL as we calculate it here differs from the typical representation of the value of a statistical life as e.g. in Shepard and Zeckhauser (1984), Rosen (1988), Johansson (2002), or Murphy and Topel (2006) in as far as (i) the discount factor does not include the mortality rate; and (ii) the VOL does not include the current change to the individual's wealth, $lw - c - h - \tau + \pi + s$. Both of these features are due to the absence of an annuity market.

2.4 General Equilibrium

Perfectly competitive firms in the production sector choose labor $L_Y(t)$ and capital $K_Y(t)$ so as to maximize period profit (2.8). The first-order conditions imply

$$\begin{aligned} r(t) &= Y_{K_Y}(t) - \delta && (2.21) \\ w(t) &= Y_{L_Y}(t), && (2.22) \end{aligned}$$

i.e. the factor prices are equalized with their respective marginal products.

Likewise, perfectly competitive providers of health care choose labor $L_H(t)$ and capital $K_H(t)$ so as to maximize period profit (2.9). From the first-order condition we obtain

$$\begin{aligned} r(t) &= p_H(t) F_{K_H}(t) - \delta && (2.23) \\ w(t) &= p_H(t) F_{L_H}(t). && (2.24) \end{aligned}$$

Combining these conditions with (2.21) and (2.22) we obtain

$$p_H(t) = \frac{Y_{L_Y}(t)}{F_{L_H}(t)} = \frac{Y_{K_Y}(t)}{F_{K_H}(t)}, \tag{2.25}$$

implying that capital and labor inputs are distributed across the production and health care sector in a way that equalizes the marginal rate of transformation (i.e. the relative output gain in production as compared to the output loss in health care from re-allocating one factor unit from health care into production) with the price for health care. The higher the latter, the greater the marginal rate of transformation, implying that more workers will be allocated to the health care sector. With appropriate Inada conditions, $Y_{L_Y}(K_Y, 0) = Y_K = (0, AL_Y) = \infty$ and $F_{L_H}(K, 0) = F_K(0, L_H) = \infty$ we always have an interior allocation with $L_H(t) = L(t) - L_Y(t) \in (0, L(t))$ and $K_H(t) = K(t) - K_Y(t) \in (0, K(t))$.

2.4.1 Market Clearance and General Equilibrium

Our setting involves four markets: two input markets for capital and labor, respectively; and two output markets for health care and for final goods, respectively. From the four market clearing conditions

$$\begin{aligned} K_Y(t) + K_H(t) &= K(t), \\ L_Y(t) + L_H(t) &= L(t) \\ F(t) &= H(t), \\ Y(t) &= C(t) + \dot{K}(t) + \delta K(t), \end{aligned}$$

we obtain a set of equilibrium prices $\{r^*(t), w^*(t), p_H^*(t)\}$ as well as the level of net capital accumulation $\dot{K}(t)$. We provide a more detailed description of the general equilibrium structure in Appendix 2.8.2.

2.5 Impact of Medical Progress

Demand for health care and value of life (VOL): In Appendix 2.8.4 we show that the impact of medical progress, as measured by an increase in the level of medical technology, $dM > 0$, on the demand for health care at (a, t) is described by

$$\frac{dh\,(a,t)}{dM} = \underbrace{\frac{-\mu_{hM}}{\mu_{hh}}}_{\text{(i)}} + \underbrace{\frac{\mu_h\,(a,t)}{\mu_{hh}}}_{<0} \left(\frac{1}{p_H\,(t)} \underbrace{\frac{dp_H\,(t)}{dM}}_{\text{(ii)}} - \frac{1}{\psi\,(a,t)} \underbrace{\frac{d\psi\,(a,t)}{dM}}_{\text{(iii)}} \right). \tag{2.26}$$

Term (i) represents the effect of medical technology on the demand for health care through changes in the effectiveness of care. If technology raises the marginal effectiveness of health care ($\mu_{hM} < 0$), term (i) is positive and more health care will be consumed at (a, t) in response to medical progress. Term (ii) implies that the demand for health care tends to fall if medical progress raises the price for health care. Finally, the demand for health care changes in line with the impact of medical progress on the VOL [term (iii)].

The impact of medical progress on the VOL can be written as

$$\frac{d\psi\,(a,t)}{dM} = \int_a^{\omega} R(\widehat{a},a) \Bigg(- v\,(\widehat{a}, t+\widehat{a}-a) \underbrace{\int_a^{\widehat{a}} \frac{dr(t+\hat{\hat{a}}-a)}{dM} d\hat{\hat{a}}}_{\text{(iii.i)}} \underbrace{\frac{dv\,(\widehat{a}, t+\widehat{a}-a)}{dM}}_{\text{(iii.ii)}} \Bigg) d\widehat{a} \tag{2.27}$$

where $v\,(\widehat{a}, t+\widehat{a}-a)$ and $R(\widehat{a}, a)$ are given by (2.16) and (2.17), respectively, and where

$$\frac{dv\,(\widehat{a}, t+\widehat{a}-a)}{dM} = \left(1 - \frac{uu_{cc}}{u_c^2}\right) \frac{dc\,(\widehat{a}, t+\widehat{a}-a)}{dM}. \tag{2.28}$$

Thus, technology bears on the VOL through two channels: through changes in the interest rate at which the monetary value of each remaining life year is discounted [term (iii.i)], and through changes in age-specific consumption over the remaining life-course [term (iii.ii) and (2.28)]. According to (iii.i), the VOL increases whenever improvements in medical technology reduce the interest rate, an effect that arises only in general equilibrium. Noting that $1 - \frac{uu_{cc}}{u_c^2} > 0$ (see Appendix 2.8.4), term (iii.ii) implies that a positive effect of medical technology on future consumption translates into an increase in the demand for health care.

Generally, we can write $c\,(\widehat{a}, t+\widehat{a}-a) = c\,(a,t) \exp\left[\int_a^{\widehat{a}} g_c(\hat{\hat{a}}, t+\hat{\hat{a}}-a) d\hat{\hat{a}}\right]$, where $c\,(a,t)$ is the initial consumption level at birth, and where

$$g_c(\hat{\hat{a}}, t+\hat{\hat{a}}-a) := \frac{u_c}{u_{cc} c(\hat{\hat{a}}, t+\hat{\hat{a}}-a)} \left[\rho - r(t+\hat{\hat{a}}-a) + \mu(\hat{\hat{a}}, t+\hat{\hat{a}}-a)\right]$$

is rate of consumption growth at $(\hat{\hat{a}}, t+\hat{\hat{a}}-a)$ as given by the dynamic Euler equation (2.18). Thus, we have

$$\frac{dc\,(\widehat{a}, t+\widehat{a}-a)}{dM} = c\,(\widehat{a}, t+\widehat{a}-a) \left\{ \frac{1}{c\,(a,t)} \frac{dc\,(a,t)}{dM} + \int_a^{\widehat{a}} \frac{dg_c(\hat{\hat{a}}, t+\hat{\hat{a}}-a)}{dM} d\hat{\hat{a}} \right\}, \tag{2.29}$$

according to which the impact of medical progress on consumption at $(\widehat{a}, t+\widehat{a}-a)$ is governed by two possibly offsetting effects: the impact on initial consumption $c\,(a,t)$, which is implicitly determined through the life-cycle budget constraint, and the impact on the growth rate of consumption over the life-cycle, the latter of which depends in particular on changes in the interest rate and the mortality rate. More specifically, medical change tends to increase the growth rate of consumption at $(\hat{\hat{a}}, t+\hat{\hat{a}}-a)$ to the extent that it increases the spread between interest rate and mortality rate $r(t+\hat{\hat{a}}-a)-\mu(\hat{\hat{a}}, t+\hat{\hat{a}}-a)$, e.g. by lowering mortality.

Prices: Given the various offsetting effects in (2.26)-(2.29) it is difficult to arrive at a general statement about the impact of medical technology on the VOL and on the demand for health care without placing undue restrictions on the model. At this point, we therefore content ourselves with having identified the various channels through which medical progress feeds on consumption and the demand for health care and defer a quantitative assessment of the various offsetting effects to our numerical analysis in Section 2.6.

In the following, let us assume that the production in the final goods and health care sector, respectively, is described by the set of Cobb-Douglas production functions

$$Y\,(t) = K_Y\,(t)^{\alpha}\left[A\,(t)\,L_Y(t)\right]^{1-\alpha} \tag{2.30}$$

$$F\,(t) = K_H\,(t)^{\beta}\left[L_H(t)\right]^{1-\beta}, \tag{2.31}$$

with $\alpha, \beta \in [0,1]$. The general equilibrium feedback on the demand for health care is then driven by changes in the market interest rate. Noting from Appendix 2.8.3 that all prices in the economy can be calculated as a function of the interest rate, we show in Appendix 2.8.4 that

$$\frac{dw\,(t)}{dM} = -\frac{\alpha}{1-\alpha}\frac{w\,(t)}{r\,(t)+\delta}\frac{dr\,(t)}{dM}, \tag{2.32}$$

$$\frac{dp_H\,(t)}{dM} = \frac{p_H\,(t)}{r\,(t)+\delta}\frac{\beta-\alpha}{1-\alpha}\frac{dr\,(t)}{dM}, \tag{2.33}$$

The general equilibrium impact of medical progress on the wage rate as well as on the price for health care is thus determined by its effect on the market interest rate. Most importantly, the impact of medical change on the wage rate is always opposite to its impact on the interest rate. This is because a reduction (increase) in the market interest rate leads to an increase (reduction) of capital employed in production which translates into an increase (decrease) in the marginal productivity of labor. The effect of medical progress on the price of health care is ambiguous. As equation (2.33) indicates, we have $sgn\frac{dp_H(t)}{dM} = -sgn\frac{dr(t)}{dM}$ if and only if $\beta < \alpha$, i.e. if and only if the capital elasticity is lower in the health care sector as compared to the remaining industry. In Section 6.1 we will provide empirical evidence to the effect that this is, indeed, the case. Whenever medical change induces a reduction in the interest rate, this will then lead to a corresponding boost in the wage rate, which also drives up the price for health care, the latter being produced in a relatively labor intensive way.

While we are unable to present a closed theoretical expression for the effect of medical progress on the market interest rate, $\frac{dr(t)}{dM}$, we can draw on the mechanics of the capital market to derive some insight into the matter. Denote by $K_Y^d\,(t,r)$ and $K_H^d\,(t,r)$ the capital demand functions in the final goods and health care sector, respectively. From (2.21) and (2.23) it is readily checked that ceteris paribus capital demand decreases in the interest rate r and does not directly depend on M. In contrast, the supply of capital $K^s(t,r,M)$ can be shown ceteris paribus to increase with the interest rate and with the level of technology M. Denote by $r(t)$ the interest rate that equilibrates the capital market such that $K_Y^d(t,r(t)) + K_H^d(t,r(t)) = K^s(t,r(t),M)$ in period t and consider now an improvement in medical technology, $dM > 0$. While it is difficult to assess the general equilibrium impact, it is easy to see that the instantaneous impact involves an outward shift of the capital supply function and, thus, $K_Y^d(t,r(t))+K_H^d(t,r(t)) < K^s(t,r(t),M+dM)$. The excess supply of capital then implies a downward pressure on the interest rate, $\frac{dr(t)}{dM} < 0$. But then an improvement of medical technology should also imply $\frac{dw(t)}{dM} > 0$ and $\frac{dp_H(t)}{dM} > 0$. This intuition is, indeed, confirmed by the numerical analysis in Section 6.3.1.

Economic performance (GDP): Finally, consider the impact of medical progress on the GDP per capita as a measure of economic performance. Note that in our framework GDP is defined as the sum of output in the final goods and health care sector, as measured in units of the final good, $GDP(t) = Y(t) + p_H(t)F(t)$. Expressing GDP per capita

$$\frac{GDP(t)}{N(t)} = \frac{L(t)}{N(t)}\frac{GDP(t)}{L(t)}$$

as the product of the employment rate $\frac{L(t)}{N(t)}$ and the GDP per worker $\frac{GDP(t)}{L(t)}$ it is easy to see that the impact of medical progress on economic performance comes (i) through a change in the employment rate; and (ii) through a change in the GDP per worker. The impact of medical innovation on the employment rate strongly depends on the age-profile of mortality rates and their dependency on medical progress. While the dependency is generally ambiguous, we would conjecture that in developed economies in which technology-related gains in survival are concentrated amongst the older population, the likely impact of medical progress on the employment rate is negative, and this is, indeed, confirmed by our numerical simulation calibrated to the US setting.

In Appendix 2.8.3 we show that for the Cobb-Douglas functions in (2.30) and (2.31) we can write the equilibrium level of GDP per worker as a function of the employment share $\lambda(t) := L_Y(t)/L(t)$ and the aggregate capital intensity $K(t)/L(t)$

$$\begin{aligned}\frac{GDP(t)}{L(t)} &= \frac{Y(t)+p_H(t)F(t)}{L(t)} = \left[1+\frac{p_H(t)F(t)}{Y(t)}\right]\frac{Y(t)}{L(t)} \\ &= \frac{1-\alpha+(\alpha-\beta)\lambda(t)}{1-\beta}A(t)^{1-\alpha}\left[\frac{\alpha(1-\beta)}{\beta(1-\alpha)+(\alpha-\beta)\lambda(t)}\frac{K(t)}{L(t)}\right]^{\alpha} \end{aligned} \quad (2.34)$$

Taking the total differential of this expression with respect to M we can then show that (see Appendix 2.8.4)

$$\begin{aligned}\frac{d}{dM}\left(\frac{GDP(t)}{L(t)}\right) &= \frac{-(1-\alpha)(\alpha-\beta)^2[1-\lambda(t)]}{[1-\alpha+(\alpha-\beta)\lambda(t)][\beta(1-\alpha)+(\alpha-\beta)\lambda(t)]}\frac{GDP(t)}{L(t)}\frac{d\lambda(t)}{dM} \\ &\quad +\alpha\frac{GDP(t)}{K(t)}\frac{d}{dM}\left(\frac{K(t)}{L(t)}\right). \end{aligned} \quad (2.35)$$

As is readily verified we have that $\frac{d}{dM}\left(\frac{GDP(t)}{L(t)}\right) > 0$ holds if $\frac{d\lambda(t)}{dM} \leq 0$ and $\frac{d}{dM}\left(\frac{K(t)}{L(t)}\right) \geq 0$. Thus, medical progress tends to raise GDP per worker if (i), for a given structure of the economy as described by the employment share $\lambda(t)$, it leads to capital deepening, i.e. to an increase in the economy-wide capital intensity $\frac{K(t)}{L(t)}$; and (ii) it induces a shift in resources to the more labor intensive health care sector, as measured by a decline in the employment share of final goods production $\lambda(t)$.[19] Our numerical analysis in section 2.6 shows that, indeed, medical innovation triggers both an increase in the aggregate capital stock per worker and a reduction in final goods employment. Thus, its impact on the GDP per worker is unambiguously positive. Whether or not this induces an increase in GDP per capita then depends on the extent to which the the employment rate $L(t)/N(t)$ is curbed by medical progress. For the US health care context studied in Section 2.6 , we find the increase in the GDP per worker to be the (weakly) dominating effect.

2.6 Numerical Analysis

Following a description of our numerical analysis, we present the outcomes for three scenarios, consisting of a benchmark and two numerical experiments. The benchmark features a realistic economy calibrated to US data, reflecting the year 2003. The experiments involve (i) the impact of an unanticipated medical advance, leading to a reduction in mortality; and (ii) the impact of the same advance when it is anticipated.

2.6.1 Specification of the Numerical Analysis

The main components of our numerical model are specified as follows.

Demography

With model time progressing in single years, individuals enter the model economy at age 20 and can live up to a maximum age 100.[20] In our model, a "birth" at age 20 implies that $\omega = 80$. Population growth is partly endogenous due to endogenous mortality and partly exogenous due to a fixed growth rate of "births" $\nu = 0.013$, which is calibrated to match the elderly share of the adult (20 years and older) US population, equaling 17.6% according to the decennial census in the US in 2000. Due to the exogenous path of births, our results will not be confounded by a variation in birth numbers across the experiments.

Mortality

The force of mortality μ is endogenously determined in the model, depending on health care, h, as a decision variable; an exogenous level of medical technology, M; and an exogenous age-dependent base mortality, $\widetilde{\mu}(a)$. As not all reductions in mortality can be attributed to health

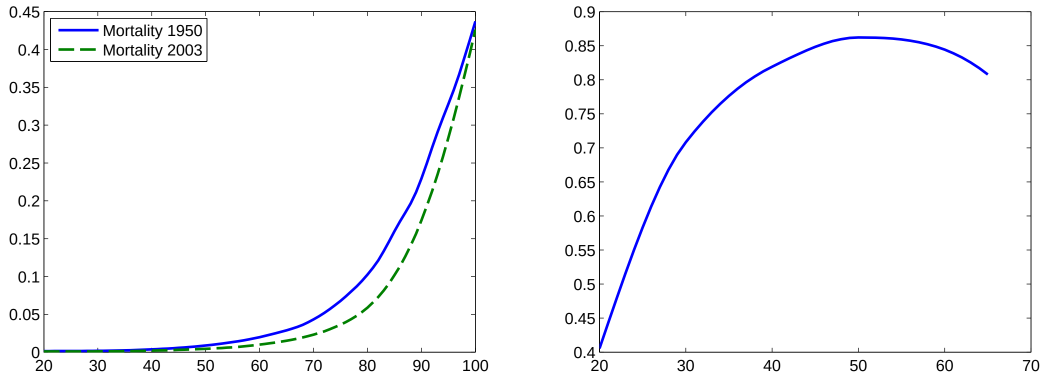
[19] It is easy to verify that a decline in the employment share $\lambda(t)$ will in optimum be accompanied by a decline in $K_Y(t)/K(t)$.

[20] We follow the bulk of the literature and neglect life-cycle decisions during childhood.

expenses or technological progress (see e.g. Hall and Jones 2007), we introduce an exogenous factor $I(a)$ that captures changes in age-dependent mortality rates due to exogenous circumstances. Generalizing Kuhn et al. (2011, 2015) we formulate

$$\mu(a,t) = \widetilde{\mu}(a) \cdot \Big(I(a) - \eta(a) \left[h(a,t) \cdot M(t) \right]^{\epsilon(a)} \Big),$$

where $\eta(a)$ and $\epsilon(a)$ are parametric functions that reflect decreasing efficiency of health care with age. The base mortality $\widetilde{\mu}(a)$ reflects a mortality profile that is higher in level (to a sufficient extent) than the US mortality in the year 2003, which we aim to replicate in the calibration. For this purpose we employ for $\widetilde{\mu}(a)$ single year mortality rates for the year 1950 in the US, as reported in the Human Mortality Database (HMD) (see Figure 2.1a). The age-dependent parametric functions $\eta(a)$, $\epsilon(a)$ and $I(a)$ are then chosen to approximate age-specific health expenditures and mortality $\mu(a,t)$ in the year 2003.[21] We normalize the state of medical technology to the year 2003 and, thus, set $M(t) \equiv 1$ in the benchmark case.



(a) US 1950 and 2003 Force of mortality (HMD) *(b) Age-specific labor employment schedule*

Figure 2.1: Mortality and labor employment age-profiles

Utility

We assume instantaneous utility to be given by

$$u(a,t) = b + \frac{(c(a,t) - c_0)^{1-\sigma}}{1-\sigma},$$

where $c_0 = \$11000$ is an exogenous minimal consumption level.[22],[23] We choose the inverse of the elasticity of intertemporal substitution to be $\sigma = 1.75$ which is within the range of em-

[21] The 2003 mortality rates are again taken from HMD. Due to limited data availability, we use health expenditure data for the year 2000, as provided in Meara et al. (2004).

[22] Dollar values are to be interpreted as year 2003 Dollars throughout.

[23] We use the minimum consumption for reasons of improving the fit of the consumption profile. While the minimum level is never hit in optimum, it helps to avoid an unrealistically sharp drop in consumption during the oldest ages.

pirically consistent values, as suggested by Chetty (2006). Setting $b = 8$ then guarantees that $u(a,t) \geq 0$ throughout. Furthermore, $b = 8$ generates a VOL that lies within the range of plausible estimates, as suggested in Viscusi and Aldy (2003). Finally, we assume a rate of time preference $\rho = 0.02$.

Effective labor supply and income

We proxy the effective supply of labor $l\,(a)$ by an age-specific income schedule (see Figure 2.1b), constructed from 2003 earnings data, as contained in the Current Population Survey (CPS) provided by the Bureau of Labor Statistics (BLS). We rescale the schedule such that the employment-population ratio $L(t)/N(t)$ matches the empirical value of 62% for the US in 2003 as reported by the BLS. Individuals at the age 65 or older are assumed to have no income from labor but receive a fixed social security pension for the remainder of their lifetime, as detailed further on below.

Production

There are two production functions in the model. Production of the final good is described by

$$Y(t) = K_Y(t)^\alpha (A(t)L_Y(t))^{1-\alpha},$$

where $K_Y(t)$ and $L_Y(t)$ denote capital and labor in final good production, where $L_Y(t)$ is the workforce working in this sector, and where $A(t)$ is an exogenous technology index. $A(t)$ is calibrated so that $l(50)w(t)$ matches the average earnings of a 50-year old in 2003; the elasticity of capital α is chosen to be $1/3$.

The health care sector produces medical goods and services that individuals purchase with a view to lowering their mortality. Its production is given by

$$F(t) = K_H(t)^\beta (L_H(t))^{1-\beta},$$

where $K_H(t)$ and $L_H(t)$ denote capital and labor in this sector. For the production elasticity of capital in the health care sector we take an estimate from Acemoglu and Guerrieri (2008) and set $\beta = 1/5$. Finally, we assume a rate of capital depreciation equal to $\delta = 0.05$.

Health Insurance, Medicare and Social Security

Health expenditures are subsidized through two different sources: (a) private health insurance with coinsurance rate ϕ_P and (b) Medicare for the elderly (available after retirement) with coinsurance rate ϕ_{MC}. Private health insurance is financed through a "risk-adequate" premium equal to the expected health expenditure covered by the insurance for an individual at a given time and age. It is thus given by $\tau_P = [1 - \phi_P(a,t)]\, p_H(t)h^*(a,t)$, where $h^*(a,t)$ denotes the equilibrium demand for health care at (a,t). Following Zhao (2014) we assume that 70% of the US workforce is health insured, with 70% of expenses being covered (in 2000). Thus, we assume that 51% of health expenditures are paid out-of-pocket on average among the working population. Zhao (2014) states that 35% of the elderly have health insurance with a coverage of 30%, leading to average health insurance subsidies of 10.5%. Medicare is financed through a payroll tax, with the rate $\hat{\tau}_{MC}$ being endogenously determined such that the Medicare budget constraint holds. We assume that Medicare covers 38 % of the health expenses of the elderly[24]. This results in 51.5% out-of-pocket expenditures for the elderly. In total, the out-of-pocket share of health expenses paid by the individual is

$$\phi = \begin{cases} 0.51 \text{ if } a < a_R \\ 0.515 \text{ if } a \geq a_R, \end{cases}$$

where a_R is the mandatory age of retirement. The budget-constraint for Medicare is given as follows:

$$\int_{a_R}^{\omega} [1 - \phi_{MC}(a,t)]\, p_H\,(t)\, h(a,t) N(a,t) da = \hat{\tau}_{MC}(t) w(t) L(t),$$

where $1 - \phi_{MC}(a,t)$ is the share of health expenditures paid by Medicare and where $\hat{\tau}_{MC}$ is the payroll tax for Medicare.

Social security, received by retirees, is financed through a payroll tax which is determined endogenously from the social security budget constraint:

$$\int_{a_R}^{\omega} \pi(a,t) N(a,t) da = \hat{\tau}_{\Pi}(t) w(t) L(t),$$

where $\pi(a,t)$ is the social security pension and $\hat{\tau}_{\Pi}$ the payroll tax devoted to social security. We assume social security benefits to be exogenous and use the CPS Annual Social and Economic Supplement data for the year 2003 which states an approximately \$10300 mean social security income for individuals aged 65 years or older in 2003. Thus, we set $\pi(a,t) = \$10300$ for $a \geq a_R$ and otherwise to zero.

Altogether, individuals face the following taxes (including the premium for the private health insurance):

$$\tau(a,t) = \underbrace{\hat{\tau}_{\Pi}(t) l(a) w(t)}_{=\tau_{\Pi}(a,t)} + \underbrace{\underbrace{\hat{\tau}_{MC}(t) l(a) w(t)}_{=\tau_{MC}(a,t)} + \underbrace{[1 - \phi_P(a,t)]\, p_H(t) h^*(a,t)}_{\tau_P(a,t)}}_{=\tau_H(a,t)}.$$

Overview of Functional Forms and Parameters

Table 2.1 summarizes the functional forms and parameters we are employing. Table 2.2 shows further parameters and functional forms that are used in the calibration to match various empirical targets. The $\equiv$ symbol denotes that the function is assumed to be constant in all arguments.

In the following, we will present the numerical results (see Appendix 2.8.5 for details on the solution of the numerical problem) for the benchmark case and three numerical experiments. We focus on a selection of the most salient outcomes.

[24] This value was calculated based on the following data of the US economy in 2003: Share of the elderly in total health spending =40% (NHEA); health share in the GDP =15% (NHEA); Medicare share in the GDP =2.3% (Zhao 2014).

Parameter & Functional Forms	Description
$\omega = 80$	life span
$t_0 = 120$	entry time of focal cohort, year 2003
$\rho = 2\%$	pure rate of time preference
$\sigma = 1.75$	inverse elasticity of intertemporal substitution
$c_0 = \$11000$	subsistence minimum
$a_R = 65$	mandatory retirement age
$\delta = 5\%$	rate of depreciation
$\alpha = 1/3$	elasticity of capital in Y
$\beta = 1/5$	elasticity of capital in F
$u(a,t) = b + \frac{(c(a,t)-c_0)^{(1-\sigma)}}{1-\sigma}$	instantaneous utility function
$B(t) = B_0 \exp[\nu t]$	number of births
$s(t) = \frac{\Upsilon_B(t)}{N(t)}$	transfer from accidental inheritances
$Y(t) = K_Y(t)^{\alpha}(A(t)L_Y(t))^{(1-\alpha)}$	production in manufacturing sector
$F(t) = K_H(t)^{\beta}(L_H(t))^{1-\beta}$	production in health sector
$\mu(a,t) = \widetilde{\mu}(a)\left(I(a) - \eta(a)\left[h(a,t)M(t)\right]^{\epsilon(a)}\right)$	age-time specific mortality rate
$\phi(a,t) = \{0.51 \text{ if } a < a_R,\ 0.515 \text{ if } a \geq a_R\}$	age-specific total coinsurance

Table 2.1: Parameters and functional forms

Parameter & Functional Forms	Description	Targets to match
$b = 8$	constant offset in utility function	Value of Life
$\nu = 0.013$	growth rate of births	Population share of 65 years and older
$I(a)$	exogenous impacts on mortality	Life-expectancy
$\epsilon(a)$	concavity in mortality function	Age-specific health expenditures
$\eta(a)$	effectiveness of health care	Age-specific health exp. and life-expectancy
$M(t) \equiv 1$	medical technology	Aggregate health exp. and life-expectancy
$A(t) \equiv 2.995$	manufacturing technology	GDP per capita
$\pi(a,t) = \{0 \text{ if } a < a_R,\ \$10300 \text{ if } a \geq a_R\}$	pension	Social Security
$\phi_P(a,t) = \{0.51 \text{ if } a < a_R,\ 0.895 \text{ if } a \geq a_R\}$	age-specific private coinsurance	Data in Zhao (2014)
$\phi_{MC}(a,t) = \{1 \text{ if } a < a_R,\ 0.62 \text{ if } a \geq a_R\}$	age-specific Medicare coinsurance	Data in Zhao (2014)

Table 2.2: Targets to match

2.6.2 Benchmark

In order to economize on space we illustrate the benchmark allocation in the same graphs as our first experiment: unanticipated medical advance (see Figures 2.3-2.5). The benchmark allocation is depicted by blue, solid plots throughout, whereas the experiments are depicted by green, dashed plots. Some figures also contain red, dotted plots, which refer to a partial equilibrium allocation.

The salient features of the benchmark allocation can be summarized as follows. Consumption of the focal cohort, entering at $t_0 = 120$ (when they are 20 years old), is hump-shaped (see Figure 2.3). The fact that the interest rate (approx. 4.3%) lies above the rate of time preference (2%) implies a rising consumption until around age 70. Due to missing annuity markets, consumption falls, however, at higher ages as implied by the individual Euler equation (2.18). Individual health expenditures follow a hump-shaped pattern (Figure 2.3). While the demand for care grows very moderately up to age 40, it exhibits from then on a strong increase up to age 80 before dropping again for the highest ages. Figure 2.2 illustrates our model fit with respect to age-specific health care expenditures[25]. Similar to the simulation in Hall and Jones (2007), we underestimate health care expenditures until approximately age 40 and overestimate them until the peak at approximately age 80. This is likely due to our focus on health care expenditures affecting survival, as opposed to, for instance, costs caused by pregnancy. Nevertheless, we match age-specific health expenditures by Meara et al. (2004) until age 80 within a reasonable margin of error. While health care expenditures do not fall in Meara et al. (2004), who use an open age interval for all ages 80 years and older, our result of falling health expenditures after age 80 is in line with the simulation in Hall and Jones (2007) and the qualitative life-cycle pattern observed in Martini et al. (2007).[26]

The value of life (VOL) peaks at approx. age 50 (Figure 2.3), which is consistent with empirical evidence on the value of a statistical life in Aldy and Viscusi (2008). The remaining life expectancy at age 20 is 58.0 years in the benchmark case and, thus, matches the empirical value for the US in 2003 (58.1 years, HMD) very closely.

It is worth of note that given our assumption of constant A, M and ν, prices and per-capita quantities are constant in the benchmark scenario. Thus, a steady state appears to exist although we are not imposing it. In the benchmark model GDP per capital amounts to \$39700 [\$39700 according to Table 1.5.5 of the revised National Income and Product Accounts of the Bureau of Economic Analysis (BEA), 2003], and health expenditures per capita to \$5720 [\$5750 according to NHEA, 2003]. The health share (in GDP) in the benchmark case is 14.4% and matches the data from the National Health Expenditure Accounts provided by CMS.[27] Furthermore, the benchmark model features a Medicare share of 2.3% [2.3% according to Zhao (2014)]. A sum-

[25]The age-specific health care expenditure data from Meara et al. (2004) and those from Hall and Jones (2007) were both taken from the simulation program employed by Hall and Jones (2007), as available at http://web.stanford.edu/ chadj/datasets.html.

[26]Indeed, the averaging of health care expenditures across the highest age groups is prone to mask an ultimate decline with age as the population shares used for the weighting are rapidly declining, too. Furthermore, a hump-shaped pattern is not inconsistent with the finding that health care utilization/expenditure increases with the closeness to death (e.g. Zweifel et al. 1999). This is because the "cost of dying" itself is declining with age for the highest ages (e.g. Cutler 2007).

[27]GDP and the health share are calculated as $GDP(t) = p_H(t)H(t) + Y(t)$ and $\frac{p_H(t)H(t)}{GDP(t)} = \frac{p_H(t)H(t)}{p_H(t)H(t)+Y(t)}$, respectively.

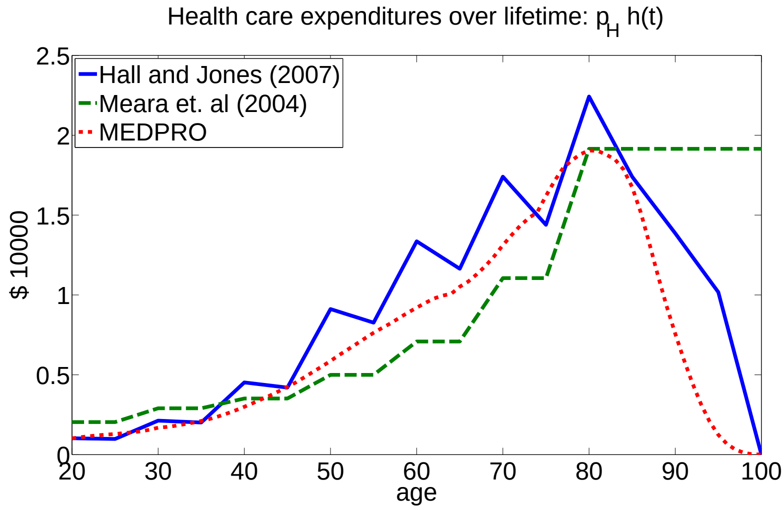


Figure 2.2: Health care expenditure over lifetime from the simulation in Hall and Jones (2007) (blue, solid line), the empirical data in Meara et al. (2004) (green, dashed line) and the MEDPRO Simulation (red, dotted line)

mary of the model's fit is provided in Table 2.3.[28,29]

Name	Data	Benchmark	Medical advance
Capital-output ratio	3.1	3.3	3.5
GDP per capita	$39700	$39700	$40000
Health spending per capita	$5750	$5720	$6420
Health spending (% of GDP)	14.4%	14.4%	16.0 %
Life expectancy at age 20	58.1	58.0	59.5
Medicare payroll tax rate, $\hat{\tau}_{MC}$	2.9 %	3.4 %	3.8 %
Medicare expenditures (% of GDP)	2.3%	2.3 %	2.7 %
Population share 65 years and older	17.6 %	17.5 %	18.4 %
Employment-Population ratio	62 %	62 %	61.5 %

Table 2.3: Fit of the benchmark model (data provided for the year 2003) and outcomes for an unanticipated medical advance

Before setting out on the experiments a clarifying remark is warranted on the purpose and

[28]The capital-output ratio was calculated as the ratio of the capital stock and the gross domestic product as provided in the National Income and Production Accounts of the Bureau of Economic Analysis (BEA) in 2003. In the model it is calculated as $K(t)/GDP(t)$.

[29]Note, that the population share of individuals aged 65 or older as well as the employment-population ratio refers to the total population aged 20 or older.

design of our numerical analysis. The main objective of our analysis lies in an analytical and quantitative understanding of the mechanisms which are underlying the macro-economic impacts of medical change. In order to avoid that these impacts are confounded by other sources of change, we have structured our numerical analysis in a way that the economy is "quasi-stationary" in the years surrounding the shock. This is why we are abstracting from time-trends in the states of technology, $A(t)$ and $M(t)$ as well as in the birth rate ν, the appropriate calibration of which would have allowed us to arrive at a more realistic dynamic representation of the economy.[30] This notwithstanding, we have calibrated the model to the US economy in the year 2003 in order to provide a realistic static backdrop for our experiments.

2.6.3 Medical Advance

Unanticipated Medical Advance

We consider here an unanticipated increase in the state of the medical technology from $M(t) = 1$ for $t \leq 150$ to $M(t) = 2$ for $t > 150$. The advance of medical technology renders the use of health care in lowering mortality more effective.[31] The timing implies that the focal cohort, entering the model at $t_0 = 120$, is aged 50 at the point of the innovation.

Based on a comparison of steady-state values, we find that the innovation raises the remaining life-expectancy of a 50 year old by some 1.1 years and induces additional (discounted) expenditures of about \$19000 over the remaining life-course. These magnitudes are broadly in line with evidence provided by Cutler (2007) on the impact of revascularisation, as was introduced into the US during the late 1980s. Cutler finds that for a patient with myocardial infarction, revascularisation would raise life-expectancy by about 1 year and induce about \$40000 in additional expenditure. While the impact of innovation in our model is, thus, comparable in the order of magnitude, it should be borne in mind that the figures are not directly comparable, as in Cutler (2007) the values apply (ex-post) to individuals who have had a heart attack, whereas in our model they apply (ex-ante) to a representative agent.

At the level of the individual, we find the following effects of an unanticipated medical advance: As Figure 2.3 illustrates, and as one would expect, the innovation induces individuals at age 50 to reallocate expenditure from consumption to health care. Indeed, the drop in consumption is persistent over the remaining life-cycle but the highest ages, where the increase in survival chances induces individuals to raise consumption. When it comes to the impact of the innovation on the demand for health care (as measured by individual health expenditure), a more

[30] For instance, we could match both, the age-structure and the rate of population growth in 2003 (0.9%) by assuming an appropriate time-profile of the birth rate ν prior to the year 2003. While this would give us a (more) realistic description of the demographic change following the year 2003, the impact of this on the economy would interfere with our experiments.

[31] To see this note that

$$\begin{aligned}
\mu_h(a,t) &= -\widetilde{\mu}(a)\eta(a)\epsilon(a)M(t)^{\epsilon(a)}h(a,t)^{\epsilon(a)-1} < 0, \\
\mu_M(a,t) &= -\widetilde{\mu}(a)\eta(a)\epsilon(a)M(t)^{\epsilon(a)-1}h(a,t)^{\epsilon(a)} < 0, \\
\mu_{hM}(a,t) &= -\widetilde{\mu}(a)\eta(a)(\epsilon(a))^2[M(t)h(a,t)]^{\epsilon(a)-1} < 0.
\end{aligned}$$

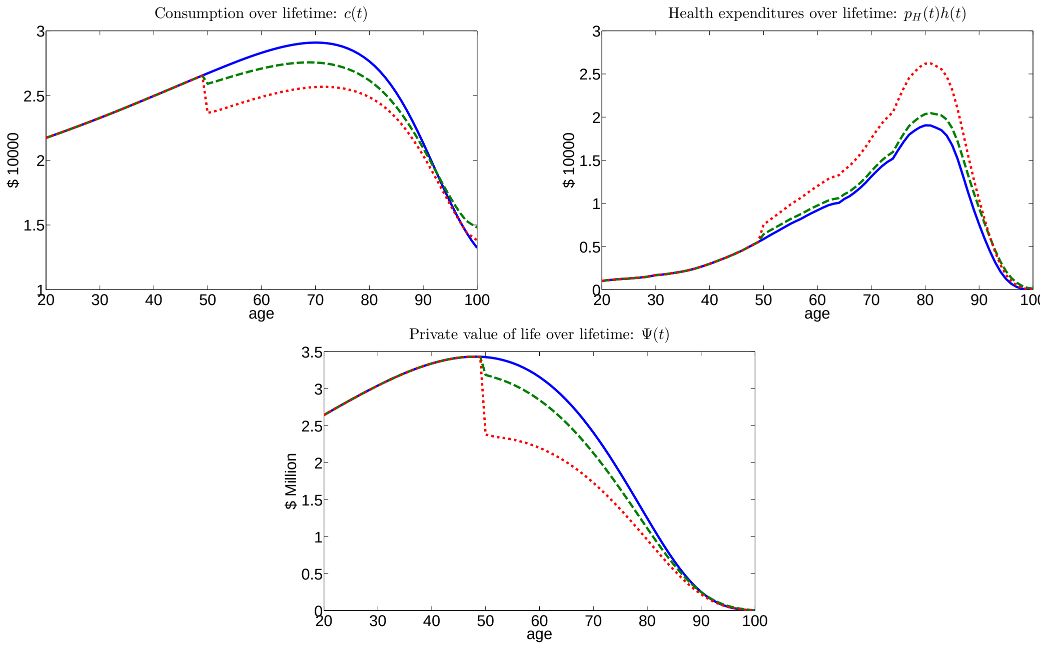


Figure 2.3: Life-course consumption, health expenditure and value of life profiles for benchmark case (blue, solid line), for the unanticipated shock of M in the general equilibrium (green, dashed line) and the partial equilibrium effect (red, dotted line)

ambiguous picture emerges in Figure 2.3: For a given set of prices, the expenses for medical care would increase for all age groups by a substantive amount (see the red, dotted plot). However, such a partial equilibrium take is inappropriate, as the general equilibrium impact of the innovation on the underlying demand and supply system needs to be taken into account. Once we do this, much of the demand expansion vanishes (see green, dashed plot). This notwithstanding, the medical innovation raises remaining life-expectancy at age 20 from 58.0 to 59.1 years for a member of the focal cohort.[32] Notably, the strong increase in demand for a constant set of prices would induce an additional gain of only 0.35 life years.

Equation (2.26) affords some insight into the demand response of individual health care to medical progress. Obviously, the increased marginal effectiveness of health care through medical progress ($\mu_{hM} < 0$) boosts demand, an effect that is consistent with the empirical evidence in Baker et al. (2003), Cutler and Huckman (2003), Wong et al. (2012) and Roham et al. (2014).[33] The effect is dampened, however, by the ensuing reduction in consumption over the remaining life-time, which tends to diminish the VOL (but within the highest age groups) and,

[32]The increase in life-expectancy is large enough such that the drop in consumption is more than overcompensated with respect to lifetime utility. For the focal cohort that experiences the medical innovation at the age of 50 we obtain a 0.9% increase in lifetime welfare. For those born at the time of the innovation, the welfare gain equals to 1.4% as they can enjoy the benefits of new technology throughout their whole lifetime.

[33]Roham et al. (2014) also show that the bulk of the expenditure increase associated with more intensive treatments lies with the age groups 55 and over with a peak increase within the age group 75-79 [see their Figure 6]. Qualitatively, this is very similar to the age-profile of the expenditure increase in our model.

thus, the individual's willingness to pay for health care. Notably, the consumption level tends to drop because a greater part of the life-cycle budget is allocated to health care and because the remaining budget now needs to be spread over a longer life-time. According to Equation (2.29), however, improved survival chances also induce individuals to shift consumption into higher age classes, a force that leads to increasing consumption at the highest ages.

Overall, the reallocation of resources from consumption to health care in response to medical progress tends to be substantive in a partial equilibrium context. In general equilibrium, it is subject, however, to additional impacts from the price changes induced. Most notably, medical progress triggers a reduction in the market interest rate r and an increase in the price for health care p_H (which will be discussed later).[34] While the reduction in the market interest rate works to increase the value of life and, thus, boosts health demand, the negative impact of a rising price of health care is dominating. Hence, in the general equilibrium scenario health demand is dampened compared to the partial equilibrium case due to the price increase for health care. We find that while per capita health care expenditure would increase by some 30 percent in partial equilibrium, in general equilibrium they increase by only 12.2 percent, and, thus, by less than a half.[35]

Although per capita demand for health care and the associated expenditure, $p_H(t)H\left(t\right)/N\left(t\right)$, have increased after the innovation, (see Figure 2.4) the magnitude of the effect varies across age-groups. Specifically, those over 80 exhibit a very modest demand increase in spite of the innovation. For these cohorts the willingness to pay for care, as measured by the VOL, is so low that the value of the survival gains from the innovation barely outweighs the price increase. Finally, and strikingly, the medical innovation leads to a reduction in the VOL of the focal individual past age 50 at which the innovation has become available (see Figure 2.3). At face value, the lower willingness to pay for survival follows from the reduction in consumption over the remaining life-course.

However, a different interpretation can be attached to it in light of the fact that the demand of health care is non-decreasing in response to the medical innovation over the full life-cycle. Rewriting the first-order condition for the demand of health care (2.14) to $\psi\left(a,t\right) = -\phi\left(a,t\right)p_H\left(t\right)\mu_h^{-1}$, we find that the VOL is equated to the effective (or quality-adjusted) price of medical care $-\phi\left(a,t\right)p_H\left(t\right)\mu_h^{-1}$, the latter depending on both the market price and the marginal impact on mortality of health care, $-\mu_h$. Recalling that $\mu_{hh} > 0$, an increasing demand for care would ceteris paribus imply a greater effective price. But then it must be true that the medical innovation has lowered the effective price for medical care (recall that $\mu_{hM} < 0$) to an extent that it over-compensates the increase in the market price, $p_H\left(t\right)$. Notably this finding is consistent with evidence produced by Cutler et al. (1998) who find that while the price for heart attack treatments, as measured by a Service Price Index, was increasing over the time span 1983-1994, the quality-adjusted price was effectively declining. From this perspective, the

[34] The increase in the price of health care is well in line with the fact that the US consumer price index (CPI) for medical care consistently grows in excess of the CPI for all items (see US Bureau of Labor Statistics).

[35] Fonseca et al. (2013) find within a partial equilibrium model calibrated to the US context that over the time span 1965-2005 an increase of health care expenditure by 247 percent and an increase in life expectancy by 9.6 years could be attributed to medical change. Assuming linearity, this would imply that an innovation-induced increase in life expectancy by 1.1 years would be associated with an increase in expenditure by 28 percent, which is consistent with our partial equilibrium result.

decline in the VOL following the medical innovation can be interpreted in terms of basic consumption theory: An optimal choice between the two goods, survival and consumption, is given if the marginal rate of substitution between survival and consumption, i.e. the VOL, equals the price of survival in terms of consumption goods, i.e. the effective price of medical care. But then a decrease in the price of survival triggers a reallocation from consumption to survival (through the purchase of additional health care), implying a decline in the marginal rate of substitution and, thus, in the VOL.

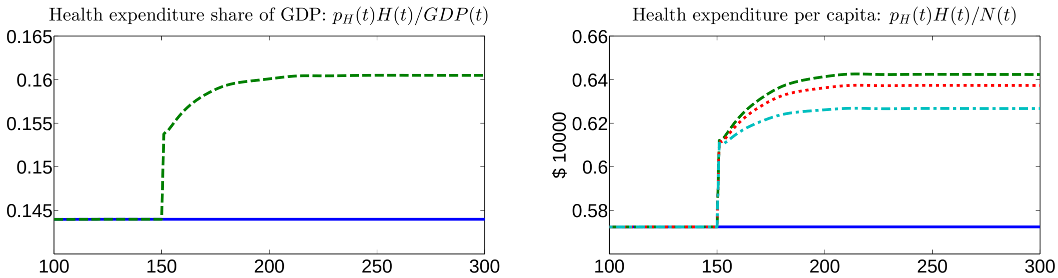


Figure 2.4: Health expenditure share of GDP (left panel) and health expenditure per capita (right panel) for the benchmark (blue, solid line) and for the unanticipated increase in M in general equilibrium (green, dashed line). The cyan, dashed-dotted line indicates the pure shift in individual demand, $h(a,t)$, holding the population shares, $N(a,t)/N(t)$, and the price of medical care, $p_H(t)$, constant. The red, dotted line denotes the effect holding only $p_H(t)$ constant.

The innovation at $t = 150$ induces an increase in the health expenditure share of the GDP by some 1.6 percentage points (Figure 2.4, left panel; and Table 2.3). Underlying this increase in the health share is a strong increase in per capita health expenditure by some 12.2 percent (in the new steady state). The right panel in Figure 2.4 decomposes the increase in per capita health expenditure into an increase in individual demand at each given age, $h(a,t)$, given the pre-innovation age-structure and price for health care (corresponding to the cyan, dashed-dotted line), the additional impact of a changing age-structure, as measured by the age-shares $N(a,t)/N(t)$ (corresponding to the distance between the cyan, dashed dotted and the red, dotted lines), and the increase in the price for health care, $p_H(t)$ (corresponding to the distance between the red, dotted and the green, dashed line). Overall, the instantaneous boost to demand amounts to a 6.7 percent increase in medical expenditure per capita (=55 percent of the total increase), with a further 2.8 percent increase following during the adjustment process (=23 percent of the total effect). The reason for why individual demand increases over and above the instantaneous impact lies with the fact that later born cohorts have been able to accumulate additional savings for the purchase of health care. The shift in the population structure toward higher ages with more intensive health care needs amounts to an expenditure increase by 1.8 percent (=15 percent of the total effect), with the price increase adding another 0.9 percent (=7 percent of the total effect). While a total of 78 percent of the increase in per capita health expenditure following the innovation is, thus, explained by the boost to individual demand, induced population aging and price inflation play a significant part over the transition phase.

The shift from final goods production to health care that is following the innovation leads to a reduction of the employment share in the manufacturing sector, a reduction in the interest

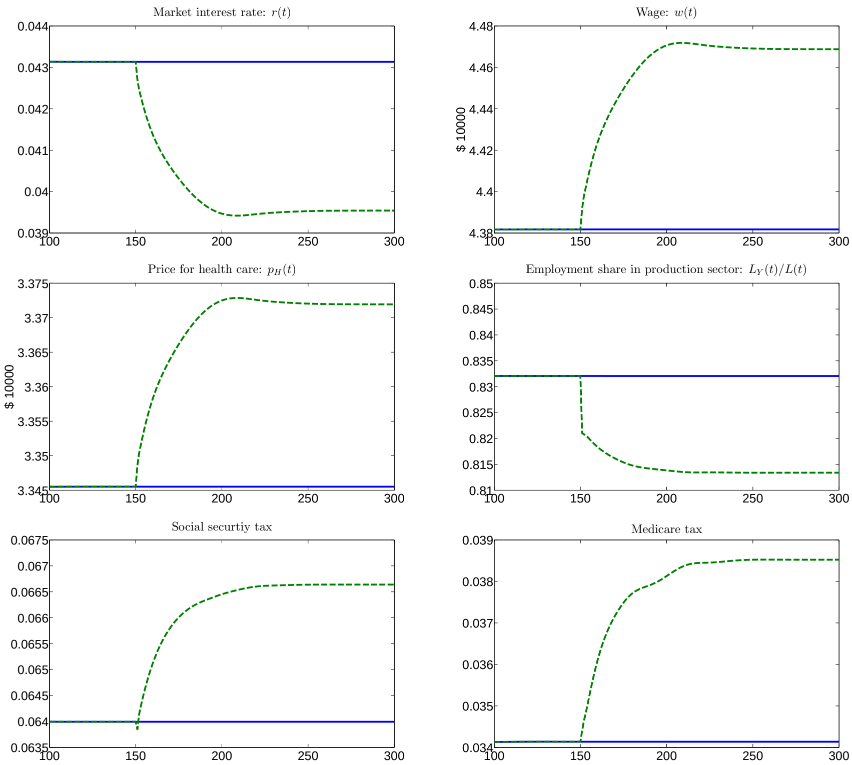


Figure 2.5: Market prices, employment share and taxes

rate and an increase in the wage rate (see Figure 2.5). The change in the factor prices comes with an increase in the price of health care,[36] which is underlying the dampening of the demand response to innovation.[37] Furthermore, the social security payroll tax rises, following the pronounced increase in longevity, despite the simultaneous increase in the gross wage. Similarly, Medicare payroll taxes increase as a consequence of both greater health spending and the boost in longevity.

These sectoral and price adjustments notwithstanding, the medical advance has very little impact on GDP per capita (see Table 2.3). The survival gains induced by the innovation are greatest among older cohorts and, for a fixed retirement age, lead to a 1 percent reduction in the employment-population ratio, $L(t)/N(t)$.[38] At the same time, however, the expansion of the expected retirement period and the prospect of greater health expenditures in the presence of a more effective medical technology trigger additional savings, translating into a 4 percent

[36] According to Equations (2.32) and (2.33) the increase in the wage rate and in the price of health care is directly linked to the lower market interest rate.

[37] A partial equilibrium perturbation of p_H enables us to determine the price elasticity of per-capita health care expenditures for the benchmark calibration. We find a price elasticity of -0.3, which is close to the estimated mean elasticity of -0.2 determined in the RAND Health Insurance Experiment (Manning et al. 1987).

[38] The medical innovation raises the remaining life expectancy at age 20 by 1.0 years from 58.04 years (and, thus, by 1.3 percent) and remaining life expectancy at age 65 by .81 years from 18.02 years (and, thus, by 4.5 percent).

increase in the capital stock per capita, $K(t)/N(t)$[39] Overall, this leads to capital deepening, i.e. to a higher $K(t)/L(t)$, which in optimum induces a shift of resources to the more labor intensive health care sector.[40] As we have shown in Section 2.5, both the increase in $K(t)/L(t)$ and the shift in resources to the health care sector lead to an increase in GDP per worker. Our numerical analysis shows that for the US context we are studying, this effect is strong enough to compensate (even mildly over-compensate) the decline in the employment rate.

Thus, we can summarize the following set of insights.

Result 1 *(i) Medical innovation leads to a reallocation of consumption to health care expenditures for all but the highest ages, and to a reallocation of consumption to higher ages. (ii) The general equilibrium impact of a mortality reducing medical innovation on the demand for health care tends to be dampened by an associated price increase. (iii) About 78 percent of the increase in per capita health care expenditure following the medical innovation are due to an increase in individual demand, about 15 percent are due to induced population aging, and 7 percent are due to a price increase. (iv) Medical innovation leads to a reduction in the VOL and in the effective (quality-adjusted) price for medical care. (v) Medical innovation tends to stimulate additional saving. (vi) The ensuing increase in the economy-wide capital intensity, combined with the shift of employment into the health-care sector increase the economy-wide productivity, i.e. GDP per worker by enough to compensate the reduction of the employment-population ratio, leading to little impact on GDP per capita.*

It is worth noting that the transitional dynamics following a medical innovation tie in closely with recent findings about the impact of capital deepening on the structural composition of an economy. Specifically, Acemoglu and Guerrieri (2008) show for a two-sector economy that capital deepening, i.e. an increase in the economy-wide capital intensity tends to raise the output share of the capital-intensive sector but at the same time induces a shift of both labor and capital inputs into the labor intensive sector. These shifts are accompanied by an increase in the wage rate, as is the case in our model. Acemoglu and Guerrieri (2008) go on to show that the same process is underlying unbalanced growth whenever productivity growth is larger in the capital-intensive sector (see also Baumol 1967).

While the transition to a new equilibrium that is following a medical innovation in our model follows a similar process of unbalanced growth à la Baumol (1967), this is for rather different reasons. First, technical progress occurs in the health care sector; second, and importantly, medical progress works through the household side of the economy: Through its impact on survival and the consequent shift of the age-structure toward older cohorts, medical progress triggers an increase in savings, and, thus, in the per capita supply of capital while at the same time reducing the per capita supply of labor. Notably, this impact is present even when holding the aggregate demand for health care fixed. As we have seen, capital deepening and the sectoral shift combine to render the overall economy more productive, as measured by GDP per worker.

[39] Indeed, these channels have been confirmed empirically by Bloom et al. (2003) and De Nardi et al. (2010).

[40] As we have seen already, these shifts in quantities are accompanied by an increase in the wage rate, the latter inducing an increase in the price for health care.

Anticipated Medical Advance

In many instances, medical advances do not arrive as "shocks", but they are anticipated in terms of prior medical research and/or the clinical trials leading to the admission of new medical technologies or pharmaceuticals. Thus, it is appropriate to take into account consumers' anticipation of such innovations. In the following, we consider once again a medical innovation from $M(t) = 1$ to $M(t) = 2$, but assume now that it is fully anticipated. In order to gain a better understanding of the anticipation effect we assume that the innovation is taking place at $t = 200$, with the focal cohort entering at $t_0 = 170$.

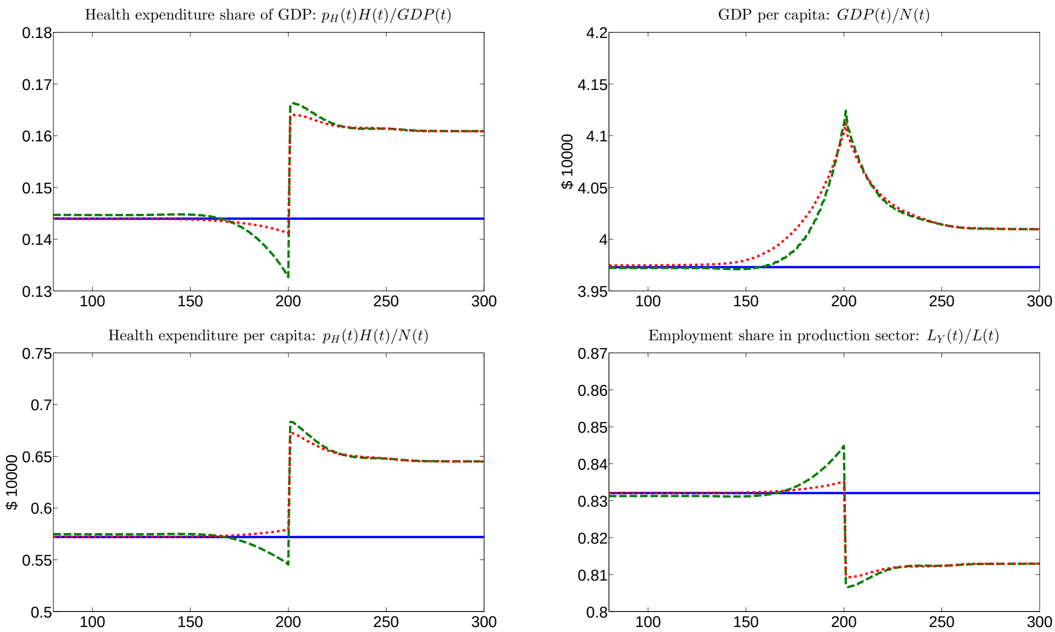


Figure 2.6: Macroeconomic variables for benchmark case (blue, solid line), for the anticipated advance in M (green, dashed line) and anticipated advance where health demand is fixed before the shock of M (red, dotted line)

To study the role of anticipation in modulating the impacts of medical innovation, it is instructive to focus on macroeconomic variables.[41] Figure 2.6 plots how the health share of GDP, the health care expenditures per capita, and the employment share in the production sector, $L_Y(t)/L(t)$ respectively, develop over time when individuals are anticipating the innovation. For the moment, we focus on the blue, solid line, representing the benchmark scenario as well as on the green, dashed line representing the anticipated advance in technology. Each of the three quantities exhibits a particular pattern, reflecting the impact of anticipation at aggregate level. Reading the figures backwards in time, the innovation at $t = 200$ eventually leads to

[41] As compared to the previous case of a non-anticipated medical innovation, anticipation does not vastly alter the life-cycle allocation of the focal cohort. One distinction is that consumption is reduced smoothly over the full life-cycle, allowing the individual to avoid the utility loss from a sudden drop in consumption at the arrival of the innovation.

the expected increase in the health share and in the per capita expenses on health care over and above their respective benchmark levels, as well as to a corresponding shift of employment from production to the health care sector.[42]

Notably, however, for a time span of about 30 years before the innovation, health expenditures (and consequently the health share) fall below their benchmark levels. This amounts to an anticipation effect, where individuals postpone the consumption of care to wait for the innovation to occur.[43] The corresponding shrinking of the health care sector is reflected in a temporary boost to the employment share in final goods production.[44]

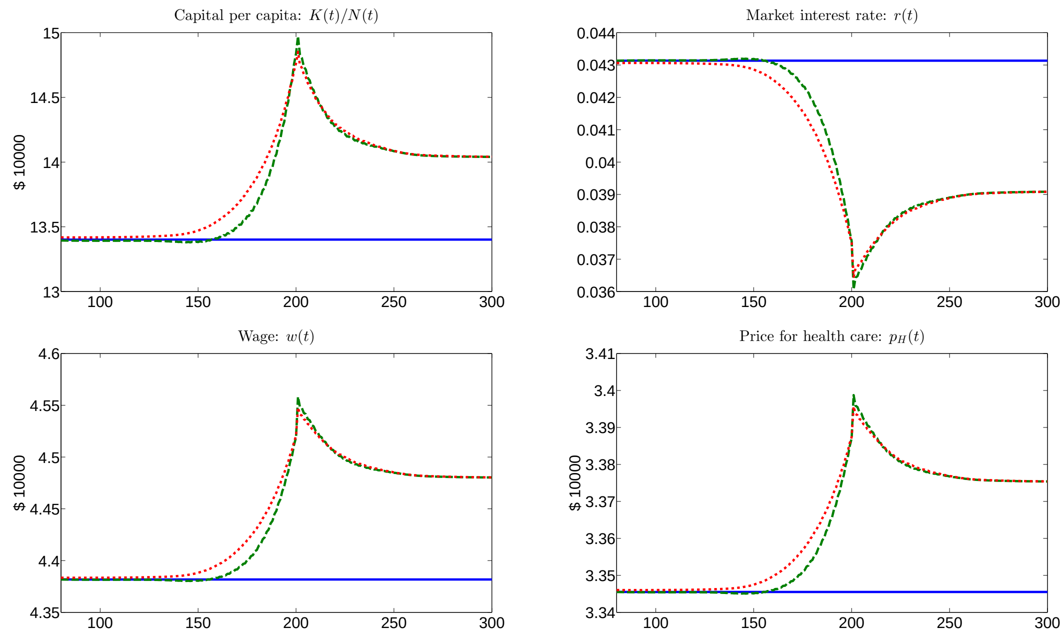


Figure 2.7: Capital per capita and market prices

Figure 2.7 plots the development of the capital per capita, $K(t)/N(t)$, the market interest rate, $r(t)$, the wage rate, $w(t)$ and the price for health care, $p_H(t)$. The paths show a pattern that differs distinctly from the one arising in the case of an unanticipated shock (recall Figure 2.5). The postponement of health expenditures over the anticipation period translates into higher saving, an effect that is complemented by an anticipative reduction in per capita consumption below its benchmark (not shown here). The resulting boost to the capital held by individuals

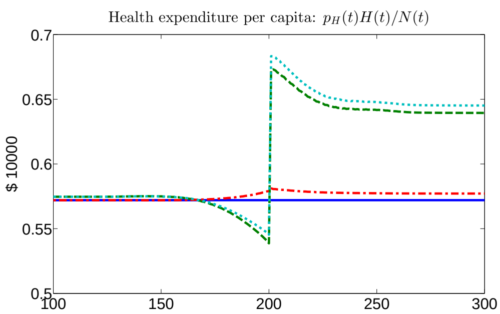
[42] GDP per capita exceeds the benchmark level by a small amount, reflecting the steady-state increase in financial wealth and the capital stock due to higher longevity after the innovation.

[43] Such a demand-reducing anticipation effect has been identified empirically in regard to the consumption of pharmaceuticals prior to the Medicare D reform aimed at including pharmaceutical expenditure into the coverage (Alpert 2016, Hu et al. 2014, Kaplan and Zhang 2017).

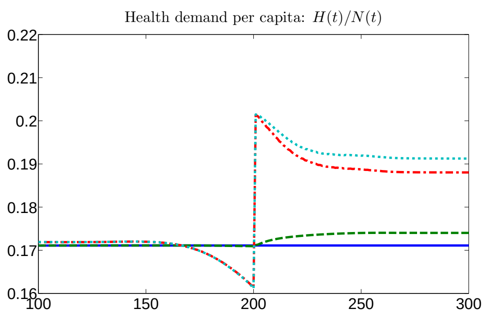
[44] A close-up look shows that the anticipation-related slump in the demand for health care itself is, in turn, anticipated in as far as prior to the slump, the demand for health care and the employment share in health care are slightly elevated over and above their benchmark levels. Overall, this amounts to an anticipation wave, akin to the one described by Feichtinger et al. (2006) for the impact of technological progress on capital accumulation.

triggers a decline in the interest rate and a boost to the wage rate. With the health care sector being relatively labor intensive, the increase in the wage rate drives up the price for health care despite the deferral of demand. At the arrival of the medical innovation, individuals begin to dissave in order to purchase greater quantities of what is more effective health care now, and over time capital per capita falls back to its new steady-state level, which nevertheless lies above the benchmark. The factor prices and the price for health care do not return to their initial levels either. The reason for this lies with the post-innovation shift of economic activity towards the more labor intensive health care sector. Hence, while prices are driven by the supply-side over the anticipation period, they tend to be determined by the demand-side after the innovation. Finally, the boost in capital per capita over the anticipation period translates into a temporary boom of the economy, as measured by GDP per capita (see Figure 2.6).

We conclude this second experiment by isolating the drivers behind the changes in the level of per capita health expenditure. Figure 2.8a decomposes the change in health expenditure from the benchmark (blue, solid line) to the outcome under the anticipated medical advance (cyan, dotted line) into two partial effects: a price effect (red, dashed-dotted line), holding constant per capita demand $H(t)/N(t)$ at the benchmark level; and a demand effect (green, dashed line), keeping the price at the benchmark level. The overall impact of the price change is relatively small, accounting for roughly 8% of the overall increase in per capita expenditure at the point of innovation. Figure 2.8b decomposes the changes in the per capita demand for health care (blue, solid line = baseline; cyan, dotted line = experiment) into a component that reflects changes in the levels of individual demand, $h(a,t)$, for the baseline age-structure of the population (red, dashed-dotted line); and a component that reflects changes in the age-structure for the baseline age-profile of individual demand (green, dashed line). Similar to the case of an unanticipated innovation, the increase in individual demand levels is the dominant driver. Notably, there is an over-shooting of individual demand at the point of innovation, reflecting the short-run economic boom. The subsequent downward adjustment in the per capita demand for health care toward the new steady state is dampened, however, by the shift towards an older population with its higher demand for health care.



(a) Benchmark (blue, solid)
Anticipated med. advance (cyan, dotted)
Benchmark $h(a,t)$ (red, dashed-dotted)
Benchmark $p_H(t)$ (green, dashed)



(b) Benchmark (blue, solid)
Anticipated med. advance (cyan, dotted)
Benchmark $N(a,t)$ (red, dashed-dotted)
Benchmark $h(a,t)$ (green, dashed)

Figure 2.8: Decomposition of per capita health expenditures and demand

We can summarize as follows.

Result 2 *The anticipation of a mortality reducing innovation leads to (i) the contraction of the demand and supply for health care to a level below the benchmark for a period prior to the innovation; (ii) the accumulation of extra capital prior to the innovation and for a certain period, following the innovation; and (iii) to a concomitant reduction (increase) in the interest rate (wage rate and price for health care) prior to the innovation. (iv) By inducing extra saving, anticipation generates a temporary economic boom. (v) The changes in health expenditure per capita before and after an anticipated innovation are predominantly demand driven rather than price driven, with a peak in demand arising at the point of innovation.*

One could argue that the reduction in health care in anticipation of an innovation lacks realism in as far as health care bears on survival. We do not wish to imply that individuals facing life-threatening conditions are deferring treatments. However, anticipatory adjustments are quite probable in regard to the intensity of given treatments such as e.g. drug prescriptions (Alpert 2016, Kaplan and Zhang 2017). They are also conceivable in as far as the utilization of distinct treatments with different intensities respond to current and expected prices and benefits (e.g. Cutler and Huckman (2003) for treatments of coronary disease). For our representative consumer approach, changes in the distribution of treatments across the patient population translate into adjustments in the intensity of care.

These arguments notwithstanding, we have studied an alternative scenario in which the demand for health care is fixed to the benchmark level before the medical innovation materializes. Although individuals continue to fully anticipate the advance, they are now restricted in their response to changes in their saving behavior. In Figures 2.6 and 2.7 this scenario is represented by the red, dotted lines. In Figure 2.6, we observe that although the demand for health care is fixed before the shock, expenditures increase due to an increase in the price for health care. Importantly, however, in this scenario, too, individuals forego consumption and increase savings in anticipation of the innovation. The impact is strong enough to trigger a temporary boom similar to the one observed in the scenario without restriction. Notably the accumulation of additional capital and the associated boost to GDP sets in even earlier when individuals are not allowed to change their demand for health care in an anticipative way. Prices react almost identically in comparison to the previous experiment (see Figure 2.7). We can, thus, conclude that while changes to the health care sector in anticipation of a medical innovation are somewhat difficult to predict, the anticipatory boost to savings and, consequently, to GDP appears to be a robust result.[45]

2.7 Conclusion

We have set out an OLG model built around the endogenous demand and supply of health care. In contrast to much of the received macro-economic literature on health and health care, our

[45] In a further robustness check, that we do not present here, we assume that the technological advance is fully anticipated but evolves over a period of 30 years. Again, we observe the same anticipation pattern, albeit smaller in magnitude, as in the scenario where the advance arrives as a shock.

model involves a rich model of the life-cycle, based on a realistic pattern of mortality. This allows us to characterize in detail the individual life-cycle allocation of consumption and health care, and to construct macro-economic aggregates that are based on a realistic age-structure of the population. At the micro-economic level, we can study in detail how the demand for health care responds to medical progress, taking into account induced price changes and changes in the willingness-to-pay for health care, as summarized by the value of life.

Based on a calibration of the model to the US economy in the year 2003, our numerical analysis is designed to provide a quasi-experimental identification of the channels through which changes in medical technology are transmitted between individual choices and macro-economic dynamics. Our numerical experiments yield a number of policy relevant, and potentially challenging, insights.

First, we find that a medical innovation that increases the remaining life expectancy at age 20 by some 1.1 years, boosts health expenditure per capita by some 12.2 percent, with 0.9 percentage point owing to price inflation, 1.8 percentage points owing to a shift in the age-structure towards older individuals with greater consumption of health care, and 9.5 percentage points owing to an increase in individual demand. Our finding that the expansion in health expenditure is mostly driven by an increase in utilization is well in line with recent evidence (Bundorf et al. 2009, Chernew and Newhouse 2012). However, our model also suggests that in spite of its modest contribution to expenditure growth in accounting terms, the increase in the price for health care has a significant impact on demand as described in the following.

Second, more than half of the partial equilibrium impact on the individual demand for health care of a mortality reducing innovation is neutralized in general equilibrium by an increase in the price for medical care. This result indicates a need for a general equilibrium framework when it comes to assessing the impact of medical change on health care expenditure, as otherwise findings may be biased.

Third, for an economy with social security and health care organized in similarity to the US (as of 2003), a costless medical innovation does not have a negative impact on economic performance, as measured by GDP. This is despite a reduction in the employment rate due to a growing population of pensioners. The main mitigating channel is the accumulation of additional savings/capital for the purpose of financing consumption over an extended life-course and purchasing more effective health care at a higher price. Indeed, this channel is very much in line with evidence for the US on savings related to health expenditures in old age (e.g. De Nardi et al. 2010). Overall, the capital deepening of the economy always combines with the shift in economic activity to the health care sector in raising GDP per worker. As it turns out for our calibration, this effect more than compensates the decline in the employment rate. Two caveats are worth of note here: The cost of medical innovation, e.g. through the absorption of production factors within a medical R&D sector may after all induce a drag on economic growth (Jones 2016).[46] In addition, the question as to whether additional savings are induced in the wake of a medical innovation is likely to depend on the particular design of the social security system. To the extent that expenditures during retirement are financed through public transfers,

[46]Note, however, that within a decentralized economy with R&D-driven growth a la Romer (1990) the increase in the capital intensity of final goods production that follows the absorption of (relatively more) labor by a growing health care sector, provides a stimulus for conventional R&D (Kuhn and Prettner 2016).

the savings response is prone to be weaker, implying that the reduction in the employment rate is not sufficiently offset through the accumulation of capital. Additional offsetting impacts arise if health improvements not only translate into lower mortality but also into a greater propensity to provide labor into older ages (Kuhn and Prettner 2016).

Fourth, mortality reducing medical innovations tend to come with a reduction in the value of life over large parts of the life-course. This finding has two interesting ramifications. At face value, the reduction in the value of life arises from a reallocation by the individual of resources from consumption to health care. While per se, this is reflecting an efficient response by the individual to the availability of more effective health care, it also implies that individuals may be less willing to prevent risks to their life. Thus, some of the benefits of medical innovations in terms of improved survival prospects may well be offset by the adoption of less healthy life-styles. As we have shown, the reduction in the value of life also implies a reduction in the effective (quality-adjusted) price of medical care as triggered by the innovation. This is in line with evidence for the US, as provided in Cutler et al. (1998) and suggests that in settings in which individuals choose the demand for health care, the value of life can be interpreted as a marginal rate of substitution, the decline of which reflects a shift in consumption toward survival by means of (additional) health care.

Fifth, anticipation of a medical innovation may come with a deferral in the demand for medical care prior to the innovation with consequences for the sectoral structure and the price structure. Furthermore, individuals always reduce consumption and boost their saving in anticipation of the advance, inducing a boost to the capital stock per capita which is strong enough to trigger a temporary economic boom. The boom is accompanied by a peak in the nominal price for medical care at the point of innovation, leading to a dampening of the impact of medical innovation on the effective price of care. While these effects are only temporary and vanish over the transition to the long-run steady state, they suggest that care needs to be taken about possible anticipation effects when assessing the impacts of medical innovation on economic and health outcomes. While we are unaware of empirical evidence on anticipation effects in the context of medical innovation, their empirical relevance has been established in the context of health policy reform (Alpert 2016, Hu et al. 2014, Kaplan and Zhang 2017) and strikes us as conceivable in the innovation context, too, certainly in regard to the anticipatory boost in savings.

In this present article, we have abstracted from long-run trends to productivity and population in order to avoid that these trends obfuscate the identification of the transmission channels of medical progress that were at the heart of this analysis. In the next chapter, however, we will include more realistic dynamics in regard to productivity growth as well as background trends of insurance coverage and population in order to arrive at a quantitative assessment of the role of various health expenditure drivers in the US of the last decades. In particular we will study the role of induced medical progress through insurance expansion by explicitly modeling a medical R&D sector. Beside accounting for the rise in health expenditures, we will study the joint dynamics of longevity and welfare and the respective impacts on the rest of the economy.

2.8 Appendix

2.8.1 Optimal Solution to the Individual Life-Cycle Problem

The individual's life-cycle problem, i.e. the maximization of (2.1) subject to (2.2) and (2.3) can be expressed by the Hamiltonian

$$\mathcal{H} = uS - \lambda_S \mu S + \lambda_k \left(rk + lw - c - \phi p_H h - \tau + \pi + s \right),$$

leading to the first-order conditions

$$\mathcal{H}_c = u_c S - \lambda_k = 0, \tag{2.36}$$

$$\mathcal{H}_h = -\lambda_S \mu_h S - \lambda_k \phi p_H = 0, \tag{2.37}$$

and the adjoint equations

$$\dot{\lambda}_S = (\rho + \mu)\, \lambda_S - u, \tag{2.38}$$

$$\dot{\lambda}_k = (\rho - r)\, \lambda_k. \tag{2.39}$$

Optimality conditions (2.13) and (2.14): Evaluating (2.36) at two different ages/years (a, t) and $(\widehat{a}, t + \widehat{a} - a)$, equating the terms and rearranging gives us

$$\begin{aligned} \frac{u_c (\widehat{a}, t + \widehat{a} - a)}{u_c (a, t)} &= \frac{\lambda_k (\widehat{a}, t + \widehat{a} - a)}{\lambda_k (a, t)} \frac{S (a, t)}{S (\widehat{a}, t + \widehat{a} - a)} \\ &= \exp \left\{ \int_a^{\widehat{a}} \left[\rho + \mu \left(\widehat{\widehat{a}}, t + \widehat{\widehat{a}} - a \right) - r \left(t + \widehat{\widehat{a}} - a \right) \right] d\widehat{\widehat{a}} \right\}, \end{aligned} \tag{2.40}$$

which is readily transformed into the Euler equation (2.13) as given in the main body of the article.

Inserting (2.36) into (2.37) allows to rewrite the first-order condition for health care as

$$-\mu_h (a, t) \frac{\lambda_S (a, t)}{u_c (\cdot)} = \phi (a, t)\, p_H (t). \tag{2.41}$$

Integrating (2.38) we obtain

$$\lambda_S (a, t) = \int_a^{\omega} u (\widehat{a}, t + \widehat{a} - a) \exp \left[- \int_a^{\widehat{a}} (\rho + \mu)\, d\widehat{\widehat{a}} \right] d\widehat{a}.$$

Using this, we can express the private VOL as

$$\psi (a, t) := \frac{\lambda_S (a, t)}{u_c (a, t)} = \int_a^{\omega} \frac{u_c (\widehat{a}, t + \widehat{a} - a)}{u_c (a, t)} \frac{u (\widehat{a}, t + \widehat{a} - a)}{u_c (\widehat{a}, t + \widehat{a} - a)} \exp \left[- \int_a^{\widehat{a}} (\rho + \mu)\, d\widehat{\widehat{a}} \right] d\widehat{a}.$$

Substituting from (2.40) and rearranging we obtain (2.15) as given in the main body of the article. Inserting this into (2.41) gives condition (2.14) in the main body of the article.

Dynamics (2.18) and (2.19): Total differentiation of (2.36) with respect to age gives

$$\begin{aligned} & u_{cc}S\dot{c}+u_c\dot{S}-\dot{\lambda}_k \\ = \;& u_{cc}S\dot{c}-u_c\mu S-(\rho-r)\,\lambda_k \\ = \;& u_{cc}S\dot{c}-(\rho-r+\mu)\,u_cS=0. \end{aligned}$$

From this we obtain the consumption dynamics (2.18) as given in the main body of the article.

Holding prices and the state of medical technology constant, total differentiation of $-\mu_h\,(a,t)\,\psi\,(a,t)-\phi\,(a,t)\,p_H\,(t)=0$ with respect to age gives

$$-\left(\mu_{hh}\dot{h}+\mu_{ha}\right)\psi-\mu_h\dot{\psi}-p_H\dot{\phi}=0.$$

Substituting $p_H=-\mu_h\psi\phi^{-1}$ from (2.14) and rearranging, we obtain the dynamics for health care as reported in (2.19) within the main body of the article.

2.8.2 Characterization of General Equilibrium

For each period t we have the following unknown variables:

- inputs $\{K_Y\,(t)\,,K_H\,(t)\,,L_Y(t),L_H(t)\}$,
- prices $\{r\,(t)\,,w\,(t)\,,p_H\,(t)\}$,
- aggregate demand $\{C\,(t)\,,H\,(t)\}$,
- aggregate net saving, equivalent to the change in the capital stock $\dot{K}\,(t)$,

summing up to 10 variables. These are determined through

- 4 first-order conditions on factor inputs (2.21)-(2.24), which give the factor demand functions $\{K_Y^d\,(r,w;A,M,B)\,,K_H^d\,(r,w,p_H;M,B)\,,$ $L_Y^d\,(r,w;A,M,B)\,,L_H^d\,(r,w,p_H;M,B)\}$, depending on prices as well as on technology and population $\{A,M,B\}$;[47]
- a set of first-order conditions (2.13) and (2.14) for $a\in[0,\omega]$, which together with the individual's life-cycle budget constraint determine the age-specific levels of consumption $c\,(a,t)$ and health care $h\,(a,t)$. Aggregation according to (2.6) and (2.7) gives the demand for consumption $C\,(r,w,p_H;M,B,\phi)$and health care $H^d\,(p_H;M,B,\phi)$, depending on the three prices as well as on technology, population and the vector of co-insurance rates;[48]

[47] Note here that $K_Y^d\,(r,w;A,M)$ and $L_Y^d\,(r,w;A,M)$ may vary with M and B through its impact on the aggregate supply of effective labor L.

[48] Through the life-cycle budget constraint and the individual Euler equation the demand function $C\,(\cdot)$ is also contingent on the expectation about future prices over the remaining life-course. The same applies to the demand function $H^d\,(\cdot)$ for which the future price paths filter in through the VOL.

- 4 market clearing conditions

$$
\begin{aligned}
K_Y^d(r,w;A,M,B)+K_H^d(r,w,p_H;M,B) &= K,\\
L_Y^d(r,w;A,M,B)+L_H^d(r,w,p_H;M,B) &= L(M,B),\\
F(K_H^d(r,w,p_H;M,B),L_H^d(r,w,p_H;M,B)) &= H^d(p_H;M,B,\phi),\\
Y(K_Y^d(r,w;A,M,B),AL_Y^d(r,w;A,M,B))) &= C(r,w,p_H;M,B,\phi)+\dot{K}+\delta K,
\end{aligned}
$$

which determine the set of equilibrium prices $\left\{r^*\left(A,M,B,\phi,\dot{K}\right),\right.$ $\left.w^*\left(A,M,B,\phi,\dot{K}\right),p_H^*\left(A,M,B,\phi,\dot{K}\right)\right\}$ and aggregate net saving, as captured by $\dot{K}$.

2.8.3 Equilibrium Relationships with Cobb-Douglas Technologies

Consider the Cobb-Douglas-specifications in (2.30) and (2.31). From the first-order conditions (2.21), (2.22), (2.23) and (2.24) we then obtain the (implicit) factor demand functions

$$
\begin{aligned}
K_Y^d(t) &= \frac{\alpha Y(t)}{r(t)+\delta}, &(2.42)\\
L_Y^d(t) &= \frac{(1-\alpha)Y(t)}{w(t)}, &(2.43)\\
K_H^d(t) &= \frac{\beta p_H(t)F(t)}{r(t)+\delta}, &(2.44)\\
L_H^d(t) &= \frac{(1-\beta)p_H(t)F(t)}{w(t)}. &(2.45)
\end{aligned}
$$

Combining (2.42) with (2.43) and (2.44) with (2.45) we obtain the equilibrium capital intensity

$$
\begin{aligned}
k_Y^*(t) &:= \frac{K_Y^d(t)}{L_Y^d(t)}=\frac{\alpha}{1-\alpha}\frac{w(t)}{r(t)+\delta}, &(2.46)\\
k_H^*(t) &:= \frac{K_H^d(t)}{L_H^d(t)}=\frac{\beta}{1-\beta}\frac{w(t)}{r(t)+\delta}. &(2.47)
\end{aligned}
$$

and, thus, $K_Y^d(t)=k_Y^*(t)L_Y^d(t)$. Using $k_Y^*(t)$ in (2.30) to rewrite $Y(t)=L_Y^d(t)A(t)^{1-\alpha}(k_Y^*)^\alpha$ and inserting this in (2.43) we can solve for the equilibrium wage as a function of the interest rate

$$
w^*(t)=\widehat{w}(r(t);A(t))=(1-\alpha)A(t)\left[\frac{\alpha}{r(t)+\delta}\right]^{\frac{\alpha}{1-\alpha}}. \tag{2.48}
$$

This, in turn, determines the capital intensities $k_Y^*(t)=\widehat{k}_Y(r(t);A(t))$ and $k_H^*(t)=\widehat{k}_H(r(t);A(t))$. Using the market clearing condition $F(p_H^*(t);K_H^*(t),L_H^*(t)) = H^d(p_H^*(t);M(t),B(t))$

and (2.44) and (2.45) we obtain the general equilibrium price for health care as

$$\begin{aligned} p_H^*(t) &= \widehat{p}_H\left(r(t), w^*\left(t\right), H_d^*(t)\right) \\ &= \widehat{p}_H\left(r\left(t\right); A\left(t\right), M\left(t\right), B\left(t\right)\right) \\ &= \frac{(r+\delta)^{\beta} w^{1-\beta}}{\beta^{\beta}(1-\beta)^{1-\beta}}. \end{aligned} \tag{2.49}$$

Reinserting this, we obtain the equilibrium utilization of health care, as $H^d\left(p_H^*\left(t\right); M\left(t\right), B\left(t\right)\right) = \widehat{H}\left(r(t); A\left(t\right), M\left(t\right), B\left(t\right)\right)$. Using (2.45) we can determine now $L_H^*\left(t\right) = \widehat{L}_H\left(p_H^*\left(t\right), w^*\left(t\right), H_d^*(t)\right) = \widehat{L}_H\left(r(t); A\left(t\right), M\left(t\right), B\left(t\right)\right)$. The labor market equilibrium then determines

$$L_Y^*\left(t\right) = L\left(t\right) - L_H^*\left(t\right),$$

where $L\left(t\right) = \widehat{L}\left(r(t); A\left(t\right), M\left(t\right), B\left(t\right)\right)$.[49] This implies the restriction

$$\widehat{L}\left(r(t); A\left(t\right), M\left(t\right), B\left(t\right)\right) \geq \widehat{L}_H\left(r(t); A\left(t\right), M\left(t\right), B\left(t\right)\right).$$

Given this is satisfied, we now have all inputs and outputs as functions of $r\left(t\right)$ and the states $\{A\left(t\right), M\left(t\right), B\left(t\right)\}$.

2.8.4 Impact of Medical Technology

Impact on the demand for health care and on the VOL: Totally differentiating the first-order condition for individual health demand, $-\phi(a,t)p_H\left(t\right) - \mu_h\left(a,t\right)\psi\left(a,t\right) = 0$, with respect to the state of technology $M\left(t\right)$ gives

$$-\phi dp_H - \left(\mu_{hh} dh + \mu_{hM} dM\right)\psi - \mu_h d\psi = 0$$

which transforms to

$$\begin{aligned} \frac{dh\left(a,t\right)}{dM\left(t\right)} &= \frac{-1}{\mu_{hh}}\left[\mu_{hM} + \frac{1}{\psi\left(a,t\right)}\left(\phi\frac{dp_H\left(t\right)}{dM\left(t\right)} + \mu_h\left(a,t\right)\frac{d\psi\left(a,t\right)}{dM\left(t\right)}\right)\right] \\ &= \frac{-1}{\mu_{hh}}\left[\mu_{hM} + \mu_h(a,t)\left(\frac{1}{\psi(a,t)}\frac{d\psi(a,t)}{dM(t)} - \frac{1}{p_H(t)}\frac{dp_H(t)}{dM\left(t\right)}\right)\right]. \end{aligned} \tag{2.50}$$

The impact of technology on the private value of life, as defined in (2.15), is given by

$$\frac{d\psi\left(a,t\right)}{dM\left(t\right)} = \int_a^{\omega} \frac{dv\left(\widehat{a}, t+\widehat{a}-a\right)}{dM\left(t\right)} R\left(\widehat{a},a\right) + v\left(\widehat{a}, t+\widehat{a}-a\right)\frac{dR(\widehat{a},a)}{dM} d\widehat{a}$$

$$= \int_a^{\omega} \frac{dv\left(\widehat{a}, t+\widehat{a}-a\right)}{dM\left(t\right)} R\left(\widehat{a},a\right) - v\left(\widehat{a}, t+\widehat{a}-a\right) R(\widehat{a},a)\int_a^{\widehat{a}} \frac{dr(t+\hat{\hat{a}}-a)}{dM} d\hat{\hat{a}} d\widehat{a} \tag{2.51}$$

[49] Note that through the impact of the demand for health care on the pattern of survival, labor supply becomes a function of the prices and the states of the economy.

where

$$\begin{aligned}\frac{dv\,(a,t)}{dM\,(t)} &= \left(\frac{u_c u_c - u u_{cc}}{u_c^2}\right)\frac{dc\,(a,t)}{dM\,(t)} \\ &= \left(1-\frac{u u_{cc}}{u_c^2}\right)\frac{dc\,(a,t)}{dM\,(t)}.\end{aligned}$$

Note, that $(1-\frac{uu_{cc}}{u_c^2})$ is always positive: Assuming b is sufficiently large and $c > c_0$, $u(c) = b + \frac{(c-c_0)^{1-\sigma}}{1-\sigma} > 0$, $u_c = (c-c_0)^{-\sigma} > 0$ and $u_{cc} = -\sigma(c-c_0)^{-\sigma-1} < 0$. Equation (2.26) is then obtained by inserting (2.51) into (2.50).

Impact on the the wage rate and price for health care:[50] In the following we derive equation (2.32) and (2.33). We use equation (2.48) from Appendix 2.8.3 and obtain

$$\begin{aligned}\frac{dw}{dM} &= -A\alpha^{\frac{1}{(1-\alpha)}}(r+\delta)^{\frac{1}{(\alpha-1)}}\frac{dr}{dM} \\ &= -A\left(\frac{\alpha}{r+\delta}\right)^{\frac{1}{(1-\alpha)}}\frac{dr}{dM} \\ &= -\frac{\alpha}{1-\alpha}\frac{w}{r+\delta}\frac{dr}{dM}.\end{aligned}$$

Hence, given equation (2.49), it then holds, that

$$\begin{aligned}\frac{dp_H}{dM} &= \frac{1}{\beta^\beta(1-\beta)^{1-\beta)}}\left[\beta(r+\delta)^{\beta-1}\frac{dr}{dM}w^{1-\beta} + (r+\delta)^\beta(1-\beta)w^{-\beta}\frac{dw}{dM}\right] \\ &= \frac{1}{\beta^\beta(1-\beta)^{1-\beta)}}\frac{dr}{dM}(r+\delta)^{\beta-1}w^{1-\beta}\left[\beta-(1-\beta)\frac{\alpha}{1-\alpha}\right] \\ &= \frac{p_H}{r+\delta}\frac{\beta-\alpha}{1-\alpha}\frac{dr}{dM}.\end{aligned}$$

Impact on the GDP per worker: In the following we will assume Cobb-Douglas specifications (2.30) and (2.31) of the production functions, see Appendix 2.8.3 for details. The GDP is defined as the sum of output value in the health care sector, $p_h F$, and in the final good sector, Y. Hence, GDP per unit of labor is given by

$$\frac{GDP}{L} = \frac{1}{L}\Big(p_H F + Y\Big) = \frac{Y}{L}\left(\frac{p_H F}{Y}+1\right).$$

Defining the employment share of the final goods sector as $\lambda := \frac{L_Y}{L}$ one can then show that

$$\frac{GDP}{L} = \left[\frac{1-\alpha}{1-\beta}\frac{1-\lambda}{\lambda}+1\right]A^{1-\alpha}\left(\frac{K_Y/L_Y}{K/L}\right)^\alpha\lambda\left(\frac{K}{L}\right)^\alpha \tag{2.52}$$

where we used equation (2.30) together with

$$\frac{p_H F}{Y} = \frac{1-\alpha}{1-\beta}\frac{1-\lambda}{\lambda} \tag{2.53}$$

[50] In the following, we drop the time index for notational convenience.

which follows from dividing equation (2.45) by (2.43) and rearranging The economy-wide capital-intensity can be expressed as

$$\frac{K}{L}=\frac{K_Y+K_H}{L_Y+L_H}=\frac{\alpha Y+\beta p_H F}{(1-\alpha)Y+(1-\beta)p_H F}\frac{w}{r+\delta}=\frac{(1-\alpha)\beta+(\alpha-\beta)\lambda}{(1-\alpha)\,(1-\beta)}\frac{w}{r+\delta} \tag{2.54}$$

where equation (2.53) was employed. Using in addition (2.46) we can write

$$\frac{K_Y/L_Y}{K/L}=\frac{\alpha\,(1-\beta)}{(1-\alpha)\beta+(\alpha-\beta)\lambda}.$$

Substituting this into (2.52) and rearranging we obtain

$$\frac{GDP}{L}=\frac{1-\alpha+(\alpha-\beta)\,\lambda}{1-\beta}A^{1-\alpha}\left[\frac{\alpha\,(1-\beta)}{\beta\,(1-\alpha)+(\alpha-\beta)\,\lambda}\right]^{\alpha}\left(\frac{K}{L}\right)^{\alpha}$$

as reported in equation (2.34). Taking the total derivative with respect to medical technology then yields

$$\begin{aligned}\frac{d}{dM}\left(\frac{GDP}{L}\right) &= (\alpha-\beta)\frac{GDP}{L}\left[\frac{1}{1-\alpha+(\alpha-\beta)\,\lambda}-\frac{\alpha}{\beta\,(1-\alpha)+(\alpha-\beta)\,\lambda}\right]\frac{d\lambda}{dM}\\ &\quad +\alpha\frac{GDP/L}{K/L}\frac{d}{dM}\left(\frac{K}{L}\right)\\ &= \frac{-\,(1-\alpha)\,(\alpha-\beta)^2\,(1-\lambda)}{[1-\alpha+(\alpha-\beta)\,\lambda]\,[\beta\,(1-\alpha)+(\alpha-\beta)\,\lambda]}\frac{GDP}{L}\frac{d\lambda}{dM}\\ &\quad +\alpha\frac{GDP}{K}\frac{d}{dM}\left(\frac{K}{L}\right),\end{aligned}$$

as reported in in equation (2.35) in the main body of the article. Note, that the denominator $[1-\alpha+(\alpha-\beta)\,\lambda]\,[\beta\,(1-\alpha)+(\alpha-\beta)\,\lambda]$ is positive as follows from equation (2.54).

2.8.5 Solving the Numerical Problem

We pursue the following steps towards tracing out the numerical solution, sketched here for the benchmark scenario, using the specific functional forms presented in section 2.6:

1. We derive from the first-order condition for consumption (2.13) the relationship

$$[c\,(a,t_0+a)-c_0]^{-\sigma}=[c\,(0,t_0)-c_0]^{-\sigma}\exp\left\{\int_0^a[\rho-r(t_0+\hat{a})+\mu(\hat{a})]\,d\hat{a}\right\}. \tag{2.55}$$

2. We derive the life-cycle budget constraint

$$\int_0^{\omega}\left[\begin{array}{c}w\,(t_0+a)\,l\,(a)-c\,(a,t_0+a)+\pi(a,t)\\ -\phi(a,t)p_H\,(t_0+a)\,h\,(a,t_0+a)-\tau(a,t)+s(t_0+a)\end{array}\right]R\,(a,0)\,da=0,$$

with $R(a, 0)$ as given by (2.17). We then insert (2.55) and obtain the consumption level

$$c(0, t_0) - c_0 = \frac{\int_0^\omega \begin{bmatrix} w(t_0 + a)\, l(a) - c_0 + \pi(a, t) \\ -\phi(a, t) p_H(t_0 + a)\, h(a, t_0 + a) - \tau(a, t) + s(t_0 + a) \end{bmatrix} R(a, 0)\, da}{\int_0^\omega \exp\left\{\int_0^a \left[\frac{1-\sigma}{\sigma} r(t_0 + \hat{a}) - \frac{\rho + \mu(\hat{a})}{\sigma}\right] d\hat{a}\right\} da} \tag{2.56}$$

for an individual born at t_0, contingent on the stream of health care, $h(a, t_0 + a)$, and the set of prices $\{w(t_0 + a), r(t_0 + a), p_H(t_0 + a)\}$ over the interval $[t_0, t_0 + \omega]$.

3. We derive from the first-order condition for health care (2.14) a vector of age-specific demand levels

$$h(a, t_0 + a) = \left(\frac{\lambda_s(a, t_0 + a)\,[c(a, t_0 + a) - c_0]^\sigma\, \tilde{\mu}(a)\eta(a)\epsilon(a) M(t_0 + a)^{\epsilon(a)}}{\phi(a, t) p_H(t_0 + a)}\right)^{\frac{1}{1-\epsilon(a)}} \tag{2.57}$$

for all $a \in [0, \omega]$.

4. We show in Appendix 2.8.3 that the set of prices $\{w(t_0 + a), p_H(t_0 + a)\}$ as well as all input and output quantities can be expressed in terms of the interest rate $r(t_0 + a)$ alone.

5. Using (2.55) together with (2.57) we can calculate the life-cycle allocation for consumption, $c(a, t_0 + a)$, depending on the allocation for health expenditures, $h(a, t_0 + a)$, $\forall a \in [0, \omega]$ and on the set of prices $\{w(t_0 + a), r(t_0 + a), p_H(t_0 + a)\}$ over the interval $[t_0, t_0 + \omega]$. Vice versa, the allocation of health expenditures can be calculated from the allocation of consumption and the macroeconomic prices.

6. We apply these calculations on initial guesses of c and h iteratively. We then use the results as an initial guess to the age-structured optimal control algorithm, as presented in Veliov (2003). This yields an optimal allocation of individual consumption and health expenditures contingent on an initially assumed $r(t_0 + a)$.

7. Drawing on this, we apply the following recursive approximation algorithm: (i) Guess an initial interest rate $r(t_0 + a)$ and derive the optimal life-cycle allocation. (ii) Based on this, calculate the market interest rate $r^*(t_0 + a)$ from the capital market equilibrium $K^d(r(t_0 + a), \widehat{w}(r(t_0 + a))) = K^s(r(t_0 + a))$. (iii) Adjust the initial interest rate, so that it approaches $r^*(t_0 + a)$, e.g. by setting $r_1(t_0 + a) := r_0(t_0 + a) + \epsilon(r^*(t_0 + a) - r_0(t_0 + a)), \quad \epsilon \in (0, 1]$. The process converges to an interest rate for which households optimize and capital demand equals capital supply. The output market clearing condition, $Y(t_0 + a) = C(t_0 + a) + \dot{K}(t_0 + a) + \delta K(t_0 + a)$ then determines the dynamics of the capital stock to the next period. (iv) This process is reiterated in a recursive way, employing a solution algorithm based on Newton's method. Equations (2.55)-(2.57) allow us to verify ex-post an optimum life-cycle allocation for the focal cohort born at t_0. While the numerical algorithm cannot determine in a precise way the optimal allocation for other cohorts, it nevertheless structures the allocation in a way that approximates the optimum for all cohorts.

CHAPTER 3

Health insurance, endogenous medical progress, and health expenditure growth

This second article, that has been jointly written with Michael Kuhn from the Vienna Institute of Demography, analyzes the drivers of health care expenditure growth in the US from 1960 to 2005. In particular, we pay close attention to the role of insurance expansions, taking into account the role of induced medical progress as well as complementarities with income growth. We extend the model framework from chapter 2 by introducing a third sector that uses profits accruing in the health care sector in order to develop more effective medical technology. We find that the US insurance expansion from 1960 to 2005 can account for a large share of the rise in US health spending but also for the boost to the rate of medical progress. A welfare analysis shows that while the moral hazard associated with the expansion of health insurance creates largely excessive health care expenditure as such, the gains in life expectancy brought about by induced medical progress more than compensate for this.

3.1 Introduction

Across the globe, large increases in health spending have been accompanying the economic development of numerous countries. In the United States, the share of the GDP spent on health care grew from 5 percent in 1960 to 17.5 percent in 2014, see Figure 3.1. Against this backdrop, a steady stream of research has emerged that enquires into the causes of this development. Since the seminal work by Newhouse (1992), medical progress has been recognized as a main driver of this strong increase in medical spending, with income growth (Hall and Jones 2007) and the expansion of social security (Zhao 2014) playing an additional role.[1] According to recent

[1] See Chernew and Newhouse (2012) and Chandra and Skinner (2012) for two recent surveys on medical spending growth in general and its relation to medical progress in particular.

analysis by Fonseca et al. (2013) about 30 percent of health care spending growth in the US over the period 1965-2005 can be explained by medical progress. While income growth explains only 4 percent in its own right, Fonseca et al. (2013) attribute 57 percent of the spending increase to a complementarity between medical progress and income growth.

Interestingly, health insurance continues to be assigned only a minor role in most of the research on the theme.[2] In light of the rapid expansion of health insurance in the US (see Figure 3.1), where out-of-pocket spending fell from around 55 percent in 1960 to around 15 percent in 2005 (Baicker and Goldman 2011), this is somewhat surprising, especially when considering the prominence that is assigned to moral hazard incentives in health insurance (see e.g. Zweifel and Manning 2000). While early research by Feldstein (1971, 1977) identified the expansion of health insurance as a major driver of the increase in health care spending, the seminal research building on the RAND health insurance experiment pointed the opposite direction: in light of a rather modest price elasticity of health care spending, insurance could not really explain the spending boom (Manning et al. 1987, Newhouse 1992).

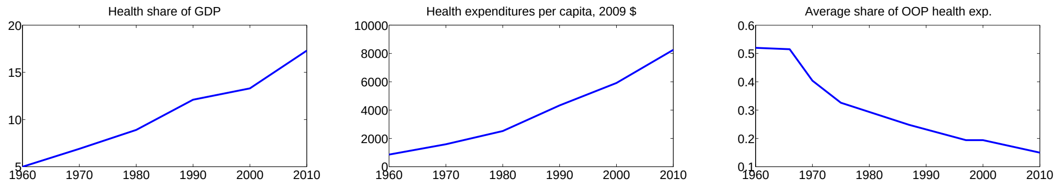


Figure 3.1: Health share of GDP, health expenditures per capita in 2009 $ and average share of out-of-pocket expenditures (OOP) in the US from 1960 to 2010. Data sources are discussed in section 3.3.1.

A conjecture by Weisbrod (1991) suggests a more indirect pathway through which health insurance may bear on the development of health expenditure: He hypothesizes that the expansion of health insurance coverage created incentives for medical R&D firms to develop new technology. Indeed, Clemens (2013) finds empirical support for this hypothesis: about 25 percent of recent medical-equipment innovation is explained by the expansion of US health insurance over the past half century.[3] Through a standard decomposition analysis, he then shows that insurance-induced innovation accounts for 15 percent of the long-run increase in US health care spending. In a related analysis, Finkelstein (2007) shows that health insurance, does, indeed, explain a spending increase that is more than six times larger than the one suggested by the RAND health insurance experiment once macro-economic responses, such as induced entry into the hospital market, are accounted for. She also provides evidence that is suggestive of the adoption of new (cardiac) technologies following the introduction of Medicare.

While these papers provide compelling evidence for a more important role of health insurance in explaining medical spending, their empirical focus does not allow a coherent understanding of the channels through which health insurance, medical progress and income growth

[2] E.g. in Fonseca et al. (2013) health insurance accounts for 8 percent of medical spending growth.

[3] Similar evidence includes Baker (2001) and Baker and Phibbs (2002) who find that increasing HMO market shares, implying less generous insurance coverage, were associated with slower diffusion and lower availability of the high-cost magnetic resonance imaging technology as well as the spread of neonatal intensive care units. Acemoglu and Linn (2004) and Finkelstein (2004) find a large impact of potential market size on the development of new medical drugs and vaccines, respectively.

interact in determining the demand for health care, health care spending and ultimately economic performance. In order to gain a more complete understanding of the underlying mechanisms, this article examines an OLG economy with a realistic demographic structure, in which consumers demand health care for the purpose of lowering mortality. Health care is provided within a medical sector, and the demand for medical innovations, in turn, follows as a derived demand on the part of health care providers. Both the health care sector and the medical R&D sector employ capital and labor, competing for resources with a final goods production sector.

We characterize the optimal life-cycle allocation in terms of consumption and health care and show how it evolves with age, with the extent of health insurance and with the state of medical technology. Solving the profit maximization problem of perfectly competitive providers within the final goods and health care sectors, we can characterize the optimal structure of supply and factor demand as well as the aggregate dynamics. We then employ our model to analyze numerically the impact of health insurance on medical progress, health expenditure and economic performance. To this end, we calibrate the model to reflect the development of the US economy over the time span 1965-2005 as it occurred in the presence of expanding health insurance. Against this benchmark, we then study the economic development under a counterfactual scenario in which we freeze the coverage of health insurance at its 1965 level, i.e. the level before the introduction of Medicare. Our results show that the expansion of health insurance has, indeed, contributed strongly to the expansion of health care spending, and that induced medical progress plays a significant role in this. Consumers reallocate a large share of their expenditure from consumption to health care and experience a significant reduction in mortality rates, in particular, in old age. Strikingly, economic performance, as measured by GDP growth, is not harmed despite the substantial reallocation of resources from final goods production to the health care sector.

In quantitative terms our analysis suggests that, in isolation, medical progress and insurance expansion can explain about 14% of the expenditure increase over the time span 1965-2005 each, whereas income growth explains about 16%. Similar to Fonseca et al. (2013), the remaining 56% of the expenditure increase are explained by complementarities between the three drivers. While we identify the income-insurance complementarity to be the strongest, medical progress also exhibits significant complementarity to both, income and insurance. When comparing the development of health care expenditure per capita in a benchmark scenario involving the observed expansion of health insurance against a counterfactual scenario in which insurance is frozen at its 1965 level, we find that the expansion of health insurance explains about 60% of the expenditure increase. This compares well with an estimate by Finkelstein (2007) who extrapolates her findings in respect to the introduction of Medicare to the more broader expansion of health insurance and finds that the latter explains about 50% of the spending increase from 1950 to 1990.

We also find that the expansion of health insurance has induced substantial medical R&D. Namely, it raises the rate of medical progress by about 41%, a figure that compares to an estimate of 33% by Clemens (2013) who is, however, only accounting for the impact of Medicare/Medicaid but not for the expansion of private health insurance. We then decompose the insurance induced increase in health care spending into a moral hazard effect associated with the subsidization of health care, and the spending increase associated with induced medical change. While moral hazard explains about 81% of the insurance-induced increase in health care spending, the opposite is true for the impact on life-expectancy: Overall, the expansion of health insurance has contributed 2.3 years to the increase in life expectancy between 1965 and 2000. Two of these years are attributable to the insurance-induced medical change, whereas the "pure" insurance effect contributed only 0.3 years.

These findings suggest an ambivalent role of health insurance expansion. Abstracting in our model from shocks to health care spending, the insurance expansion per se is mostly wasteful by generating a substantial increase in health care spending without much gain in health outcomes, a typical moral hazard effect. The distortion from moral hazard is offset, however, by the inducement of additional medical progress, which is generating substantial benefits. A comparison of the lifetime utility of the birth cohorts 1900-1980 reveals that while the moral hazard effect per se is, indeed, generating (modest) welfare losses for most of the birth cohorts, these are strongly overturned when induced medical progress is taken into account. Indeed, we find that all cohorts have benefited from the expansion of health insurance, the gain being strongest for later-born cohorts. This is partly due to the longer accumulation of medical knowledge and partly due to the fact that within a growing economy individuals exhibit an increasing willingness to pay for improvements to life-expectancy (Hall and Jones 2007), and are therefore willing to tolerate a growing drag on consumption growth (for similar findings see Jones 2016, Kuhn and Prettner 2016).

In focusing on the role of endogenous medical progress, our article is related to Clemens (2013) who also identifies insurance-induced innovation as an expenditure driver. He focuses on geographical variations in the expansion of insurance coverage as well as on the role of "innovating-by-doing" on the part of physicians in facilitating the diffusion of innovations. In contrast, our contribution amounts to a full general equilibrium account with a medical R&D sector that is distinct from the health care sector, and a set of overlapping generations of consumers with endogenous demand for health care. Our focus also differs in that we are interested in particular in the role of complementarities in the generation of medical innovation and in the welfare implications of health-insurance expansion. Other papers dealing with endogenous medical progress are Jones (2016) who considers the optimal mix of medical R&D as opposed to conventional R&D from a social planner perspective, and Koijen et al. (2016) who study the impact of regulatory risks on medical innovation. Apart from the obvious differences in the policy focus, our key distinction from Jones (2016) is that he does not consider the evolution of medical progress in a decentralized economy, whereas our key distinction from Koijen et al. (2016) is the overlapping generations framework with endogenous mortality. Neither of the works focuses on the impact of health insurance.[4] Closer in spirit is a recent paper by Böhm et al. (2017) who consider the role of R&D-driven medical progress which improves health and longevity within an OLG economy and the extent of which can be controlled by a public purchaser of health care technology. Studying the trade-off between containing health care spending and granting access to medical progress, the authors also find that the gains from medical progress outweigh the savings on expenditure. Their work differs from ours in a number of dimensions. Most importantly, they do not consider the private demand for health care nor the role of health insurance

[4] Our work is also related to a literature examining the role of exogenous medical progress on health care expenditure and economic performance (Fonseca et al. 2013, Schneider and Winkler 2016, chapter 2 of this thesis).

in steering this demand. Their calibration being based on the UK NHS, they rather consider a public health care system with direct rationing. Furthermore, their numerical experiments are forward looking (up to the year 2050) rather than backward looking such as ours.

The macro-economic impact of health insurance (reform) features in Jung and Tran (2016) and Conesa et al. (2017) who study the impact on economic performance and welfare of the introduction of the 2010 Affordable Care Act (Obama Care) and of a (hypothetical) removal of Medicare, respectively. Examining in a way the reverse scenario to ours, Conesa et al. (2017) find that while consumers would benefit in a new steady state without Medicare, even the cumulated welfare gains would be lower than the welfare loss along the transition path. Neither of the two works considers medical progress.[5] This article is thus complementary to these works in as far as they study the trade-off between moral hazard and the direct gains from insurance, whereas we are considering the trade-off between moral hazard and the dynamic benefits generated from health insurance through the stimulation of medical progress.[6] Strikingly, in combination with Conesa et al. (2017) our results suggest a strong case for maintaining health insurance. While Conesa et al. (2017) find that health insurance should not be abolished owing to high short-term welfare losses, we find it should not be abolished owing to the inducement of medical progress with lasting long-term benefits.

The remainder of the article is organized as follows. The following section introduces the model and characterizes the individual life-cycle optimum and general equilibrium. Section 3.3 introduces the numerical calibration and presents the findings for the benchmark. Section 3.4 explores by various counterfactual experiments the role of health insurance, income and social security as drivers of medical change, as well as the implications for the development of health expenditure. It also features a welfare analysis. Section 3.5 concludes. Some proofs and formal elements of the analysis have been relegated to an Appendix.

3.2 The Model

3.2.1 Individual problem

We consider an OLG model in which individuals choose consumption and health care over their life-course. Individuals are indexed by their age a at time t, with $t_0 = t - a$ denoting the birth year of an individual aged a at time t. At each age, individuals are subject to a mortality risk, where $S(a,t) = \exp\left[-\int_0^a \mu(\widehat{a}, h(\widehat{a}, \widehat{t}), M(\widehat{t}))d\widehat{a}\right]$ is the survival function at (a,t), with $\mu(a, h(a,t), M(t))$ denoting the force of mortality. Following chapter 2 we assume that mortality can be lowered by the consumption of health care $h(a,t)$, the impact of which depends on the state of the medical technology $M(t)$ at time t. More specifically, we assume that the mortality

[5]One additional difference to Conesa et al. (2017) is that their model does not embrace a specific health care sector. As emerges from the analyzes in chapter 2 and Kuhn and Prettner (2016), respectively, the reallocation of production factors across sectors plays a significant role, however, in channeling the economic impact of changes to the health care system.

[6]This is what Bhattacharya and Packalen (2012) call "the other ex-ante moral hazard", which they consider, however, in a quasi-static partial equilibrium setting.

rate $\mu(a,h(a,t),M(t))$ satisfies

$$\begin{aligned}\mu(a,h(a,t),M(t)) &\in (0,\tilde{\mu}(a,t)] \quad \forall\,(a,t)\,;\\ \mu_h(\cdot) &< 0,\ \mu_{hh}(\cdot)>0;\\ \mu_h(a,0,M(t)) &= -\infty,\ \mu_h(a,\infty,M(t))=0 \quad \forall\,(a,t)\,;\\ \mu_M(\cdot) &< 0,\ \mu_{MM}(\cdot)\geq 0,\ \mu_{hM}(\cdot)<0 \quad \forall\,(a,t)\,.\end{aligned}$$

where $\tilde{\mu}(a,t)=\mu(a,0,M(t))$ is the "natural "mortality rate for an individual aged a at time t when no health care is consumed. By purchasing health care, an individual can lower the instantaneous mortality rate, and can thereby improve survival prospects, but can only do so with diminishing returns.[7]

Individuals enjoy period utility $u(c(a,t))$ from consumption $c(a,t)$. Period utility is increasing and concave: $u_c(\cdot)>0$, $u_{cc}(\cdot)\leq 0$. Individuals maximize the present value of their expected life-cycle utility

$$\max_{c(a,t),h(a,t)} \int_0^{\omega} e^{-\rho a}u(c(a,t))S(a,t)da \tag{3.1}$$

by choosing a stream of consumption and health care on the interval $[0,\omega]$, with ω denoting the maximal possible age, with $\rho\geq 0$ denoting the rate of time preference, and with $S(a,t)$ denoting the survival function.[8] While we will continue to interpret $S\,(a,t)$ as survival alone, the function may, in fact, be interpreted as a more general measure of health that is subject to depreciation over the life-course (see e.g. Chandra and Skinner 2012, Kuhn et al. 2015). Assuming that utility from consumption and utility from good health are multiplicatively separable, one could generalize the interpretation of (3.1) to include not only health-dependent duration of life but also health-dependent quality of life.

The individual faces as constraints the dynamics of survival and the dynamics of individual assets $k(a,t)$, as described by[9]

$$\begin{aligned}\dot{S}(a,t) &= -\mu(a,h(a,t),M(t))S(a,t), &(3.2)\\ \dot{k}(a,t) &= r\,(t)\,k(a,t)+l(a)w(t)-c(a,t)\\ &\quad -\phi\,(a,t)\,p_H(t)h(a,t)-\tau\,(a,t)+\pi\,(a,t)+s(t), &(3.3)\end{aligned}$$

[7]Zweifel et al. (2005) provide empirical evidence of decreasing returns to health expenditure in the reduction of mortality. The decreasing returns assumption is also reflected in other empirical work on the relationship between health care and mortality (e.g. Baltagi et al. 2012, Hall and Jones 2007). Medical technology, in turn, enhances the returns to health care. While this assumption is not self-evident, it is consistent with empirical evidence that medical progress boosts the demand for medical care (see e.g. Baker et al. 2003, Cutler and Huckman 2003, Roham et al. 2014, Wong et al. 2012).

[8]Note that from the individual's perspective age and time progress simultaneously, following the identity $a\equiv t-t_0\in[0,\omega]$ for $t\in[t_0,t_0+\omega]$. Thus, we have $\int_0^{\omega}e^{-\rho a}u(c(a,t))S(a,t)da=\int_0^{\omega}e^{-\rho a}u(c(a,t_0+a))S(a,t_0+a)da=\int_{t_0}^{t_0+\omega}e^{-\rho t}u(c(t-t_0,t))S(t-t_0,t)dt$.

[9]In the following, we will use the $\dot{()}$ notation to indicate both the derivative $\dot{x}\,(a,t):=x_a+x_t$ for life-cycle variables and the derivative $\dot{X}\,(t):=X_t$ for aggregate variables. Drawing again on the identity $t\equiv t_0+a$ from the individual's perspective, it follows that $\dot{x}\,(a,t)$ collapses into a single dimension.

with the boundary conditions

$$\begin{aligned} S(0,t_0) &= 1, \quad S(\omega, t_0+\omega) = 0 & (3.4)\\ k(0,t_0) &= k(\omega, t_0+\omega) = 0. & (3.5) \end{aligned}$$

Here, (3.2) describes the reduction of survival according to the force of mortality. According to (3.3) an individual's stock of assets $k(a,t)$ (i) increases with the return on the current stock, where $r(t)$ denotes the interest rate at time t; (ii) increases with earnings $l(a)w(t)$, where $w(t)$ denotes the wage rate at time t, and where $l(a)$ denotes an individual's effective age-dependent labor supply; (iii) decreases with consumption, the price of consumption goods being normalized to one; (iv) decreases with private health expenditure, $\phi(a,t)\,p_H(t)h(a,t)$, where $p_H(t)$ denotes the price for health care, and where $\phi(a,t)$ denotes an (a,t)-specific rate of coinsurance; (v) decreases with an (a,t)-specific tax, $\tau(a,t)$; (vi) increases with (a,t)-specific benefits $\pi(a,t)$; and (vii) increases with a transfer $s(t)$ by which the government redistributes accidental bequests in a lump-sum fashion. We follow Zhao (2014) and others by considering a setting without an annuity market.[10] Finally, we assume that the survival function is bounded between 1 at birth and 0 at the maximum feasible age ω [see (3.4)], and that individuals enter and leave the life-cycle without assets [see (3.5)].

3.2.2 Aggregation

Denoting by $B(t-a)$ the size of the birth cohort at $t_0 = t-a$, the cohort aged a at time t has the size

$$N(a,t) = S(a,t)B(t-a).$$

By aggregating over the age-groups who are alive at time t we obtain the following expressions for the population size,[11] aggregate capital stock, aggregate effective labor supply, aggregate consumption, aggregate demand for health care, aggregate fiscal income from taxation, and aggregate social security payments, each at time t:

[10] This is well in line with evidence that few individuals annuitise their wealth (e.g. Reichling and Smetters 2015, Warshawsky 1988).

[11] In a slight abuse of notation, $N(t)$ denotes the population size at time t, whereas $N(a,t)$ represents the size of the cohort aged a at time t.

$$
\begin{aligned}
N(t) &= \int_0^\omega S(a,t)B(t-a)da, && (3.6)\\
K(t) &= \int_0^\omega k(a,t)S(a,t)B(t-a)da, && (3.7)\\
L(t) &= \int_0^\omega l(a,t)S(a,t)B(t-a)da, && (3.8)\\
C(t) &= \int_0^\omega c(a,t)S(a,t)B(t-a)da, && (3.9)\\
H(t) &= \int_0^\omega h(a,t)S(a,t)B(t-a)da, && (3.10)\\
\Upsilon(t) &= \int_0^\omega \tau(a,t)\, S(a,t)B(t-a)da, &&\\
\Pi(t) &= \int_0^\omega \pi(a,t)\, S(a,t)B(t-a)da. &&
\end{aligned}
$$

3.2.3 Production

The economy consists of a manufacturing sector, a health care sector and a medical R&D sector. In the manufacturing sector a final good is produced by employment of capital $K_Y(t)$ and labor $L_Y(t)$ according to a neoclassical production function

$$Y(A_Y(t), K_Y(t), L_Y(t)) = A_Y(t)K_Y(t)^\alpha L_Y(t)^{1-\alpha}, \tag{3.11}$$

with $A_Y(t)$ denoting total factor productivity in final goods production. A manufacturer's profit can then be written as

$$V_Y(t) = Y(A_Y(t), K_Y(t), L_Y) - w(t)L_Y(t) - [\delta + r(t)]\, K_Y(t), \tag{3.12}$$

with $\delta \geq 0$ denoting the rate of capital depreciation. Note that $V_Y(t) = 0$ in a competitive equilibrium.

Health care goods and services are produced by employment of labor $L_H(t)$, and capital $K_H(t)$ according to the production function

$$F(A_H(t), K_H(t), L_H(t)) = A_H(t)K_H(t)^{\beta_1} L_H(t)^{\beta_2}, \tag{3.13}$$

with $\beta_1 + \beta_2 < 1$, implying decreasing returns to scale, and with $A_H(t)$ denoting total factor productivity in the health care sector. Recalling the price for health care $p_H(t)$, the profit of a health care provider is then given by

$$V_H(t) = p_H(t)\, F(A_H(t), K_H(t), L_H(t)) - w(t)L_H(t) - [\delta + r(t)]\, K_H(t). \tag{3.14}$$

Note that decreasing returns to scale in the health care sector imply $V_H(t) > 0$, i.e. the existence of a producer rent, in a competitive equilibrium. Finally, we assume a medical R&D sector, the output of which is augmenting the state of medical technology $M(t)$ according to

$$\dot{M}(t) = G(A_M(t), K_M(t), L_M(t)) = A_M(t)K_M(t)^{\gamma}L_M(t)^{1-\gamma}, \tag{3.15}$$

with $K_M(t)$, $L_M(t)$ and $A_M(t)$, respectively, denoting capital and labor inputs as well as total factor productivity in the medical R&D sector. Profits in the medical R&D sector are then given by

$$V_M(t) = p_M(t)\,G(A_M(t), K_M(t), L_M(t)) - w(t)L_M(t) - [\delta + r(t)]\,K_M(t), \tag{3.16}$$

with $p_M(t)$ denoting the price for new medical technology. Again, we have $V_M(t) = 0$ as we assume a neo-classical production function. Note, that total factor productivity in the R&D sector is not $M(t)$, such that we do not model the standing on shoulder of giants effect. The productivity of health care in lowering mortality, $M(t)$, will grow endogenously according to (3.15) with the production level in the medical R&D sector being determined by the profits accruing in the health care sector which are assumed to be entirely devoted to the purchase of new technology:

$$p_M(t)G(A_M(t), K_M(t), L_M(t)) = V_H(t). \tag{3.17}$$

3.2.4 Health Insurance, Social Security and Accidental Bequests

We assume that the government and/or a third-party payer (e.g. a health insurer) raise taxes (or contribution rates, e.g. insurance premiums) for the purpose of co-financing health care at the rate $1 - \phi(a,t)$ and paying out transfer payments $\pi(a,t)$. In our numerical analysis we will assume $\pi(a,t)$ to be pension benefits, implying that

$$\pi(a,t) = \begin{cases} 0 \Leftrightarrow a < a_R \\ \pi(t) \geq 0 \Leftrightarrow a \geq a_R \end{cases}$$

with $\pi(t)$ a uniform pension benefit at time t and a_R the retirement age. In such a setting we also have

$$l(a,t) = \begin{cases} l(a) \geq 0 \Leftrightarrow a < a_R \\ 0 \Leftrightarrow a \geq a_R \end{cases}.$$

Likewise, $\tau(a,t)$ are age-specific taxes set at levels that ensure the government's and private health insurer's budget balance $\Upsilon(t) = \Pi(t) + \int_0^{\omega} [1 - \phi(a,t)]\, h(a,t)S(a,t)B(t-a)da$. Further details on the modeling of health insurance and social insurance are provided in section 3.3.1 on the calibration of the model.

Finally, we assume that

$$s(t) = \frac{\Upsilon_B(t)}{N(t)}, \tag{3.18}$$

where

$$\Upsilon_B(t) = \int_0^\omega \mu(a,t)k(a,t)N(a,t)da \tag{3.19}$$

are total accidental bequests.[12]

3.2.5 Individual Life-Cycle Optimum

In Appendix 3.6.1 we show that the solution to the individual life-cycle problem is given by the following two sets of conditions

$$\begin{aligned}
&\frac{u_c\left(c\left(a,t\right)\right)}{\exp\left\{-\int_a^{\widehat{a}}\left[\rho+\mu\left(\widehat{\widehat{a}},t+\widehat{\widehat{a}}-a\right)\right]d\widehat{\widehat{a}}\right\}u_c\left(c\left(\widehat{a},t+\widehat{a}-a\right)\right)} \\
&= \exp\left[\int_a^{\widehat{a}} r\left(t+\widehat{\widehat{a}}-a\right)d\widehat{\widehat{a}}\right], &(3.20)\\
\psi\left(a,t\right) &= \frac{-\phi\left(a,t\right)p_H\left(t\right)}{\mu_h\left(a,t\right)} \quad \forall\left(a,t\right), &(3.21)
\end{aligned}$$

describing the optimal pattern of consumption $c(a,t)$ and the demand for health care $h(a,t)$, respectively, of an individual aged a at time t. Condition (3.20) is the well-known Euler equation, requiring that the marginal rate of intertemporal substitution between consumption at any two ages/years (a,t) and $(\widehat{a}, t+\widehat{a}-a)$ equals the compound interest. Note that in the absence of annuities, the uninsured mortality risk can be interpreted as an additional factor of discounting, implying an effective discount rate $\rho + \mu(a,t)$ at any (a,t). Rising mortality then implies a downward drag on consumption toward the end of life.

Condition (3.21) requires that at each (a,t) the private value of life, i.e. the willingness to pay for survival, $\psi(a,t)$, equals the price of survival, $-\phi(a,t)p_H(t)/\mu_h(a,t)$. Here, the consumer price for health care, $\phi(a,t)p_H(t)$, is converted into a price of survival by weighting with the number of units of health care required for a unit reduction in mortality, $[\mu_h(a,t)]^{-1}$. The private VOL is defined by

$$\psi\left(a,t\right) := \int_a^\omega v\left(\widehat{a},t+\widehat{a}-a\right)R\left(\widehat{a},a\right)d\widehat{a}, \tag{3.22}$$

with

$$v\left(a,t\right) := \frac{u(c\left(a,t\right))}{u_c\left(\cdot\right)}, \tag{3.23}$$

and

$$R\left(\widehat{a},a\right) := \exp\left[-\int_a^{\widehat{a}} r\left(t+\widehat{\widehat{a}}-a\right)d\widehat{\widehat{a}}\right], \tag{3.24}$$

[12] In order to ease on notation, we will subsequently refer to the shortcut $\mu(a,t)$ for $\mu(a,h(a,t),M(t))$.

and amounts to the discounted stream of consumer surplus, $v = u(\cdot)/u_c(\cdot)$ taken over the expected remaining life-course $[a, \omega]$.[13] It is readily checked that the value of life at each (a, t) increases (i) with the level of the individual's consumption and, thus, the individual's income, and (ii) with the state of the medical technology, the latter effect arising as technology-induced mortality reductions, $\mu_M(\widehat{a}, t + \widehat{a} - a) < 0$, cause over the remaining life-course $\widehat{a} \in (a, \omega)$ a reallocation of consumption toward these later life-years. The price of survival (a, t), in turn, decreases (i) with health insurance coverage, $1 - \phi(a, t)$, at (a, t), and (ii) with the state of the medical technology, given that the latter raises the effectiveness of health care, $\mu_{hM}(a, t) < 0$. Thus, intuitively, the demand for medical care will - ceteris paribus - increase with income, with the extent of health insurance, and with the state of the medical technology. While price and income effects modify these partial equilibrium impacts, our numerical analysis shows that these same three drivers of the (individual and aggregate) demand for health care are operative in general equilibrium.

3.2.6 General Equilibrium

Perfectly competitive firms in the three sectors $j = Y, H, M$ choose labor $L_j(t)$ and capital $K_j(t)$ so as to maximize their respective period profit (3.12), (3.14) and (3.16). The six first-order conditions determine the six (sector-specific) factor demand functions, depending on the set of prices $\{r(t), w(t), p_H(t), p_M(t)\}$.[14] Likewise, we obtain the age-specific demand for consumption goods $c(a, t)$ and health care $h(a, t)$ from the set of first-order conditions (3.20) and (3.21) of the individual life-cycle problem. The age profile of individual wealth $k(a, t)$ then follows implicitly from the life-cycle budget constraint (3.3). Aggregating across the age-groups alive at each point in time t according to (3.7)-(3.10) gives us the aggregate supply of capital $K(t)$ and labor $L(t)$, as well as the aggregate demand for consumption $C(t)$ and health care $H(t)$. The general equilibrium characterization of the economy is completed by the set of five market clearing conditions

$$\begin{aligned}
L_Y(t) + L_H(t) + L_M(t) &= L(t) \\
K_Y(t) + K_H(t) + K_M(t) &= K(t) \\
Y(A_Y(t), K_Y(t), L_Y(t)) &= C(t) + \dot{K}(t) + \delta K(t) \\
F(A_H(t), K_H(t), L_H(t)) &= H(t) \\
p_M(t) G(A_M(t), K_M(t), L_M(t)) &= V_H(t)
\end{aligned}$$

corresponding to the labor market, the capital market, the market for final goods, the market for health care and the market for medical innovation, respectively. From these, we then obtain a set of equilibrium prices $\{r^*(t), w^*(t), p_H^*(t), p_M^*(t)\}$ and the level of net capital accumulation

[13]The VOL as we calculate it here differs from the typical representation of the value of a statistical life as e.g. in Shepard and Zeckhauser (1984), Rosen (1988), or Murphy and Topel (2006) in as far as (i) the discount factor does not include the mortality rate; and (ii) the VOL does not include the current change to the individual's wealth, $lw - c - h - \tau + \pi + s$. Both of these features are due to the absence of an annuity market.

[14]With appropriate Inada conditions on the production functions, we always have an interior allocation with $L_M(t) = L(t) - L_Y(t) - L_H(t) \in (0, L(t))$ and $K_M(t) = K(t) - K_Y(t) - K_H(t) \in (0, K(t))$.

$\dot{K}(t)$. Appendix 3.6.3 provides a more detailed characterization based on the Cobb-Douglas production functions specified in (3.11), (3.13) and (3.15), respectively.

3.3 Numerical Analysis: Calibration and Benchmark

Following a description of our numerical analysis, we present the outcomes for a benchmark scenario that features a realistic economy calibrated to US data from 1960 to 2005 with respect to the macroeconomic development in this period, the institutional changes as well as the life-cycle profiles (see Section 3.3.3). We subsequently use this to examine the role of health insurance in a number of counterfactual numerical experiments. Technical information on the numerical solution method is provided in Appendix 3.6.2.

3.3.1 Specification and Calibration

The main components of our numerical model are specified as follows.

Demography

Individuals enter the model economy at age 20 and can reach a maximum age of 100 with model time progressing in single years.[15] In our model, a "birth" at age 20 implies a maximum age $\omega = 80$. Population dynamics are partly endogenous due to mortality that is determined within the model and partly exogenous due to a fixed growth rate schedule of "births" $\nu(t)$. The number of births at time t is given by

$$B(t) = B_0 \exp\left[\int_0^t \nu(\hat{t})d\hat{t}\right], B_0 > 0.$$

The time-dependence of the growth rate of births will be set (in consideration of the endogenously determined mortality) to match the age-structure of the United States between 1965 and 2005, see Table 3.2.[16] Due to the exogenous path of births, our results will not be driven by changing birth numbers across the experiments. This notwithstanding, with the bulk of mortality lying beyond the fecund years since at least the second half of the 20th century, we do not expect the assumption of an exogenous flow of births to have any great impact on our results.

Mortality

The force of mortality $\mu(a,t) = \mu(h(a,t), M(t))$ is endogenously determined in the model and depends on health care, $h(a,t)$, as a decision variable, and on the level of medical technology, $M(t)$. Adapting Hall and Jones (2007), we formulate

$$\mu(a,t) = \eta(a)\,(h(a,t))^{\kappa(a)M(t)}, \tag{3.25}$$

[15] We follow the bulk of the literature and neglect life-cycle decisions during childhood.

[16] Note that our primary measures of age-structure, namely the population share of individuals aged 65 or older, as well as the employment-population ratio refer to the population aged 20 or older in the denominator. The data used in Table 3.2 hence refers to the population without individuals aged less than 20.

where $\eta(a) > 0$ and $\kappa(a) < 0$ are parametric functions that reflect the age-specific effectiveness of health care.[17] We choose $\kappa(a)M(t = 2000)$ to be in the range of age-specific elasticities of mortality with respect to health care utilization for the year 2000, as reported in Hall and Jones (2007). The term $\eta(a)$ is then determined such that the age pattern of optimal health expenditure and the endogenous level of medical technology yield the empirically observed mortality pattern for a given year.[18] For further reference, let us define the elasticity of mortality with respect to health care spending,

$$\epsilon\left(\mu, h, a, t\right) := \mu_h h/\mu = \kappa(a)M(t) < 0, \tag{3.26}$$

as "medical effectiveness". Intuitively, medical effectiveness varies with age and increases, in absolute terms, in the state of the medical technology. In our model parametrization, $\kappa(a)M(t)$ ranges from -0.2 to -0.04 in the year 2005 and is thus close to the estimates of Hall and Jones (2007). For the year 1965, for which the level of medical technology is considerably lower, $\kappa(a)M(t)$ ranges from -0.05 to -0.01. This implies a considerable increase in medical effectiveness over the period 1965-2005. While we cannot quote direct evidence on the impact of medical progress on medical effectiveness, Gallet and Doucouliagos (2017) find some evidence in a meta-regression analysis that the elasticity of mortality with respect to health spending in absolute terms does, indeed, increase over time.[19]

The increase of medical effectiveness over time notwithstanding, one may nevertheless consider the spending effectiveness to be relatively low. Here, it should be borne in mind that we are considering the impact of all health care spending on mortality, and, thus, necessarily a very "unfocused" measure of health care. Indeed, in their analysis of the effectiveness of NHS treatment programs for cancer and circulatory disease, Martin et al. (2008) report substantially higher elasticities of mortality with respect to condition-specific expenditure.

Utility

We assume instantaneous utility to be given by

$$u(a,t) = b + \frac{c(a,t)^{1-\sigma}}{1-\sigma},$$

where we choose the inverse of the elasticity of intertemporal substitution to be $\sigma = 1.2$ which is within the range of the empirically consistent values suggested by Chetty (2006).[20] Setting

[17] The functional form of $\mu(a,t)$ fulfills the properties of the mortality function outlined in section 3.2.1 within the relevant value space of h, κ and M.

[18] We use the year 1965, representing the beginning of the time period under consideration, to calibrate $\eta(a)$. The mortality rate for the US in 1965 is taken from the Human Mortality Database.

[19] While the average year of the data underlying the elasticity estimate is insignificant in all regression specifications (where the dependent variable is the spending elasticity), an increase in the age of the data by one year decreases the elasticity estimate by about 0.002. Hence, in 1965 the elasticity should be about 0.002*40 = 0.08 lower in absolute terms than the elasticity in 2005. This is roughly in line with our model parametrization.

[20] Note that Hall and Jones' (2007) most preferred value for the inverse of the elasticity of intertemporal substitution is $\sigma = 2$. Presumably this is because the higher income elasticity of health care thus implied is necessary to explain the growing health share on the basis of income growth alone. As we are accounting for insurance and medical progress as additional drivers of spending growth, our modeling implies a lower income elasticity (see more on this below) and, thus, a lower σ.

$b = 8.4$ then guarantees that $u(a, t) \geq 0$ throughout and generates an average VOL that lies within the range of plausible estimates, as suggested in Viscusi and Aldy (2003) and documented in Table 3.2. Moreover, we assume a rate of time preference $\rho = 0.03$.

Finally, we impose a minimum consumption level equal to the social security benefit at a given point in time. We do so to avoid negative asset holdings at old age, as would otherwise result from ex-ante optimization.[21] Given that retirees cannot usually loan against future pension income and given that individuals are downspending their assets in old age (as they do within our model) the minimum consumption constraint is plausible.

Finally, we assume a rate of time preference $\rho = 0.03$.

Effective Labor Supply and Income

We proxy the effective supply of labor by an age-specific income schedule taken from chapter 2. We, therefore, assume that the age-specific labor supply is constant throughout the whole time horizon with GDP per capita rising according to the data. Individuals aged 65 or older are assumed to have no income from labor but receive a fixed social security pension for the remainder of their lifetime, as detailed further on below.

Production

Each sector features a distinct production function, as given by

$$\begin{aligned} Y(A_Y(t), K_Y(t), L_Y(t)) &= A_Y(t) K_Y(t)^{\alpha} L_Y(t)^{1-\alpha}, \\ F(A_H(t), K_H(t), L_H(t)) &= A_H(t) K_H(t)^{\beta_1} L_H(t)^{\beta_2}, \\ G(A_M(t), K_M(t), L_M(t)) &= A_M(t) K_M(t)^{\gamma} L_M(t)^{1-\gamma}. \end{aligned}$$

Following the bulk of the literature, the elasticity of capital α is chosen to be $1/3$. In regard to productivity growth we assume that $A_Y(t)$ grows at a rate of 1.45% per year, such that the GDP per capita is growing in line with the data.[22]

For the production elasticity of capital in the health care sector we take an estimate from Acemoglu and Guerrieri (2008) and set $\beta_1 = 0.2$. We choose $\beta_2 = 0.78$, such that (i) profits accrue in the health care sector and (ii) the medical R&D share in total GDP lies within the range of empirical data for the given time period, see Table 3.2. Total factor productivity in the medical sector, $A_H(t)$, is assumed to grow at a rate of 0.5%, reflecting the relative slow productivity growth within labor-intensive sectors.[23]

[21] Individuals choose old-age consumption at the beginning of their life, attaching a low probability to reaching very high ages. Consumption allocated to these ages (in the absence of a minimum consumption level) is thus very low and can fall below the social security income, such that it is optimal to pay back debt (accumulated to finance consumption at earlier ages) at very high ages with excess social security income.

[22] As a data source we use the "Real gross domestic product per capita" as provided by the Federal Reserve Bank of St. Louis. Note, however, that not $A_Y(t)$ alone determines GDP per capita growth, but also the evolution of demography, medical technology, health expenditures and other factors.

[23] This choice of value is in line with Färe et al. (1997) and Spitalnic et al. (2016) who measure productivity growth in the US health care sector based on the quantity rather than the quality of services and find average productivity growth rates of 0.1-0.7 %. While medical progress in the sense of better health and mortality outcomes is measured by $M(t)$, the measure of increased quantity-related productivity is a good proxy for A_H.

For the R&D sector we assume $\gamma = 0.34$, following the capital elasticity provided in Acemoglu and Guerrieri (2008) for the category of professional and scientific services. Total factor productivity in the R&D sector $A_M = 0.35$ is assumed to be constant and is chosen such that the growth rate of the annual R&D output $\ddot{M}(t) := d\dot{M}(t)/dt$, is in accordance with the growth rate of medical patents,[24] see Table 3.2.

In our calibration we aim to match the increase in health expenditures and the health share of GDP, the data on which is taken from the National Health Expenditure Tables provided by the National Health Accounts (NHA).[25] Importantly, however, we do not directly target these variables in the model parametrization but focus on the calibration of the drivers of health care spending, namely the rate of growth of $M(t)$, as described above, as well as the insurance and income elasticity to be discussed further on below.

Finally, we assume a rate of capital depreciation equal to $\delta = 0.05$.

Health Insurance and Social Security

Health expenditures are subsidized through two different types of funds: (a) private health insurance with coinsurance rate $\phi_P(a,t)$ and (b) public insurance provided by Medicare, Medicaid and other public programs. We assume that Medicare is only available to the elderly (after the mandatory retirement age $a_R = 65$) with coinsurance rate $\phi_{MC}(a,t)$ and Medicaid only to those of working age ($a < a_R$) with a coinsurance rate $\phi_{MA}(a,t)$. The remaining public programs are assumed to be available to all age-groups at a coinsurance rate $\phi_{RP}(a,t)$. We use data on health insurance coverage in the US from from the National Center for Health Statistics (NCHS). The NCHS reports sources of payments for health care among the young (<65 years old) and the elderly, providing information on the proportions of total health expenditures that were payed for out-of-pocket (OOP) and through private insurance, Medicare, Medicaid and other public insurance programs, respectively.[26]

Figure 3.2 shows the evolution of insurance coverage from 1965 to 2005 for the young (<65 years) and the elderly in the US. In our simulation, we interpret the shares of each type of fund as exogenously given, age- and time-dependent health care subsidies.

Private health insurance is financed through a "risk-adequate" premium equal to the expected health expenditure, $p_H(t)h^*(a,t)$, covered by the insurance for an individual at a given time and age. It is thus given by $\tau_P = [1 - \phi_P(a,t)]\, p_H(t)h^*(a,t)$. As described above, we set $\phi_P(a,t)$ equal to the share of expenditures payed for by private insurance, where we obtain different co-

[24] We calculate the growth number of new medical patents based on U.S. Patent Statistics Chart, indicator "Utility Patent Grants, U.S. Origin", as provided by the U.S. Patent and Trademark Office, and on estimates about the share of health related patents since 1965, as provided by Jones (2016).

[25] In the following, all dollar values are to be understood as constant 2009 USD.

[26] We use the 1976-1977 "Health" report by the NCHS (Table 149) to obtain data from 1966 to 1975, as well as the 2015 "Health" report (Table 98) for the years 1987, 1997, 2000 and 2012 to identify the share of health expenditures funded out-of-pocket, by public programs and by private health insurance for the young and the elderly (65 and above), respectively. We then identify the share of government funds devoted to programs other than Medicare and Medicaid from the 2010 "Health" report (Table 126) for 1960 - 2006. Based on this data and by making the simplifying but realistic assumption that Medicaid is utilized only by the young and Medicare only by the elderly we can construct the time-series in Figure 3.2. All NCHS "Health" reports are available at https://www.cdc.gov/nchs/hus/previous.htm.

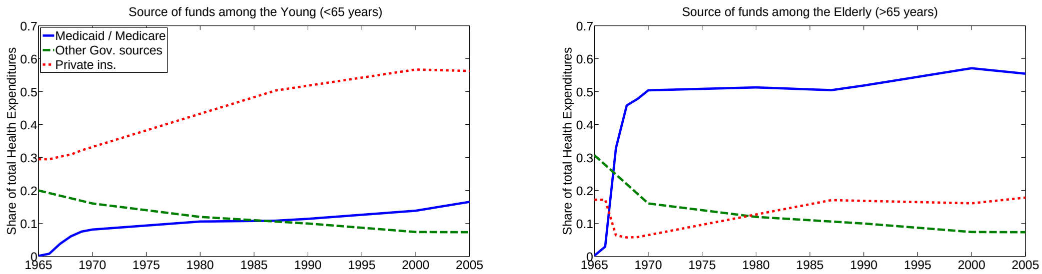


Figure 3.2: Share of total health expenditures over time covered by Medicaid (for the young) and Medicare (for the elderly), by other government programs, and by private insurance for the young (left) and for the elderly(right).

payment rates among the young and the elderly in accordance with the data. Analogously, we can construct $\phi_{MC}(a,t)$, $\phi_{MA}(a,t)$ and $\phi_{RP}(a,t)$.[27] All public programs are financed through a payroll taxes, with the rates $\hat{\tau}_{MC}$, $\hat{\tau}_{MA}$ and $\hat{\tau}_{RP}$ being endogenously determined such that the budget constraints

$$\begin{aligned}
\int_{a_R}^{\omega} [1-\phi_{MC}(a,t)]\, p_H\,(t)\, h(a,t)N(a,t)da &= \hat{\tau}_{MC}(t)w(t)L(t),\\
\int_{0}^{a_R} [1-\phi_{MA}(a,t)]\, p_H\,(t)\, h(a,t)N(a,t)da &= \hat{\tau}_{MA}(t)w(t)L(t),\\
\int_{0}^{\omega} [1-\phi_{RP}(a,t)]\, p_H\,(t)\, h(a,t)N(a,t)da &= \hat{\tau}_{RP}(t)w(t)L(t)
\end{aligned}$$

hold, where $1-\phi_x(a,t)$ is the share of health expenditures paid by program x and $\hat{\tau}_x$ is the according payroll tax.

Social security, received by retirees, is financed through a payroll tax which is determined endogenously from the social security budget constraint:

$$\int_{a_R}^{\omega} \pi(a,t)N(a,t)da = \hat{\tau}_{\Pi}(t)w(t)L(t),$$

where $\pi(a,t)$ is the social security pension and $\hat{\tau}_{\Pi}$ the payroll tax devoted to social security. We assume social security benefits to be exogenous and use the Annual Statistical Supplement provided by the Social Security Agency that provides the average monthly social security income for the years 1960-2014 (see Figure 3.3).

Altogether, individuals face the following taxes (including the premium for the private health insurance):

[27] The age-specific total co-insurance rate of health expenditures exhibits a small discontinuity at age 65 when using this calibration strategy. We smooth the jump after retirement by linearly adapting the private insurance levels of individuals after retirement.

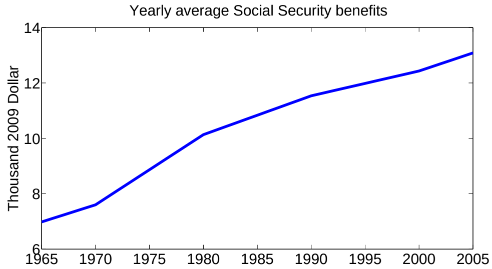


Figure 3.3: Yearly average Social Security benefits from 1965 to 2005 in 2009 US Dollars.

$$\begin{aligned}\tau(a,t) &= \underbrace{\hat{\tau}_{\Pi}(t)l(a)w(t)}_{=\tau_{\Pi}(a,t)} \\ &+ \underbrace{\underbrace{\hat{\tau}_{MC}(t)l(a)w(t)}_{=\tau_{MC}(a,t)} + \underbrace{\hat{\tau}_{RP}(t)l(a)w(t)}_{=\tau_{RP}(a,t)} + \underbrace{\hat{\tau}_{MA}(t)l(a)w(t)}_{=\tau_{MA}(a,t)} + \underbrace{[1-\phi_P(a,t)]\, p_H(t)h^*(a,t)}_{\tau_P(a,t)}}_{=\tau_H(a,t)}.\end{aligned}$$

Overview of Functional Forms and Parameters

Table 3.1 summarizes the most important parameters we are employing. Table 3.2 provides an overview on the calibration strategy and presents the match of several key target variables.

Parameter & Functional Forms	Description
$\omega = 80$	life span
$t_0 = 1950$	entry time of focal cohort
$\rho = 3\%$	pure rate of time preference
$\sigma = 1.2$	inverse elasticity of intertemporal substitution
$a_R = 65$	mandatory retirement age
$\delta = 5\%$	rate of depreciation
$\alpha = 0.33$	elasticity of capital in Y
$\beta_1 = 0.2$	elasticity of capital in F
$\beta_2 = 0.78$	elasticity of labor in F
$\gamma = 0.33$	elasticity of capital in G

Table 3.1: Model parameters

Parameter	Target	Match
$\eta(a)$	Mortality profile	Perfect match for 1965 by construction Match for other years see life-expectancy
$M(t)$	Life-expectancy	Model: 72.5 (1965), 78 (2000) Data : 72.6 (1965), 77.9 (2000)
$\nu(t)$	Share of elderly	Model: 15.2% (1965), 17.8 % (2000) Data : 14.8 % (1965), 17.3 % (2000)
σ	Income elasticity	Income elas. of 0.2 (micro) and 0.9 (macro)
b	Value of life	Model: 2 Mio. (1965), 6 Mio. (2000) Data : 7 Mio (2000)
$l(a)$	Income schedule Employment-population ratio	Perfect match by construction 2003: Model: 63 %, Data: 62 %
$A_Y(t)$	GDP per capita	see Figure 3.4
A_M	Growth rate of $\dot{M}(t)$	Model: 4.5 %, Data: 4.2 %
β_2	Medical R&D share of GDP	Model: 0.08 % (1965), 0.34 % (2000) Data : 0.06 % (1960), 0.5 % (2000)
$\phi(a,t)$	Avg. OOP expenditure share Medicare share of GDP	see Figure 3.5 see Figure 3.5

Table 3.2: Targets to match

3.3.2 Determinants of the Individual Demand for Health Care

In order to appreciate the results of our numerical analysis it is helpful to consider in some detail the way in which health insurance, income and medical technology are affecting the individual demand for health care. Specifically, we (i) report and comment on the relevant elasticities as they arise in our model, and (ii) describe the complementarity between the determinants of demand. It is important to note that we report these relationships at the level of an individual aged a at time t within a partial equilibrium context (i.e. for a given set of prices and income). While they are, thus, comparable to microeconomic evidence, they are only partially governing the dynamics of health care spending in general equilibrium.

Given the functional form of the mortality function provided in equation (3.25) and the first-order condition for health care from equation (3.21), we can derive a vector of age-specific demand levels

$$h(a,t) = \left(\frac{-\psi(a,t)\eta(a)\kappa\left(a\right)M(t)}{\phi(a,t)p_H(t)} \right)^{\frac{1}{1-\kappa(a)M(t)}}. \tag{3.27}$$

The elasticity of health care spending $p_H\left(t\right)h(a,t)$ with respect to the rate of co-insurance $\phi(a,t)$ is then given by[28]

[28] For a given $p_H\left(t\right)$, we have $\frac{d[p_H(t)h(a,t)]}{dx}\frac{x}{p_H(t)h(a,t)} = h_x\frac{h_x x}{h(a,t)} = \epsilon\left(h,x,a,t\right)$. Thus, the partial equilibrium spending elasticity with respect to x is identical to the elasticity of health care with respect to x.

$$\epsilon(h,\phi,a,t) := \frac{h_\phi \phi(a,t)}{h(a,t)} = -\frac{1}{1-\kappa(a)M(t)} < 0.$$

As $\kappa(a) < 0$, the spending elasticity is negative and smaller than unity in absolute terms. For the year 2000, our simulation yields an average insurance elasticity of -0.86.[29] This is well in line with recent empirical estimates by Kowalski (2016) and relatively close to the estimates in Eichner (1998) and Fonseca et al. (2013) who find a spending elasticity of around -0.6.[30],[31] For the economy as a whole we also calculate the arc elasticity based on a ceteris paribus decrease in the co-insurance rate from the 1965 to the 2005 level while keeping all other variables at their 1965 values.[32] Based on our benchmark simulation, we obtain an elasticity of -0.92 which is not far off the individual level elasticity.[33]

For the elasticity of health care spending with respect to (individual) income $y(a,t)$, we obtain

$$\begin{aligned}\epsilon(h,y,a,t) := \frac{h_y y(a,t)}{h(a,t)} &= \frac{1}{1-\kappa(a)M(t)} \frac{y(a,t)}{\psi(a,t)} \frac{d\psi(a,t)}{dy(a,t)} \\ &= -\epsilon(h,\phi,a,t) \times \epsilon(\psi,y,a,t) > 0.\end{aligned}$$

The age-specific income elasticity is, thus, given by the product of the spending elasticity in respect to health insurance and the elasticity of the value of life with respect to income. $\epsilon(\psi,y,a,t) > 0$. In our calibration, the economy-wide arc income elasticity is about 0.93 and

[29] We calculate the average elasticity by weighting the age-specific elasticities $\epsilon(h,\phi,a,t)$ with the respective age-shares and summing over all ages.

[30] This contrasts against the spending elasticity estimates of -0.2 to -0.3 from the original RAND health insurance experiment (Manning et al. 1987). As Kowalski (2016) points out, the original RAND estimate does not take into account the stoploss mechanism embedded into most health insurance schemes, biasing the elasticity downwards (in absolute terms.) In fact, Kowalski (2016) is able to closely reproduce the RAND estimate when stoploss is not accounted for.

More generally, no clear consensus has been reached yet about the most plausible estimates of the spending elasticity. This is not the least because some of the economic, technical and data problems involved with the estimation of non-linear insurance contracts are still waiting to be fully resolved (Aron-Dine et al. 2013).

[31] As an aside, it is worth noting that our analysis suggests that the spending elasticity is given by $\epsilon = (\mu_{hh}h/\mu_h)^{-1}$ and, thus, varies inversely with the elasticity of the marginal product of health care in the level of care. Thus, the spending elasticity should be low for those treatments which are particularly effective when precise treatment protocols and/or intensities are observed. To some extent, personalized medicine would be consistent with such a notion of effectiveness.

[32] For a variation in $x = \phi, y, M$, i.e. the rate of co-insurance, per capita income and the state of medical technology, the arc elasticity is defined as

$$\epsilon(h,x,1965,2005) := \frac{\left((p_H H)_{2005} - (p_H H)_{1965}\right) / \left((p_H H)_{2005} + (p_H H)_{1965}\right)}{(x_{2005} - x_{1965}) / (x_{2005} + x_{1965})},$$

with $\frac{(p_H H)_{2005} - (p_H H)_{1965}}{\left((p_H H)_{2005} + (p_H H)_{1965}\right)/2}$ and $\frac{x_{2005} - x_{1965}}{(x_{2005} + x_{1965})/2}$ denoting the "averaged" percentage change in $p_H H$ and j, respectively, over the time period 1965-2005.

[33] We also calculate the arc elasticity backward, i.e. starting from the 2005 state of the economy and considering a ceteris paribus increase in the co-payments to the 1965 values. Here, we obtain a value of -0.83.

thus lies within the range of estimates based on macroeconomic data, as reported in Getzen (2000), and the more recent individual level estimates provided by Acemoglu et al. (2013).[34],[35]

For the elasticity of health care spending with respect to the state of the medical technology $M(t)$, we obtain

$$\begin{aligned}\epsilon(h,M,a,t) := \frac{h_M M(a,t)}{h(a,t)} &= \frac{1+\kappa(a)M(t)\ln h(a,t)}{1-\kappa(a)M(t)} \\ &= -\epsilon(h,\phi,a,t)\times[1+\kappa(a)M(t)\ln h(a,t)] > 0.\end{aligned}$$

The elasticity of health care spending with respect to medical technology is, thus, given by the product of the spending elasticity in respect to health insurance and a scaling term $1+\kappa(a)M(t)\ln h(a,t)$ that captures the net impact of medical technology on the marginal productivity of health care. For our calibration we have (i) $h(a,t) > 1$ throughout and (ii) ranges of $M(t)$ and $h(a,t)$ over the time period under consideration for which $1+\kappa(a)M(t)\ln h(a,t) \in (0,1)$ is satisfied. Thus, for our representation of the US health care system and economy, medical technology raises the marginal product of health care, implying a positive spending elasticity. This effect tends to diminish with further increases in $M(t)$, as for high levels of medical effectiveness substantial reductions in mortality can be attained even at moderate increases in the consumption of health care. Quantitatively, we obtain a macro-economic arc elasticity of 0.64.[36] As expected, this level is somewhat lower in absolute terms than the spending elasticity with respect to insurance and income.

Indeed, all three elasticities decline in the level of medical effectiveness $\kappa(a)M(t)$, as defined in (3.26) above. This is certainly intuitive for the case of the insurance elasticity: Individuals are less prone to reduce their health care spending in response to higher co-insurance rates for ages, in which medical care is crucial [implying a high absolute value of $\kappa(a)$], and in settings where medical technology is highly effective [implying a high value of $M(t)$].[37] A similar argument can be made in respect to the income elasticity: if medical care is very effective, individuals will have little incentive to deviate (either way) from the "appropriate" level of health care.

[34] Again, calculating the arc elasticity backward, i.e. starting from the 2005 state of the economy and considering a ceteris paribus decrease in income to the 1965 values, we obtain a value of 0.9.

[35] One issue of note is that our arc elasticity of around 0.93 implicitly incorporates the increase in the price of health care caused by productivity increase in the manufacturing sector a la Baumol (1967). If we keep the price for health care fixed and evaluate the impact of a ceteris paribus increase in income, we obtain an income elasticity of merely 0.2. Both values can be reconciled with empirical evidence. Getzen (2000) points out that studies on individual-level data find income elasticities of health expenditures ranging between 0 to 0.7, whereas estimates based on regional and national level range from 0.5 to 1.5. Only the latter group of studies, however, measures implicitly the effects of Baumol's cost disease. The results by Acemoglu et al. (2013) fit nicely into this pattern: their estimate of 0.7 captures both individual level-effects as well as local (and thus limited) Baumol effects. Thus, our estimate of 0.2 should be compared to the individual-level studies while the value of 0.9 needs to be interpreted in the context of regional and national level estimates that take into account Baumol effects.

[36] The respective backward value is 0.51.

[37] While we did not find empirical evidence on how spending elasticities depend on age or the state of the medical technology, the finding by Duarte (2012) that the elasticity is typically higher for acute care (e.g. acute appendectomy) rather than elective care (e.g. psychological consultation) is consistent with our model: by definition of "urgency" one would expect acute care to be more effective at the point of treatment.

As is readily verified from (3.27), the complementarity between insurance, income and medical technology (at partial equilibrium level) is governed by the following relationships:

$$\begin{aligned} h_{\phi y} &= \frac{1}{h} \times h_y \times h_\phi = \frac{h}{\phi y} \times \epsilon(h, y, a, t) \times \epsilon(h, \phi, a, t) < 0, \\ h_{jM} &= \frac{\Omega(h, M)}{h} \times h_M \times h_j = \Omega(h, M) \frac{h}{jM} \times \epsilon(h, M, a, t) \times \epsilon(h, j, a, t); \quad j = y, \phi, \end{aligned}$$

with $\Omega(h, M) := 1 + \frac{\kappa(a)M(t)}{1+\kappa(a)M(t)\ln h(a,t)} \in (0, 1)$ for our parametrization. It is then readily checked that $h_{\phi M} < 0 < h_{yM}$. Hence, health insurance (as represented inversely by the co-payment ϕ), income and medical technology are all complementary. The complementarity between medical technology and the other two determinants is scaled down by the factor $\Omega(h, M)$. Furthermore, we have $d\Omega(h, M)/dM = \Omega_M + \Omega_h h_M = \frac{\kappa(a)[1-\kappa(a)M(t)\epsilon(h,M,a,t)]}{[1+\kappa(a)M(t)\ln h(a,t)]^2} < 0$. Thus, medical progress is associated with somewhat weaker and diminishing complementarity as compared to the complementarity between income and insurance.

3.3.3 Benchmark

In this section, we will present the benchmark economy over the period 1960-2005 and illustrate the model fit. The benchmark allocation is depicted by blue, solid line plots throughout all figures.

Macroeconomy

Figure 3.4 plots the evolution of the GDP and health expenditures per capita for the benchmark economy as well as the GDP health share, together with US data depicted by the asterisks. Reasonably well in line with the data, GDP per capita increases by a factor of about 2.8 and health expenditures by a factor of 8.5 over the time span 1960-2005.[38] The two developments imply an about three-fold increase of the health expenditure share of GDP over the 45 years under consideration.

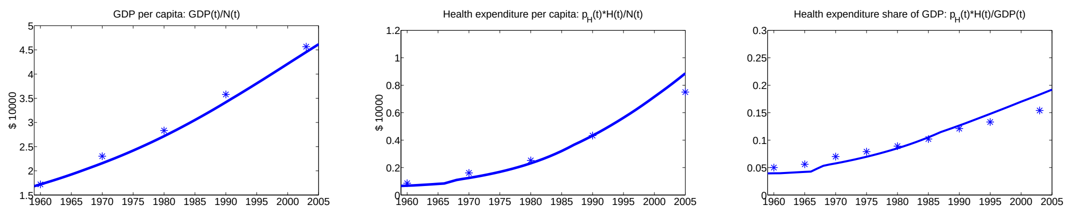


Figure 3.4: GDP and health expenditures per capita as well as the GDP share in the benchmark scenario (blue, solid line) and data (asterisks)

While the increase in GDP is predominantly driven by the exogenous growth of total factor productivity in the production sector, the increase in health expenditures is driven by several

[38] We overestimate the health expenditure growth in the 1990s. In this period, health maintenance organizations caused a temporary slowdown of expenditure growth, see Chernew and Newhouse (2012), a development that we are unable to track in our model.

exogenous trends: insurance expansion, the expansion in social security and income growth,[39] as well as by endogenous medical progress (and thus a shift from consumption to medical expenses, see chapter 2). Figure 3.5 illustrates the increase in the state of medical technology. While it is difficult to compare $M(t)$ with a real-world measure we can compare the growth rate of $\dot{M}$ (hence $\ddot{M}$) with the growth rate of medical patents over the time span 1965-2005 in the US. Our simulation yields a yearly increase of $\dot{M}$ of 4.5%, while the number of patents has increased by about 4.2% per year. Note, that we do not directly target the development of health expenditures over time in our calibration. Instead we focus on calibrating the role of medical technology through the growth rate of $\dot{M}$, as well as the contribution of insurance and income through empirically valid elasticities of health care spending. In combination, these trends yield an increase in health expenditure that is well in line with the data, implying that our model predicts quite well the outcome variable of interest.

As a result of medical progress and a greater utilization of health care, life expectancy rises, albeit not quite at the same pace as in the empirical data. This is likely due to the fact that not all reductions in mortality can be attributed to health care but changes in lifestyle and the living environment played a role as well. The average share of out-of-pocket expenditures reflects the data trend quite closely. Figure 3.5 also depicts the Medicare expenditure share of the GDP as well as the average share of out-of-pocket expenditures over the time span 1965-2005. While not targeting these model outcomes directly in our calibration, the exogenous co-insurance rates result in a good match of these variables in the simulation.[40]

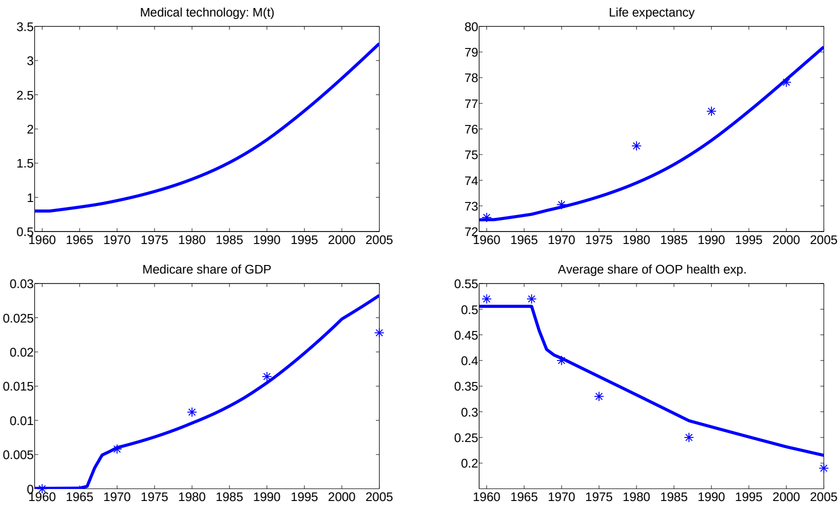


Figure 3.5: Medical technology, life expectancy, Medicare share of GDP and the average share of out-of-pocket (OOP) health expenditures

[39]Strictly speaking, income, too, emerges endogenously, as a consequence of the accumulation of production factors and their sectoral allocation. Nevertheless, the exogenous productivity trend, A_Y, is a key exogenous driver. For an illustration, see Figure 3.8 which shows the very limited impact on GDP growth of the counterfactual absence of insurance expansion.

[40]Recall Section 3.3.1 for a description of how we construct the co-insurance rates.

The growth of the health care sector has important implications for the macroeconomy. We observe in Figure 3.6 that the employment shares reflect the shift of the GDP towards the health care sector.[41] Employment in the medical R&D sector increases, too, as its size depends directly on the size of the health care sector [see equation (3.17)]. The market interest rate, $r(t)$, is endogenously determined within the model, and falls over the time period under consideration. While we cannot explain the up and down of empirical real returns on capital, we can account for the longterm increase in saving and the consequential decline in the interest rate associated with an aging population (see e.g. Aksoy et al. 2016, Bloom et al. 2003, De Nardi et al. 2010).

While boosting the supply of capital through the increase in longevity, medical progress also lowers the demand for capital by shifting production into the comparatively labor-intensive health care sector. The resulting excess supply of capital is, thus, absorbed only through a fall in the interest rate. A more detailed explanation of this mechanism was presented in chapter 2. This trend is further reinforced by the well-known Baumol (1967) effect, where productivity growth in the capital-intensive final goods sector induces a shift of production factors into the more labor-intensive health care sector. The ensuing (relative) scarcity of labor tends to depress the interest rate even further.[42]

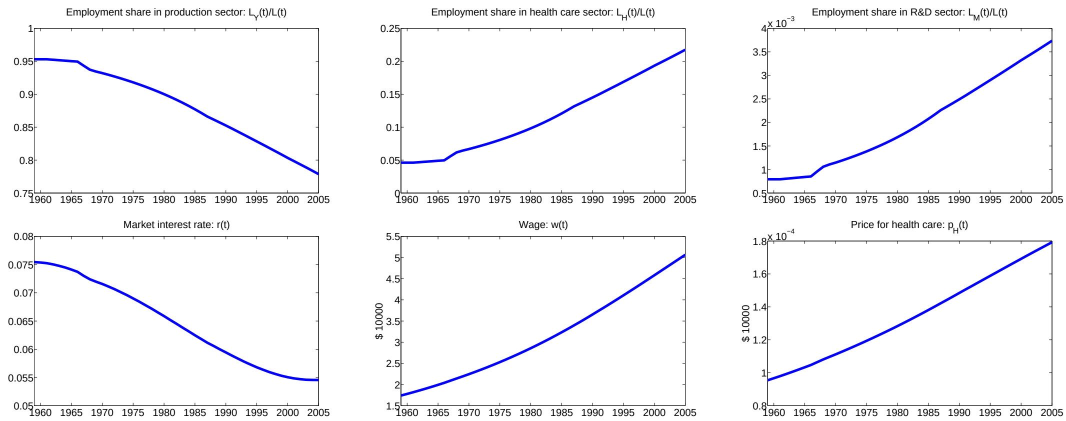


Figure 3.6: Macro variables in the benchmark scenario

Wage growth mainly reflects the increase in productivity, but wages also rise due to the increasing relative scarcity of labor as described above. As the health care sector is comparatively labor-intensive, the rising price for labor overcompensates the falling price for capital and induces a growth of the price of health care over time. In fact, we can empirically compare p_H with the ratio of the medical price index to the consumption price index (CPI) in the US, as

[41] Note that the employment shares are considerably larger than those reported by the Bureau of Labor Statistics, e.g. 7.5% in 1990 and 9.25% in 2005. Arguably this is due to a broader definition of health care employment implicit in our model. To see this note that the employment share in our model is broadly in line with the health share in GDP, whereas the employment share in the data amounts to just about half the size of the health share in GDP. This is inconsistent with the health care sector being relatively labor intensive and speaks to the fact that the production of health care is associated with significant "non-medical" employment (for e.g. the production of intermediate non-capital inputs toward the production of health care). This "non-medical" employment is counted in our model.

[42] See Acemoglu and Guerrieri (2008) for an analytical representation of this mechanism.

based on data from the Bureau of Economic Analysis (BEA). Over the time span 1980-2000, medical prices have risen 1.6-fold faster than the overall CPI according to BEA. This compares quite well to the 1.4-fold increase in p_H over the same time period in the benchmark economy. Hence, while there are other mechanisms (e.g. market concentration in the health care sector) that explain the higher rate of medical price inflation we would consider sectoral change and the resulting factor price adjustments as one key explanation.

Life-cycle

Consumption of the focal cohort, entering at $t = 1950$ aged 20, is hump-shaped, as depicted in Figure 3.7. The fact that the interest rate (5.5-7.5%) lies above the rate of time preference (3%) implies a rising consumption until around age 70. Due to missing annuity markets, consumption falls, however, at higher ages as implied by the first-order condition for consumption (3.20). Individual health expenditures also follow a hump-shaped pattern. While the demand for health care grows very moderately up to age 40, it then exhibits a strong increase up to age 80 before dropping again for the highest ages.[43] For a more thorough discussion of the underlying life-cycle dynamics we refer the reader to chapter 2.

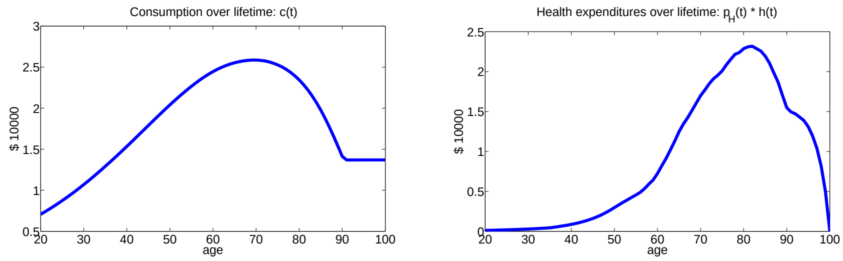


Figure 3.7: Life-cycle profiles of focal cohort aged 20 in 1950

3.4 Identifying the Impact of Health Insurance on Spending Growth

In order to gain an understanding of the role of health insurance in driving health expenditure growth, we proceed in two steps. First, we carry out a set of relatively simple comparative dynamic simulations in order to quantify the individual contributions of income, insurance and medical progress to medical spending growth, as well as the complementarities involved (see Section 3.4.1). Second, we study a counterfactual scenario in which the health insurance setting is fixed to the year 1965 in order to gauge the full impact of insurance expansion beginning with

[43]The cross-section of age-specific health expenditure for the year 2000 (not shown) matches the data in Meara et al. (2004) until age 80 within a reasonable margin of error. While health care expenditures do not fall in Meara et al. (2004), this is quite possibly due to the open age interval they employ. The averaging of health care expenditures across the highest age groups may well mask an ultimate decline with age as the population shares used for the weighting are rapidly declining, too. Indeed, Martini et al. (2007) identify a hump-shaped pattern when considering a longer range of age-specific expenditure.

the introduction of Medicare/Medicaid in 1966 and continuing with the subsequent expansion, in particular, of private health insurance (see Section 3.4.2). This scenario will explicitly account for the medical progress induced by the expansion of health insurance. We will then employ further counterfactuals to separate the moral hazard impact of insurance expansion from the spending impact of induced medical progress. We conclude the analysis by studying the welfare impact of the insurance expansion.

3.4.1 Contributors to Spending Growth

In order to gain a first impression of the contributions of income, insurance and medical progress as drivers of health care growth we consider the following set of (counterfactual) simulations: The baseline is represented by a simulation in which medical technology, age-specific co-insurance rates as well as the income level are all fixed to the level of the year 1965.[44] Letting, in three separate runs, each of the three factors evolve (up to the year 2005) in the same way as in the benchmark simulation while holding the two other factors constant at their 1965 levels, we then evaluate the impact on health care expenditures. We also simulate the effect on medical expenditures of two factors evolving jointly along their benchmark trajectories, while keeping the third factor fixed to the 1965 level. Comparing the joint effect against the sum of the individual effects allows us to quantify the extent of complementarity between the three drivers of expenditure growth. Table 3.3 summarizes the results, reporting for each of the scenarios the increase in health care spending relative to the 1965 level.

Factor	Increase in health spending
Medical Progress	+120%
Insurance Expansion	+120%
Income Growth	+140%
Medical Progress + Insurance	+330%
Medical Progress + Income	+380%
Income + Insurance	+430%
Benchmark	+850%

Table 3.3: Increase in health care expenditure relative to its 1965 level

When considered in isolation, medical progress and insurance expansion lead to a sizable and equal expansion of health care expenditure by 120%, while income growth leads to an expansion by 140%. Summing the three isolated growth trends yields an increase of health expenditure by 380% which explains only about 44% of the increase between 1965 and 2005 that is observed in the benchmark (and data). This highlights the substantial role of complementarities between the three growth factors, which account for broadly 56% of expenditure growth.[45]

[44] Furthermore, the population structure as well as the level of social security benefits are held constant at the 1965 level.

[45] Strictly speaking the expansion of social security and demographic change would explain some part of the 56% residual, these effects are small, however.

This finding is well in line with the earlier analysis by Fonseca et al. (2013) who find that 57.3% of spending growth are attributable to complementarities.[46] Contrasting the combined growth effects against the sum of the respective individual effects shows that the complementarity between insurance and income is strongest. With a combined 430% increase in health care expenditure set against a 260% increase predicted by the summed individual effects, the complementarity between insurance and income triggers an additional 170% increase. This exceeds each of the individual effects and amounts to about 40% of the combined effect. Inducing an additional 120% and 90% of expenditure growth on top of the summed individual effects, the income-medical progress and insurance-medical progress complementarities, respectively, are somewhat smaller but still of a sizable magnitude.

While the analysis so far has been informative about the contribution of the various expenditure drivers, it fails yet to account for the fact that medical progress itself is endogenous. The remainder of the analysis is, thus, seeking to identify the impact of health insurance expansion on health expenditure growth, paying particular attention to induced medical progress, while treating productivity growth as an exogenous background trend.

3.4.2 Counterfactual: No Insurance Expansion

We now simulate a counterfactual economy in which the insurance expansion from 1965 until 2005 is neglected (shown throughout by the green, dashed plot). We do so by holding public and private health insurance rates constant from 1965 onwards. Figure 3.8 shows the evolution of the GDP and health expenditures over time. While the growth of GDP per capita is barely affected, we observe a strong difference in the growth of health expenditure. Our counterfactual simulation suggests that the expansion of health insurance explains about 60% of the spending increase between 1965 and 2005.

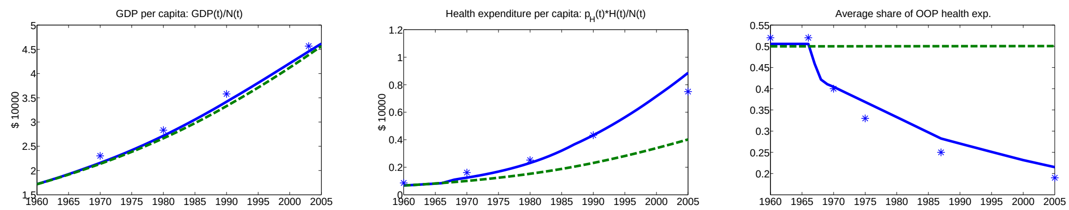


Figure 3.8: Macrovariables in the benchmark (blue, solid) and the counter-factual reflecting constant 1965 insurance level (green, dashed)

This result ties in reasonably well with an empirical finding by Finkelstein (2007) on the impact of the introduction of Medicare on health care expenditures. Relative to individual-level studies on the consequences of health insurance on medical spending (such as the RAND health

[46] Fonseca et al. (2013) differ in the attribution of expenditure growth to the three individual trends. In their model 29.9% are explained by medical progress, 7.7% are explained by insurance growth and 4.3% are explained by income growth, whereas in our model the respective figures are 14% for the first two factors and 16% for income. One reason for the much stronger contribution of medical progress is likely to lie in the partial equilibrium approach they are taking. As we show in chapter 2, however, the impact of medical progress on expenditure is strongly dampened in general equilibrium, which is the approach we are choosing.

insurance experiment), she finds a six-time larger effect when also taking into account aggregate effects of the insurance expansion, such as the adoption of medical technology and increased hospital market entries. Extrapolating the insurance elasticity of health spending found for Medicare to the overall reduction of out-of-pocket expenditures observed in the US from 1950-1990, she finds that the insurance expansion over this time period can account for approximately 50% of the overall increase in US health spending.

The absence of additional health care subsidies in the form of public or private health insurance (see plot on the average OOP share) in the counterfactual is one direct channel that explains the lower level of medical expenditures. Figure 3.9 (Medical Progress) points to another reason for the strong difference in health care spending between the benchmark and counterfactual scenario. We observe a much slower progress of medical technology in the counterfactual. This is because the absence of large-scale health insurance programs leads to a smaller health care market. The lower profits in the health care sector then translate into lower R&D expenditures as compared to the benchmark scenario. As individual demand for health care increases with the state of medical technology, even less is spent on health care in the counterfactual scenario as opposed to the benchmark case. Our analysis suggests that the expansion of health insurance led to a 41% increase in the growth rate of medical progress. This is well in line with the empirical results by Clemens (2013) who finds that the introduction of Medicare/Medicaid induced a 33% increase in the growth rate of medical patents. The additional boost to medical R&D in our model can be attributed to the concomitant expansion of private health insurance coverage.

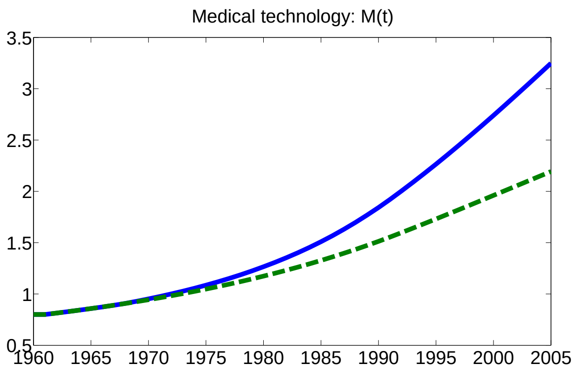


Figure 3.9: Medical Technology in the benchmark (blue, solid) and the counter-factual reflecting constant 1965 insurance level (green, dashed)

The missing expansion of health care coverage in our counterfactual, thus, slows down the growth of health care demand and consequently health care expenditure through the following channels: a direct one, transmitted through spending reductions in the presence of higher copayments; and an indirect one, transmitted through slower growth in medical R&D and, thus, through slower medical progress. As we have seen already, the complementarities between the expansion of health insurance and income growth as well as medical progress also strongly contribute to health care expenditure. Without the expansion of insurance two of the three complementarities between the growth factors are eliminated, implying a dampened impact of income growth and medical progress on health care expenditure relative to the benchmark scenario.

The impact of the counterfactual absence of an insurance expansion on the life-cycle variables is depicted in Figure 3.10. Most strikingly, we observe a drastic decrease in health care expenditures over the life-course, a consequence of less effective medical technology and higher co-payments. Consumption expenditures increase as individual budgets are less burdened by health care spending. At old age, however, individuals are reducing their consumption levels more rapidly, as the higher mortality risk induces them to discount their late-life utility more heavily as opposed to the benchmark scenario. Indeed, in the absence of the health insurance expansion, life expectancy would have increased from 72.5 years in 1965 to only 75.7 years instead of 78 years in 2000.

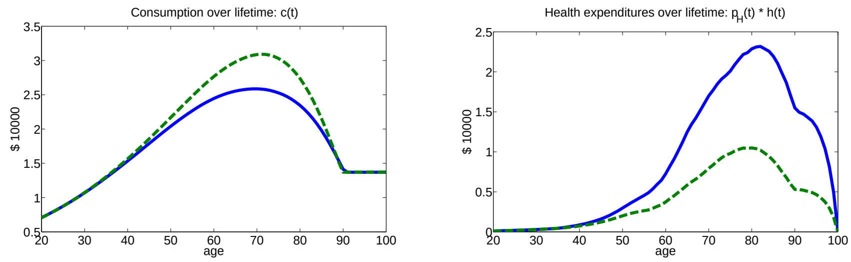


Figure 3.10: Life-cycle variables in the benchmark (blue, solid) and the counter-factual reflecting constant 1965 insurance level (green, dashed)

Finally, Figure 3.11 illustrates the impact of the health insurance expansion on prices. The much smaller growth in the health care sector in the counterfactual scenario is reflected in a lower rate of wage growth and a lower rate of health care price inflation. The effects are modest, however, in relation to the increase driven by productivity growth in final goods production. The impact of health insurance expansion on the development of the interest rate is more pronounced. The interest rate declines in the counterfactual at a much lower rate to a level that in 2005 is almost one percentage point higher compared to the benchmark. This wedge is reflecting the gap in life expectancy and, thus, the lower degree of capital accumulation in the counterfactual scenario.

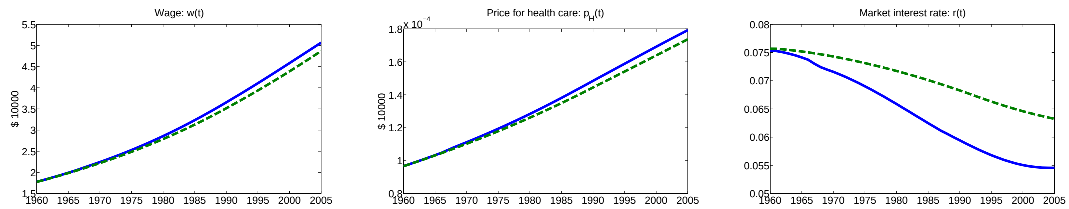


Figure 3.11: Prices in the benchmark (blue, solid) and the counter-factual reflecting constant 1965 insurance level (green, dashed)

Disentangling Moral Hazard and Induced Innovation Effect

It is instructive to disentangle the direct impact of insurance on health care spending, which can be broadly summarized as a moral hazard effect,[47] from the spending impact that arises through the stimulation of medical innovation. In order to separate the two channels we now simulate the effect of the insurance expansion in the realistic benchmark environment while the state of technology is assumed to develop according to the main counterfactual. This scenario, depicting the moral hazard channel, is illustrated by the red, dotted plot in Figure 3.12. We see that while insurance coverage evolves as in the benchmark, the state of medical technology is fixed to the counterfactual. The resulting trajectory of health expenditure shows that moral hazard accounts for a large part of the increase in expenditures from counterfactual to benchmark. The remainder is explained by induced medical progress which we have switched off in this scenario. The cyan, dash-dotted plot shows the "complementary" counterfactual simulation in which insurance is fixed to its 1965 level but medical technology evolves according to the benchmark scenario. The distance between the cyan, dash-dotted and the green dashed plot, therefore, measures the contribution of induced medical progress in a direct way. Overall, we find that about 81% of the additional spending in 2005 that is due to the expansion of health insurance can be attributed to moral hazard, whereas the remaining 19% can be attributed to induced medical progress.[48],[49]

We conclude by pointing out that while moral hazard as opposed to induced medical progress explains the majority of the spending increase, the opposite is true in respect to the benefits in terms of life-years gained. Recall here that the expansion of health insurance leads to an additional 2.3 years of life expectancy in the year 2000 (78 years in the benchmark scenario as opposed to 75.7 in the main counterfactual). We find that 2 years of this increase are due to induced-medical progress, whereas only 0.3 years are due to the introduction of health insurance. The latter result ties in with Skinner and Staiger (2015) who show that when holding the level of medical technology constant, an increase in spending had only modest marginal returns on cardiac mortality as well as with Finkelstein and McKnight (2008) who find that, 10 years after its introduction, Medicare had no discernible impact on elderly mortality. Indeed, we find that the impact of the health insurance expansion on life-expectancy evolves only (slowly) over time with the benefits from the induced medical change accruing predominantly to later-born cohorts.

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[47] Here, moral hazard is to be understood in a macro-economic sense, involving price adjustments as well as adjustments in the age structure of the population.

[48] The relatively large direct effect should not be interpreted in a way that insurance dominates medical progress as a driver of health expenditure. It should be borne in mind that the reference in this simulation is the *additional* medical progress induced by the health insurance expansion. This is especially important, when it comes to the complementarities over time: When assessing the direct impact of insurance expansion (red-dotted plots), medical progress is assumed to develop according to the main counterfactual, where the rate of progress is lower but nevertheless positive. Thus, complementarities (with both factors emerging in lockstep) are active along all three margins of the insurance-income-medical-progress nexus. In contrast, when assessing the impact through induced medical progress (cyan dash-dotted plots), there is no development over time in respect to insurance coverage. Thus, the only active complementarity is between medical progress and income. This speaks to a much weaker dynamic effect.

[49] With induced medical progress explaining 19% of the spending increase from the insurance expansion and this, in turn, explaining 60% of the overall spending increase, we find that insurance-induced medical progress explains about 11.5% of the overall increase in health care spending over the period 1965-2005. This is comparable to an estimate of 15% (regarding the spending increase 1960-2000) advanced by Clemens (2013).

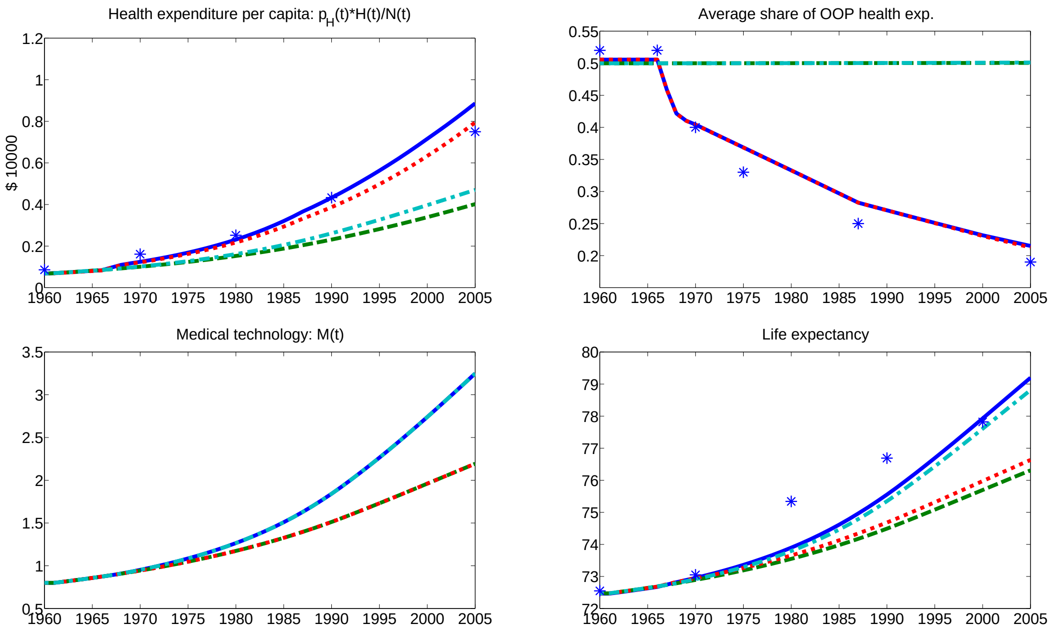

Figure 3.12: Macrovariables in (i) the benchmark (blue-solid plot); (ii) the main counterfactual without insurance expansion (green dashed plot); (iii) the counter-factual with insurance expansion but without insurance-induced medical change (red, dotted plot); (iv) the counter-factual with full medical change but without insurance expansion (cyan, dash-dotted plot)

Welfare Analysis

The fact that the expansion of health insurance over the time span 1965-2005 has led to more than a doubling of health care expenditure in 2005 suggests the scope for a substantial welfare loss. This is in particular the case in light of the fact that within our stylized model, in which health care expenditures are deterministic, health insurance is merely acting as a subsidy on health care without any offsetting benefit from risk sharing. However, the sizable impact of insurance expansion on medical progress may offer a form of dynamic return to such subsidies on health care. In order to gauge the welfare consequences of the expansion of health insurance we consider the lifetime utility of cohorts born over the time span 1900-1980 and examine how it varies across four different scenarios (see Figure 3.13): (i) the benchmark (blue-solid plot); (ii) the main counterfactual without insurance expansion (green dashed plot); (iii) the counter-factual with insurance expansion but without insurance-induced medical change (red dotted plot); and (iv) the counter-factual with full medical change but without insurance expansion (cyan, dash-dotted plot). For the purpose of comparison we have normalized to one the lifetime utility of the cohort born in 1900 along the benchmark trajectory.

Naturally, lifetime utility increases with the birth year for all scenarios, as later born cohorts benefit from both productivity growth, translating into higher consumption and health care spending, and medical progress, translating into more effective spending and increasing longevity. A comparison across scenarios reveals the following. Starting from the main counterfactual (with health insurance frozen to the 1965 level, green dashed plot), consider first the direct effect of the introduction of health insurance (red, dotted plot). Here, we obtain the expected result that most cohorts experience a reduction in their lifetime utility. This is precisely because of the moral hazard effect of health insurance, triggering excessive health care spending at the expense of consumption. Although this distortion is increasing over time, the associated welfare loss is nevertheless modest even for the latest born cohort. Notably, our calibration suggests that cohorts born between 1900 and 1910 should have benefited from the expansion of health insurance even when induced medical progress is not accounted for. This is because these cohorts were already retired or close to retirement when Medicare/Medicaid was introduced in 1966. Consequently they enjoyed cheaper access to health care without having to pay the taxes.

Starting again from the main counterfactual (with health insurance frozen to the 1965 level), consider now the isolated impact of the induced medical change (cyan, dashed-dotted plot). In spite of the associated (moderate) spending increase, all cohorts benefit from this. Notably, the gains are building up over time, disproportionately benefiting later born cohorts, with the cohort born in 2005 experiencing a 5 percentage point increase in lifetime utility. This relates mostly to cumulating increases in life expectancy afforded by the higher growth rate in the state of medical technology.

The benchmark scenario, embracing both health care expansion and induced medical progress, then balances the two offsetting tendencies from moral hazard and induced medical progress. As it turns out, the benefits from additional medical progress outweigh by a significant amount the utility loss from excessive health care payments for all cohorts. Note that in contrast to the previous counterfactual with induced medical progress for constant 1965 health insurance, the benefit from additional life-years afforded through higher medical progress is now offset by a growing level of excess expenditure from moral hazard. Thus, a priori it is not quite clear whether the welfare gains from greater life expectancy are really worth the increasing moral hazard. However, as is easily seen from Figure 3.13 the welfare loss from moral hazard is by far not increasing as much over time as the gains from medical technology. The explanation for this lies with the ongoing income growth: As long as per capita consumption is increasing over time, individuals tend to assign an increasing value to life (Hall and Jones 2007). This argument extends to the presence of moral hazard, where individuals are willing to tolerate an increasing distortion from health insurance in exchange for an increase in lifetime, as long as this only slows down but does not reverse consumption growth.[50]

We conclude with the observation that the subsidization of health care expenditure that is implied by health insurance contracts is justified as a means to overcome an intergenerational - and to lesser extent intragenerational - externality associated with the inducement of medical progress: at each point in time, individuals are underinvesting in health care, as they are not taking into account the impact of a higher spending level on medical progress and, thus, on future survival gains.[51] With the direction of the externality, thus, flowing from older to younger (or even yet unborn) generations there is an issue about how the older cohorts can be compensated

[50] According to a related application of this argument the growth drag imposed by a large health care system (Kuhn and Prettner 2016) or by an ongoing shift of R&D activity into the medical sector Jones (2016) is not harmful to welfare as long as there is ongoing GDP/consumption growth.

[51] Kuhn et al. (2011) show in a related OLG framework that the presence of positive spillovers of health care spending on the survival of others serves as a justification for the subsidization of health care, coming e.g. in the form

for stimulating medical progress. Here, the introduction and expansion of Medicare is likely to play an important role: The tax-financed provision (or subsidization) of health care for the elderly tends to impose a transfer from younger, working-age generations to the old. While in the absence of induced medical progress such a system would be both inefficient and biased against the young, it also provides the appropriate compensation from the young to the old for the inducement of medical progress. Indeed, the health insurance expansion in the US turns out to be a Pareto improvement for the cohorts under consideration. This suggests that tax-financed health care can take on a similar role to unfunded social security if it compensates older generations for the cost of educating and, thus, raising the human capital of younger cohorts (Andersen and Bhattacharya 2017, Boldrin and Montes 2005).

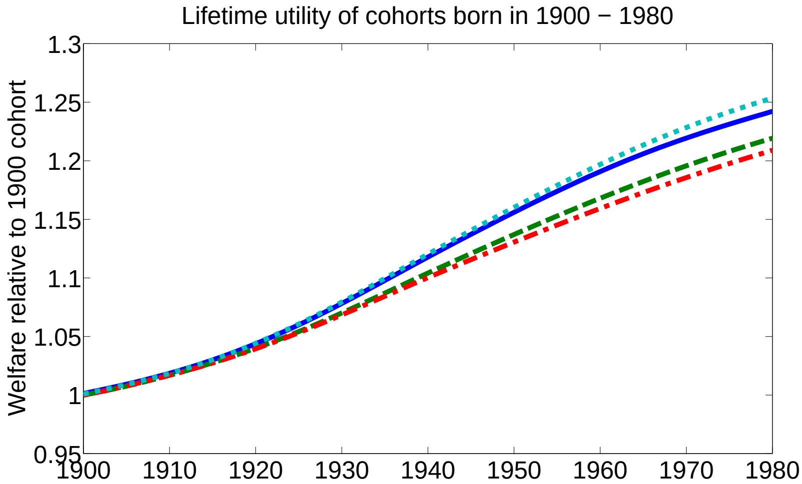

Figure 3.13: Lifetime welfare for cohorts born from 1900 to 1980 in (i) the benchmark (blue-solid plot); (ii) the main counterfactual without insurance expansion (green dashed plot); (iii) the counter-factual with insurance expansion but without insurance-induced medical change (red, dotted plot); (iv) the counter-factual with full medical change but without insurance expansion (cyan, dash-dotted plot)

3.5 Conclusion

We have studied the aggregate impact of the health insurance expansion in the US between 1965 and 2005 on health care spending, taking account not only the direct effect through decreases in OOP spending but also the indirect effect through induced medical progress. For this purpose we have constructed a continuous time model of an economy with overlapping generations subject to endogenous mortality and with three sectors: final goods production, health care and medical R&D; and calibrated it to US data covering the time span 1960-2005. Our simulation traces closely the development of most key indicators (such as GDP per capita, the health share, life expectancy, the share of the population 65+, the Medicare share, the growth rate of medical

of health insurance. In that setting, however, the externality associated with health spending is merely contemporary and does not have a lasting effect.

R&D, and the medical R&D share) and explains very well medical price inflation due to the joint impact of productivity growth in the final goods sectors a la Baumol (1967) and medical progress itself.

A first set of results shows that medical progress, insurance expansion and income growth in isolation contribute broadly equally to the increase in health care spending but that more than half of the expenditure increase is explained by the nexus of complementarity between the three drivers. Focusing on the role of health insurance in explaining health care spending growth and medical progress, we find strong effects, with health insurance explaining 60 percent of the 850 percent increase in health care expenditure between 1965 and 2005, and explaining 41 percent increase in the growth rate of medical R&D. Both results are well aligned with empirical evidence. When decomposing the impacts of health insurance on health care spending into a direct moral hazard effect and the impact through medical progress we find moral hazard to explain about 81 percent of the spending increase with the remaining 19 percent falling on medical progress. Looking at the benefits of health insurance in terms of improving health and longevity, we find that while the expansion of health insurance has increased life expectancy by an extra 2.3 years in 2005, only 0.3 years are attributable to the higher health care expenditure associated with moral hazard, whereas 2 years are attributable to induced medical progress. This suggests that while the excessive health care spending due to moral hazard is, indeed, wasteful to a large extent, there are sizable dynamic benefits to health insurance through the stimulation of medical progress. A comparison of lifetime utility for cohorts born in the years 1900-1980 shows that while the moral hazard associated with the expansion of health insurance creates modest welfare losses for all but the very early born cohorts, the gains in life expectancy from the induced medical progress more than compensate for this, leading to welfare gains for all cohorts. Indeed, the dynamic development of US health insurance could be viewed as a mechanism to overcome - at least partly - the dynamic externality involved with the stimulation of medical advances toward future gains in life expectancy by way of current health care spending.

While this result speaks to a dynamic role of health insurance that extends well beyond the benefits from risk sharing, it also suggests that there may be more efficient ways for stimulating medical progress. We leave to future research a more detailed analysis of such policies as well as a more detailed analysis of the distribution of the welfare gains and losses from medical progress and health insurance across the different generations. Given the quantitatively substantial size of the intergenerational externality, the present work raises a set of interesting questions as to the dynamic efficiency of different types of health care finance as well as to the dynamic consequences of health care reforms. We relegate these issues to future research.

3.6 Appendix

3.6.1 Optimal Solution to the Individual Life-Cycle Problem

The individual's life-cycle problem, i.e. the maximization of (3.1) subject to (3.2) and (3.3) can be expressed by the Hamiltonian

$$\mathcal{H} = uS - \lambda_S \mu S + \lambda_k \left(rk + lw - c - \phi p_H h - \tau + \pi + s\right),$$

leading to the first-order conditions

$$\begin{aligned} \mathcal{H}_c &= u_c S - \lambda_k = 0, && (3.28) \\ \mathcal{H}_h &= -\lambda_S \mu_h S - \lambda_k \phi p_H = 0, && (3.29) \end{aligned}$$

and the adjoint equations

$$\begin{aligned} \dot{\lambda}_S &= \left(\rho + \mu\right) \lambda_S - u, && (3.30) \\ \dot{\lambda}_k &= \left(\rho - r\right) \lambda_k. && (3.31) \end{aligned}$$

Evaluating (3.28) at two different ages/years (a,t) and $(\widehat{a}, t + \widehat{a} - a)$, equating the terms and rearranging gives us

$$\begin{aligned} \frac{u_c\left(\widehat{a}, t + \widehat{a} - a\right)}{u_c\left(a,t\right)} &= \frac{\lambda_k\left(\widehat{a}, t + \widehat{a} - a\right)}{\lambda_k\left(a,t\right)} \frac{S\left(a,t\right)}{S\left(\widehat{a}, t + \widehat{a} - a\right)} \\ &= \exp\left\{ \int_a^{\widehat{a}} \left[\rho + \mu\left(\widehat{\widehat{a}}, t + \widehat{\widehat{a}} - a\right) - r\left(t + \widehat{\widehat{a}} - a\right)\right] d\widehat{\widehat{a}} \right\}, \quad (3.32) \end{aligned}$$

which is readily transformed into the Euler equation (3.20) as given in the main body of the article.

Inserting (3.28) into (3.29) allows to rewrite the first-order condition for health care as

$$-\mu_h\left(a,t\right) \frac{\lambda_S\left(a,t\right)}{u_c\left(\cdot\right)} = \phi\left(a,t\right) p_H\left(t\right). \quad (3.33)$$

Integrating (3.30) we obtain

$$\lambda_S\left(a,t\right) = \int_a^{\omega} u\left(\widehat{a}, t + \widehat{a} - a\right) \exp\left[-\int_a^{\widehat{a}} \left(\rho + \mu\right) d\widehat{\widehat{a}} \right] d\widehat{a}.$$

Using this, we can express the private VOL as

$$\psi\left(a,t\right) := \frac{\lambda_S\left(a,t\right)}{u_c\left(a,t\right)} = \int_a^{\omega} \frac{u_c\left(\widehat{a}, t + \widehat{a} - a\right)}{u_c\left(a,t\right)} \frac{u\left(\widehat{a}, t + \widehat{a} - a\right)}{u_c\left(\widehat{a}, t + \widehat{a} - a\right)} \exp\left[-\int_a^{\widehat{a}} \left(\rho + \mu\right) d\widehat{\widehat{a}} \right] d\widehat{a}.$$

Substituting from (3.32) and rearranging we obtain (3.22) as given in the main body of the article. Inserting this into (3.33) and rearranging gives condition (3.21) in the main body of the article.

3.6.2 Solving the Numerical Problem

We pursue the following steps towards tracing out the numerical solution, sketched here for the benchmark scenario, while using the specific functional forms presented in section 3.3:

1. We derive from the first-order condition for consumption (3.20) the relationship

$$c\,(a,t_0+a)^{-\sigma} = c\,(0,t_0)^{-\sigma}\exp\left\{\int_0^a \left[\rho - r(t_0+\hat{a}) + \mu(\hat{a})\right] d\hat{a}\right\}. \tag{3.34}$$

2. We derive the life-cycle budget constraint

$$\int_0^\omega \left[\begin{array}{c} w\,(t_0+a)\,l\,(a) - c\,(a,t_0+a) + \pi(a,t) \\ -\phi(a,t)p_H\,(t_0+a)\,h\,(a,t_0+a) - \tau(a,t) + s(t_0+a) \end{array}\right] R\,(a,0)\,da = 0,$$

   with $R\,(a,0)$ as given by (3.24). We then insert (3.34) and obtain the consumption level

$$c\,(0,t_0) = \frac{\int_0^\omega \left[\begin{array}{c} w\,(t_0+a)\,l\,(a) + \pi(a,t) \\ -\phi(a,t)p_H\,(t_0+a)\,h\,(a,t_0+a) - \tau(a,t) + s(t_0+a) \end{array}\right] R\,(a,0)\,da}{\int_0^\omega \exp\left\{\int_0^a \left[\frac{1-\sigma}{\sigma} r(t_0+\hat{a}) - \frac{\rho+\mu(\hat{a})}{\sigma}\right] d\hat{a}\right\} da} \tag{3.35}$$

   for an individual born at t_0, contingent on the stream of health care, $h\,(a,t_0+a)$, and the set of prices $\{w\,(t_0+a)\,, r(t_0+a), p_H\,(t_0+a)\}$ over the interval $[t_0,t_0+\omega]$. Finally, we need to keep track of the constraint on minimum consumption at the level of social security benefits. As is readily checked from the numerical analysis, this constraint is binding only at the highest ages.

3. We derive from the first-order condition for health care (3.21) a vector of age-specific demand levels

$$h(a,t_0+a) = \left(\frac{\psi(a,t_0+a)\eta(a)(-\kappa)M(t_0+a)}{\phi(a,t_o+a)p_H(t_0+a)}\right)^{\frac{1}{1-M(t_0+a)\kappa(a)}} \tag{3.36}$$

   for all $a \in [0,\omega]$.

4. We show in section 3.6.3 that the set of prices $\{w\,(t_0+a)\,, p_H\,(t_0+a)\}$ as well as all input and output quantities can be expressed in terms of the interest rate $r(t_0+a)$ alone.

5. Using (3.34) together with (3.36) we can calculate the life-cycle allocation for consumption, $c\,(a,t_0+a)$, depending on the allocation for health expenditures, $h(a,t_0+a)$, $\forall a \in [0,\omega]$ and on the set of prices $\{w\,(t_0+a)\,, r(t_0+a), p_H\,(t_0+a)\}$ over the interval $[t_0,t_0+\omega]$. Vice versa, the allocation of health expenditures can be calculated from the allocation of consumption and the macroeconomic prices.

6. We apply these calculations iteratively on initial guesses of c and h. We then use the results as an initial guess to the age-structured optimal control algorithm, as presented in Veliov (2003). This yields an optimal allocation of individual consumption and health expenditures contingent on an initially assumed $r(t_0 + a)$.

7. Drawing on this, we apply the following recursive approximation algorithm: (i) Guess an initial interest rate $r(t_0 + a)$ and derive the optimal life-cycle allocation. (ii) Based on this, calculate the market interest rate $r^*(t_0 + a)$ from the capital market equilibrium $K^d\left(r(t_0+a), \widehat{w}\left(r(t_0+a)\right)\right) = K^s\left(r(t_0+a)\right)$. (iii) Adjust the initial interest rate, so that it approaches $r^*(t_0 + a)$, e.g. by setting $r_1(t_0 + a) := r_0(t_0 + a) + \epsilon(r^*(t_0 + a) - r_0(t_0 + a)), \quad \epsilon \in (0, 1]$. The process converges to an interest rate for which households optimize and capital demand equals capital supply. The output market clearing condition, $Y(t_0 + a) = C(t_0 + a) + \dot{K}(t_0 + a) + \delta K(t_0 + a)$ then determines the dynamics of the capital stock to the next period. (iv) This process is reiterated in a recursive way, employing a solution algorithm based on Newton's method. Equations (3.34)-(3.36) allow us to verify ex-post an optimum life-cycle allocation for the focal cohort born at t_0. While the numerical algorithm cannot determine in a precise way the optimal allocation for other cohorts, it nevertheless structures the allocation in a way that approximates the optimum for all cohorts.

3.6.3 Equilibrium Relationships with Cobb-Douglas Technologies

Consider the Cobb-Douglas-specifications

$$
\begin{aligned}
Y(t) &= A_Y(t) K_Y(t)^{\alpha} \left[L_Y(t)\right]^{1-\alpha} && (3.37)\\
F(t) &= A_H(t) K_H(t)^{\beta_1} \left[L_H(t)\right]^{\beta_2}, && (3.38)\\
G(t) &= A_M(t) K_M(t)^{\gamma} \left[L_M(t)\right]^{1-\gamma} && (3.39)
\end{aligned}
$$

with α, β_1, β_2 and $\gamma \in [0, 1]$, and $\beta_1 + \beta_2 < 1$. Period profits are then given by

$$
\begin{aligned}
V_Y(t) &= Y(A_Y(t), K_Y(t), L_Y(t)) - w(t)L_Y(t) - [\delta + r(t)]\, K_Y(t), && (3.40)\\
V_H(t) &= p_H(t)\, F(A_H(t), K_H(t), L_H(t)) - w(t)L_H(t) - [\delta + r(t)]\, K_H(t), && (3.41)\\
V_M(t) &= p_M(t)\, G(A_M(t), K_M(t), L_M(t)) - w(t)L_M(t) - [\delta + r(t)]\, K_M(t). && (3.42)
\end{aligned}
$$

Perfectly competitive firms in the three sectors choose labor and capital so as to maximize their respective period profit (3.40)-(3.42). The first-order conditions imply

$$
\begin{aligned}
r(t) + \delta &= Y_{K_Y}(t) = p_H(t)\, F_{K_H}(t) = p_M(t)\, G_{K_M}(t) && (3.43)\\
w(t) &= Y_{L_Y}(t) = p_H(t)\, F_{L_H}(t) = p_M(t)\, G_{L_M}(t), && (3.44)
\end{aligned}
$$

i.e. the factor prices are equalized with their respective marginal value products, where the prices for health care, $p_H(t)$, and medical technology, $p_M(t)$, respectively are taken into account.

From the first-order conditions (3.43) and (3.44) we then obtain the factor demand functions

$$K_Y^d(t) = \frac{\alpha Y(t)}{r(t)+\delta}, \tag{3.45}$$

$$L_Y^d(t) = \frac{(1-\alpha)Y(t)}{w(t)}, \tag{3.46}$$

$$K_H^d(t) = \frac{\beta_1 p_H(t)F(t)}{r(t)+\delta}, \tag{3.47}$$

$$L_H^d(t) = \frac{\beta_2 p_H(t)F(t)}{w(t)}. \tag{3.48}$$

$$K_M^d(t) = \frac{\gamma p_M(t)G(t)}{r(t)+\delta}, \tag{3.49}$$

$$L_M^d(t) = \frac{(1-\gamma)p_M(t)G(t)}{w(t)}. \tag{3.50}$$

Combining (3.45) with (3.46) ,(3.47) with (3.48) and (3.49) with (3.50) we obtain the equilibrium capital intensity

$$k_Y^*(t) := \frac{K_Y^d(t)}{L_Y^d(t)} = \frac{\alpha}{1-\alpha}\frac{w(t)}{r(t)+\delta}, \tag{3.51}$$

$$k_H^*(t) := \frac{K_H^d(t)}{L_H^d(t)} = \frac{\beta}{\beta_2}\frac{w(t)}{r(t)+\delta}. \tag{3.52}$$

$$k_M^*(t) := \frac{K_M^d(t)}{L_M^d(t)} = \frac{\gamma}{1-\gamma}\frac{w(t)}{r(t)+\delta}. \tag{3.53}$$

and, thus, $K_Y^d(t) = k_Y^*(t)\,L_Y^d(t)$. Using $k_Y^*(t)$ in (3.37) to rewrite $Y(t) = L_Y^d(t)\,A_Y(t)\,(k_Y^*(t))^{\alpha}$ and inserting this in (3.46) we can solve for the equilibrium wage as a function of the interest rate

$$w^*(t) = \widehat{w}(r(t); A_Y(t)) = (1-\alpha)\,A_Y(t)^{\frac{1}{1-\alpha}}\left[\frac{\alpha}{r(t)+\delta}\right]^{\frac{\alpha}{1-\alpha}}.$$

This, in turn, determines the capital intensities $k_Y^*(t) = \widehat{k}_Y(r(t); A_Y(t))$, $k_H^*(t) = \widehat{k}_H(r(t); A_Y(t))$ and $k_M^*(t) = \widehat{k}_M(r(t); A_y(t))$. Using the market clearing condition $F(p_H^*(t); K_H^*(t), L_H^*(t), A_H(t)) = H^d(p_H^*(t); M(t), B(t))$ and (3.47) and (3.48) we obtain the general equilibrium price for health care as

$$\begin{aligned} p_H^*(t) &= \widehat{p}_H(r(t), w^*(t); H_d(t), A_H(t)) \\ &= \widehat{p}_H(r(t); H_d(t), A_Y(t), A_H(t), M(t), B(t)) \\ &= \left(\frac{H^d(t)^{1-\beta_1-\beta_2}}{A_H(t)}\frac{(r+\delta)^{\beta_1}w^{\beta_2}}{\beta_1^{\beta_1}\beta_2^{\beta_2}}\right)^{1/(\beta_1+\beta_2)}. \end{aligned}$$

Reinserting this, we obtain the equilibrium utilization of health care, as $H^d\left(p_H^*\left(t\right); M\left(t\right), B\left(t\right)\right) = \widehat{H}\left(r(t); A\left(t\right), M\left(t\right), B\left(t\right)\right)$. Using the market clearing condition $V_H = p_M G$ and (3.49) as well as (3.50) we obtain

$$\begin{aligned} p_M^*(t) &= \widehat{p}_M\left(r(t), w^*(t)\right) \\ &= \widehat{p}_M\left(r(t); A(t), M(t), B(t)\right) \\ &= \frac{1}{A_M}\frac{(r+\delta)^\gamma w^{1-\gamma}}{\gamma^\gamma(1-\gamma)^{1-\gamma}}. \end{aligned}$$

Using (3.48) with $F(t) = H_d^*(t)$ we can determine now $L_H^*\left(t\right) = \widehat{L}_H\left(p_H^*\left(t\right), w^*\left(t\right), H_d^*(t)\right) = \widehat{L}_H\left(r(t); A\left(t\right), M\left(t\right), B\left(t\right)\right)$. Knowing $L_H^*(t)$ we can determine $K_H^*(t)$ from (3.52), and consequently the value of V_H^* in equation (3.41). It is now possible to calculate $L_M^*(t)$ based on equation (3.50) using $V_H = p_M G$. The labor market equilibrium then determines

$$L_Y^*\left(t\right) = L\left(t\right) - L_H^*(t) - L_M^*(t),$$

where $L\left(t\right) = \widehat{L}\left(r(t); A\left(t\right), M\left(t\right), B\left(t\right)\right)$.

CHAPTER 4

The Impact of Climate Change on Health Expenditures

In this last contribution of the thesis, the effect of climate-induced health risks within a continuous time OLG economy with a realistic demography and endogenous mortality are studied. Climate change enters the economy through two channels. First, a degrading environmental quality increases mortality, affecting the demand for health care. Second, production losses are caused through deteriorating climate conditions and lead to reductions in income. We explore how individuals respond to these climate change impacts with respect to their life-cycle decisions and assess the overall effect on aggregate health care demand. We put special focus on age-specific vulnerabilities of climate-induced health risks and explore the response to climate change across age-groups. We solve the model numerically and show that health care demand is subject to two opposing forces. While climate-induced mortality increases demand for medical care, reduced income tends to lower health spending, particularly among the elderly. Moreover, we find that age-specific vulnerabilities to climate change considerably shape the effect on aggregate health care demand. Our analysis, thus, highlights the important role of a full life-cycle perspective in the estimation of climate-induced health costs.

4.1 Introduction

The recently published report by the Lancet Commission, see Watts et al. (2015), has named climate change an unacceptably high and potentially catastrophic risk to human health. While a large body of literature is indicating that this risk is already felt today, worsening conditions are predicted for the future. Climate change is also likely to have strong effects on mortality. For example, the WHO estimates additional 250,000 annual deaths related to climate change by 2030, see WHO (2014). These deaths can be caused directly by climate change through more frequent extreme weather events including heat stress, floods and storms but also indirectly through water inaccessibility, spread of diseases and food insecurity. Developing countries are expected to be affected most severely, nonetheless, the developed world is also likely to suffer impacts on human health.[1] These health-related risks can have important economic spillovers, particularly on individual life-cycle planning of savings and medical care expenses but also on the aggregate health care demand on a population level. Moreover, climate change is expected to have direct negative economic consequences such as output losses, which itself will affect the income, and consequently the life-cycle decisions of individuals. Against this background, this paper explores the effect of climate-induced mortality and economic impacts on the individual life-cycle as well as on aggregate health expenditures. We do so by integrating climate change into a life-cycle model embedded in an overlapping generation structure.

First and foremost, this paper is related to studies that attempt to quantify the effect of climate change on medical expenditures. For example, Bosello et al. (2006) estimate the economic impacts of climate-induced health effects and find that health care expenditures will rise in those regions where health impacts are negative. Within the EU, a study by Watkiss et al. (2009) found a net cost of heat-induced health effects for the last decades of the 21st century, while in the prior period the reduction in cold-related mortality amounted to an economic benefit. Hutton (2011) provides a review of various studies estimating global costs of climate change adaptation, including costs that accrue in the health care sector. The studies in the survey generally find large increases in global health expenditures caused by global warming.
In all of these studies the demand for health care is, however, assumed to be linked quite mechanically with mortality as health care costs are derived as the product of disease cases and the unit cost of health interventions. Hence, the demand for health care is not embedded into a life-cycle optimization, so that these studies miss important mechanisms through which changes in life-expectancy and income feed back in health care demand. Moreover, there has been growing evidence that effects of environmental changes on health are not uniformly distributed across all age-groups. For example, Basu and Samet (2002) and Haines et al. (2006) argue that heat extremes affect mostly the elderly population due to higher vulnerability to cardiovascular diseases. By contrast, younger age groups suffer relatively more through malnutrition and vector-borne diseases (Haines et al. 2006). Given that health expenditures vary strongly by age, vulnerabilities to various health risks across age-groups are likely to influence the effect on climate-related medical costs.

Despite effects on human health, climate change is prone to have negative effects on economic performance such as through reduced labor productivity (Heal and Park 2015, Watts et al. 2015), damages to the capital stock (Stern 2013) or through losses of production output (Nordhaus 2014, Stern 2007). More generally, Pindyck (2013) and Stern (2007) argue that global warming will likely affect total factor productivity negatively and point out that it may slow down economic growth such that adverse economic impacts might compound over time. A recently emerging empirical literature studying temperature and economic outcomes in the last half century[2] has shown that countries experiencing increased temperatures, indeed, suffered not

[1]A complete overview of climate change effects on human health and its intensity in different regions is given by Markandya and Chiabai (2009) and WHO (2014).

[2]See Dell et al. (2009) and Dell et al. (2012); Dell et al. (2014) provide a review on further literature studying

only from negative level effects on output but also from a reduction of economic growth. These effects predominantly affected below-average income countries. Such adverse impacts on the economy would necessarily reduce individual income, which in consequence affects life-cycle planning and the trade-off between spending on medical care, consumption and saving.

There is a large-body of literature studying the life-cycle allocation of health and consumption expenditures. The seminal work by Grossman (1972) introduced health investments into a life-cycle model, with Ehrlich and Chuma (1990) and Ehrlich (2000) extending the framework by endogenizing mortality. Kuhn et al. (2015) develop a life-cycle model featuring a realistic demography and mortality. The model is expanded to an overlapping generation (OLG) structure in chapter 2 of this thesis. The life-cycle theory is well-established and tightly linked with a large body of empirical literature. Most relevant for our approach are studies stressing the link between longevity and savings as well as health investments through the value of life. For example, Bloom et al. (2003) and Bloom et al. (2007) show that increases in longevity lead to a rise in savings rates for all age-groups. Lorentzen et al. (2008), Oster (2012) and Oster et al. (2013) find a negative and causal relationship from mortality to investments into health as well as healthy behavior. Moreover, in a large body of literature, researches have attempted to estimate the value of a statistical life based on people's willingness to pay for small reductions in mortality or health risks, such as in Viscusi et al. (1991) or Cameron and Deshazo (2013). The estimates are used in the assessment of policies to reduce health, environmental and safety risk. The value of life serves, thus, not only as a link between the life-cycle theory and empirically observed health behavior but also as a guidance for important policy decisions.

In this paper, we are aiming at understanding the impact of climate change on the demand for health care. While we are not fully calibrating our model to a specific country and offer no quantitative estimates on health expenditure effects, our main focus lies on identifying the main channels through which climate-induced health and income losses affect medical expenditures. To achieve that, we develop an overlapping generation (OLG) economy under the influence of climate change with a realistic demography and mortality as well as an endogenous demand of health care by extending the framework from chapter 2 with respect to climate change. The demand for health care is derived from utility maximization within a life-cycle model. Health care is provided by a medical sector, employing capital and labor, competing for resources with a final goods production sector. The population is affected by climate change through two channels. First, a degrading environmental quality increases mortality and reduces life-expectancy. In particular, our model allows for age-specific vulnerabilities to climate-induced health risks. Second, climate change negatively affects economic output, such that the income of individuals is reduced.

We will confine ourselves to the analysis of a small open economy, that is governed by an exogenous world market interest rate. Furthermore, we consider climate change to be exogenous and not amenable to the behavior of the economy at hand. This choice of framework conditions reflects the situation of a country that is sufficiently small to depend on foreign capital markets and to have only a negligible influence on world wide green house gas emissions.

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the economic effects of temperature increase.

Due to the high complexity of the model and the resulting difficulty in establishing a full analytical solution, we will primarily base our analysis on a numerical simulation. As a benchmark we determine the optimal allocation of health and consumption expenditures within a laissez-faire economy and an intact natural environment. We then analyze the isolated impact of climate change on health in a first experiment and consider age-specific vulnerability to climate-induced risks in a second scenario. The adverse impact on production is analyzed in a third experiment. Lastly, we evaluate how the effects in combination affect life-cycle decisions and aggregate health spending.

To our knowledge, we are the first to incorporate climate change into a life-cycle model with realistic mortality and endogenous health care demand. We are, thus, able to provide new insights into the age-specific response to climate change, its impacts on the life-cycle and aggregate health expenditures, some of which we summarize in the following. We find an ambiguous effect of climate change on health expenditures and the health share of GDP. While income and production suffer from climate change and affect health expenditures negatively, increased mortality risks induce individuals to invest more resources towards survival. Contrary to the existing literature on climate-induced health costs, health care demand might thus decrease in the presence of climate-induced mortality increases if income losses are sufficiently high. However, even in the absence of negative income effects, the value of life is reduced as a result of diminished life-expectancies, particularly for higher age-groups. Human health and longevity might, thus, not only be affected directly through increases in mortality but also through behavioral shifts toward less investments into protective and healthy goods, resulting in a complementarity of climate-induced health risks and unhealthy behavior. Among the elderly, health spending might even fall whose value of life is most strongly reduced due to such an adverse complementarity. Furthermore, age-specific vulnerabilities to climate-induced health threats do not only influence individual life-cycle planning, but significantly shape the effect on aggregate health care demand. For example, increases in aggregate health care demand are likely to be strongest when the young are predominantly affected by health risks and their population share is large. If the mortality of primarily higher age-groups is raised or the population is relatively old, smaller increases in health expenditures are to be expected. Hence, our results highlight the role of the life-cycle perspective in the impact of climate-change on future health care demand.

The remainder of the paper is structured as follows: In the following section the model is introduced. Section 4.3 and 4.4 solve for and characterize the individual life-cycle allocation and the macroeconomic equilibrium of the economy. In section 4.5 a numerical solution to the model is presented before section 4.6 concludes.

4.2 The Model

We consider a decentralized OLG model, based on chapter 2, in which individuals choose consumption and health expenditure over their life-course. Climate change is fully taken into account but cannot be controlled by individuals. We index individuals by their age a at time t, with $t_0 = t - a$ denoting the birth year of an individual aged a at time t.

4.2.1 Mortality and Survival

At each age, individuals are subject to a mortality risk, where

$$S(a,t) = \exp\left[-\int_0^a \mu(s, h(s,t_0+s), T(t_0+s))ds\right]$$

is the survival function at (a,t), with $\mu(a, h(a,t), T(t))$ denoting the force of mortality. We follow chapter 2 by assuming that mortality can be lowered by consumption of a quantity $h(a,t)$ of health care. In this model it additionally depends on $T(t)$, describing the deviation of current temperature to the level that has prevailed before the onset of climate change.[3] More specifically and building on Kuhn et al. (2015), we assume that the mortality rate $\mu(a, h(a,t), T(t))$ satisfies

$$\begin{aligned} \mu(a,0,0) &= \tilde{\mu}(a,t),\ \mu_h(\cdot) < 0,\ \mu_{hh}(\cdot) > 0, \\ \mu_h(a,0,T(t)) &= -\infty,\ \mu_h(a,\infty,T(t)) = 0 \quad \forall\,(a,t)\,, \end{aligned}$$

where $\tilde{\mu}(a,t)$ is the "natural "mortality rate for an individual aged a at time t when no health care is consumed and the baseline temperature level $T(t) = 0$ prevails. By purchasing health care, an individual can lower the instantaneous mortality rate, and can thereby improve survival prospects, but can only do so with diminishing returns.

We assume the following properties with regard to the effect of $T(t)$ on mortality:

$$\mu_T(\cdot) > 0,\ \mu_{TT}(\cdot) > 0,\ \mu_{hT}(\cdot) < 0\,\forall\,(a,t)\,. \tag{4.1}$$

An increasing temperature deviation, thus, increases mortality and does so with increasing intensity. Furthermore, the effectiveness of health care increases as the climate conditions worsen. More specifically, we adapt the mortality function from chapter 2 and add dependency of $T(t)$ to capture the impact of climate change on the force of mortality assuming

$$\mu(a,t) = f(a,T(t))\tilde{\mu}(a,t)\left[1 - \eta(a)h(a,t)^{\epsilon}\right], \tag{4.2}$$

where $0 < \epsilon < 1$ reflects the decreasing returns of medical care on mortality. The term $\eta(a)$ represents the age-specific effectiveness of health care, which is assumed to fall over the life-course. We define the age-dependent environmental effect on mortality f as

$$f(a,T) = 1 + v(a)T(t)^{\phi_f} \tag{4.3}$$

with $\phi_f > 1$. The term $v(a) \geq 0$ reflects the vulnerability of the cohort aged a to climate changes. We can easily see that $f(a,0) = 1$, implying that in the absence of health provision the base mortality is prevailing in the baseline environment. Furthermore it holds, that $f_T > 0$, $f_{TT} > 0$ if $T > 0$, which is in line with the assumptions made in (4.1).

[3] Let $\hat{T}(t)$ be the temperature at time t and T_0 be the mean temperature of the intact environment. $T(t)$ is then defined as $\hat{T}(t) - T_0$. Using this definition of temperature deviation, we follow the bulk of the climate change model literature.

Following the 2009 Lancet Report on Climate Change health impacts, see Costello et al. (2009), we assume that climate change is amplifying existing mortality risks rather than presenting a separate threat. The risk factor $f(a, T(t))$, thus, enters the mortality function multiplicatively. The dependency on a enables us to consider cohort-dependent impacts due to different vulnerability to environmental degradation across age-groups. This effect also holds in the absence of any health provision. Moreover, our model assumes that as the temperature increases, mortality rises and does so with increasing returns. This assumption is supported by the empirical results in Deschenes and Greenstone (2011) who find a non-linear relationship between daily temperatures and annual mortality based on heat-related health effects. While T does not present daily temperatures but a yearly mean temperature, there is broad consensus that increases in mean temperatures come along with increases in frequency and magnitude of heat extremes as well as daily maximum temperatures (see IPCC 2007, Jones et al. 2015, Seneviratne et al. 2014, Watkiss et al. 2009). Lastly, one can easily verify that the cross-derivative μ_{hT} is negative in our model setting, implying that health care is more effective at higher temperature levels. As the climate worsens, individuals are facing higher mortality rates which can be more effectively lowered as compared to an already low mortality level in an intact natural environment. Evidence for higher effectiveness (and, hence, higher utilization) of health care in the presence of adverse environmental conditions may be provided by the fact that hospitalization rates for respiratory diseases are positively associated with heat extremes in the US (see Anderson et al. 2013) and in Europe (see Åström et al. 2013).[4]

4.2.2 Individuals

The utility function of individuals born at $t_0 = t - a$ is given as:

$$\max_{c(\cdot),h(\cdot)} \int_0^\omega e^{-\rho a} u\left(c(a,t)\right) S(a,t) \ da. \tag{4.4}$$

The life-time utility is, thus, given by the discounted utility stream derived from consumption weighted by the individual's survival prospects. We assume that instantaneous utility u is given by

$$u(c(a,t)) = b + \frac{(c(a,t) - c_0)^{1-\sigma}}{1-\sigma}. \tag{4.5}$$

In the spirit of Hall and Jones (2007), the parameter b is chosen such that instantaneous utility is always positive. Moreover, c_0 denotes a minimum consumption level. Individual survival S and capital k evolve according to the following differential equations:

$$\dot{S}(a,t) = -\mu(a, h(a,t), T(t)) S(a,t), \tag{4.6}$$
$$\dot{k}(a,t) = r(t)k(a,t) + l(a)w(t) - c(a,t) - \phi(t)p_H(t)h(a,t) - \tau(t) + s(t) \tag{4.7}$$

[4]Despite this evidence, it is also conceivable that climate change lowers health care effectiveness. Our analysis, hence, presents a lower-bound for otherwise even stronger negative effects on mortality.

with $S(0, t-a) = 1$ and $k(0,t) = k(\omega, t) = 0$. The market interest rate r is given exogenously, whereas the wage w and the price for one unit of health care p_H are determined within the model. The parametric function $l(a)$ describes the effective labor supply and is given exogenously.[5,6] Individuals pay a share of $\phi(t)$ of their health expenditures out-of-pocket, while the remainder is covered by a public health insurance. The resulting tax, τ, is levied as a labor income tax by the government, such that total tax income equals total health care subsidies at each point in time. Due to our negligence of perfect annuity markets, accidental bequests accrue in the model, given by $\Upsilon_B(t)$, see (4.9) further below. In the model bequeathed capital is redistributed in a lump-sum fashion through $s(t)$, where

$$s(t) = \frac{\Upsilon_B(t)}{N(t)}. \tag{4.8}$$

.

4.2.3 Macroeconomic Aggregation

The number of births $B(t)$ at time t is exogenously given. Hence, the cohort aged a at time t has the size

$$N_c(a,t) = S(a,t)B(t-a).$$

Total population, $N(t)$, and deaths, $N_d(t)$, at time t are then given as

$$N(t) = \int_0^\omega N_c(a,t)\, da \qquad N_d(t) = \int_0^\omega \mu(a,t) N_c(a,t)\, da.$$

Furthermore, aggregate capital supply, $K(t)$, labor supply, $L(t)$, consumption, $C(t)$ and health care demand, $H(t)$ are given through aggregation of individual variables as follows:

$$\begin{aligned} K(t) &= \int_0^\omega k(a,t)N_c(a,t)\ da \qquad L(t) = \int_0^\omega l(a,t)N_c(a,t)\ da \\ C(t) &= \int_0^\omega c(a,t)N_c(a,t)\ da \qquad H(t) = \int_0^\omega h(a,t)N_c(a,t)\ da. \end{aligned}$$

The total amount of accidental bequests, $\Upsilon_B(t)$, distributed at time t is given as

$$\Upsilon_B(t) = \int_0^\omega k(a,t)\mu(a,t)N_c(a,t)\, da. \tag{4.9}$$

[5] This model setting abstracts from a pension system such that individuals need to save for higher ages when their labor supply declines strongly. Note, that the fixed age-specific labor supply has similar effects on life-cycle decisions as a fixed retirement age because individuals are not able to adapt their labor supply according to, for example, changes in the life-expectancy.

[6] The model can be extended such that the individual survival chance $S(a,t)$, serving as a proxy for health, affects the effective labor supply ($l = l(a, S)$). In this case, individuals would also invest in health expenditures with a view of increasing their labor supply and, thus, income. Such a model setting yields qualitatively similar results to those presented in this paper, such that we retain the simpler model presented here.

4.2.4 Firms

The supply side of the model consists of two sectors allowing us to trace structural shifts in the economy caused by climate change. The final goods production sector satisfy the demand for consumption and capital formation whereas the health care sector provides medical goods and services. Both sectors are perfectly competitive and profit functions are given as

$$V_Y(t) = Y(\Lambda_Y(t), K_Y(t), L_Y(t)) - w(t)L_Y(t) - \delta K_Y(t) - r(t)K_Y(t), \quad (4.10)$$
$$V_H(t) = p_H(t)F(\Lambda_H(t), K_H(t), L_H(t)) - w(t)L_H(t) - \delta K_H(t) - r(t)K_H(t) \quad (4.11)$$

where Y and F are Cobb-Douglas production functions, that exhibit constant returns to scale. Hence, profits in each sector evaluates to zero. The variables $\Lambda_i(t)$, $K_i(t)$ and $L_i(t)$ describe the technological index, the demand for capital and labor employed in sector $i \in \{Y, H\}$, respectively. Capital depreciation is given by δ. The GDP is given as the sum of total production value in each sector:

$$GDP(t) = Y(t) + p_H(t)F(t).$$

4.2.5 Climate Change and Production

We assume that damages induced by the climate affect the production output in each sector and by doing so follow several studies arguing that climate change has and will likely have intensifying negative economic impacts.[7] More specifically, we adopt the well-known approach by Nordhaus (2014) and assume that

$$\Lambda_i(t) = \Lambda_0^i[1 - D(T(t))] \text{ where } i \in \{Y, H\}$$

where Λ_0^i denote the technology level in sector $i \in \{Y, H\}$ in the absence of climate change. Damages, D, are determined by the temperature level $T(t)$ and given by

$$D(T(t)) = 1 - \frac{1}{1 + dT(t)^2}$$

where $d > 0$ reflect the scale of damages. The damage function can be viewed as a climate-induced reduction of total factor productivity (approach taken by Moyer et al. 2014) but also as a reduction of production output (approach taken by Nordhaus 2014, Stern 2007). These two perspectives coincide, however, in the absence of economic growth. In fact, we will assume no exogenous growth in this model and focus on a steady-state analysis.

[7] See Heal and Park (2015), Moyer et al. (2014), Pindyck (2013), Nordhaus (2014) and Stern (2013) for a discussion of future climate change impacts and Dell et al. (2014) for an overview of historic and current effects of temperature increases on the economy.

4.2.6 Market Clearing

The labor as well as the health care market clear within the small open economy. The capital and final good market are, however, considered open and use foreign alongside with domestic resources. The market clearing conditions are, thus, given as

$$
\begin{aligned}
L_Y(t) + L_H(t) &= L(t), && (4.12)\\
K_Y(t) + K_H(t) &= K(t) + K_F(t), && (4.13)\\
Y(\Lambda_Y(t), K_Y(t), L_Y(t)) + TX(t) &= C(t) + \dot{K}(t) + \delta K(t), && (4.14)\\
F(\Lambda_H(t), K_H(t), L_H(t)) &= H(t). && (4.15)
\end{aligned}
$$

Hence, aggregate labor supply $L(t)$ coincides with the sum of labor demand in each sector. Analogously the economy's total capital demand equals aggregate savings plus net capital flows from foreign countries $K_F(t)$. Net trade $TX(t)$ and the production in the final good sector covers aggregate consumption as well as economy-wide investments and capital replacement. Lastly, the total production in the health care sector equals the aggregate demand for medical care $H(t)$.

4.3 Optimal solution to the Individual Life-cycle Problem

Following the age-structured maximum principle, see Appendix 4.7.1, we obtain the well-known Euler-equation, according to which consumption over the life-course is allocated in such a way, that the marginal substitution rate between consumption at two different times (a and $\widehat{a}$, with marginal utility at the later age being appropriately discounted) equals the compound interest rate between these points in time:

$$
\frac{u_c\left(c\left(a,t\right)\right)}{e^{-\rho(\widehat{a}-a)}u_c\left(c\left(\widehat{a},t+\widehat{a}-a\right)\right)} = \exp\left\{\int_a^{\widehat{a}} r\left(t+\widehat{\widehat{a}}-a\right) - \mu\left(\widehat{\widehat{a}},t+\widehat{\widehat{a}}-a\right)d\widehat{\widehat{a}}\right\}. \quad (4.16)
$$

Note, that the interest rate that is relevant for the individual's life-cycle planning is the market interest rate minus the mortality rate. Hence, a higher mortality lowers the marginal utility of consumption at higher ages.

We define the value of life as the monetary value of an individual's status of being alive. Mathematically, this is captured by

$$
\psi\left(a,t\right) := \frac{\lambda_S\left(a,t\right)}{u_c\left(a,t\right)}. \quad (4.17)
$$

The shadow price of survival measures the utility an individual is expected to derive over its remaining lifetime. This becomes evident when solving for λ_S (see Appendix 4.7.1) where we obtain

$$
\lambda_S\left(a,t\right) = \int_a^{\omega} u\left(\widehat{a},t+\widehat{a}-a\right)\exp\left[-\int_a^{\widehat{a}}\left(\rho+\mu\right)d\widehat{\widehat{a}}\right]d\widehat{a}.
$$

By dividing the shadow price of survival by $u_c(a,t)$, the value is converted into units of consumption or, in other words, into monetary units. Using this definition of the value of life, we can transform it to (Appendix 4.7.1)

$$\psi(a,t) = \int_a^\omega \frac{u(\widehat{a}, t+\widehat{a}-a)}{u_c(\cdot)} R(\widehat{a}, a)\, d\widehat{a}, \tag{4.18}$$

where

$$R(\widehat{a}, a) := \exp\left[-\int_a^{\widehat{a}} r\left(t+\widehat{\widehat{a}}-a\right) d\widehat{\widehat{a}}\right]. \tag{4.19}$$

Furthermore, optimal individual health care demand is given by the following equation:

$$-\mu_h(a,t)\,\psi(a,t) = \phi(t)\, p_H(t). \tag{4.20}$$

Health care demand is, thus, allocated in such a way that the consumer price of one unit of health care, $\phi(t)p_H(t)$, equals the monetary value of the marginal reduction in the mortality caused by this health investment. The monetary value of the marginal reduction in the mortality is given by the product of the marginal effect of one unit of health care on the mortality, μ_h, and the value of life, ψ.

The demand for health care over the life-course

Based on the first-order condition for health (equation 4.20) and on the actual functional form of the mortality function, given by equation (4.2), we can, through simple rearranging, derive the demand for health care as

$$h(a,t) = \left(\frac{\Psi(a,t) f(a,T) \tilde{\mu}(a) \eta(a) \epsilon}{\phi(t) p_H(t)}\right)^{\frac{1}{1-\epsilon}}. \tag{4.21}$$

Hence, health care demand over the life-cycle rises with the value of life $\Psi(a,t)$, the climate-induced mortality risk factor $f(a,T)$, the base mortality $\tilde{\mu}(a)$ and the effectiveness of health care investments $\eta(a)$. By contrast, health care demand falls with the consumer price for health care $\phi(t)p_H(t)$.

Here, the main difference of this article and existing studies on climate-induced health cost predictions becomes evident. While the latter derive health care demand as the product of a measure of mortality or morbidity and the unit price of medical care, this approach takes into account the age-specific effectiveness on mortality reductions by health care as well as the willingness to pay for survival as measured by the value of life. We are, thus, able to take account of interactions of health care demand with mortality increases and income effects. For example, an individual might prefer to increase health care demand to a lesser extent than mortality has increased, if the mortality increase reduces survival chances and, thus, the utility attached to higher ages. Negative income effects are also likely to dampen the increase in health care demand as resulting losses in consumption negatively affect the value of life.

The evolution of consumption and health expenditures over the life-course

The dynamics of consumption (see Appendix 4.7.2) is described by

$$\dot{c} = \frac{u_c}{u_{cc}}\left[\rho - r + \mu\right]. \tag{4.22}$$

Consumption rises as long as the interest rate exceeds the time preference if mortality is sufficiently small. As mortality rises with age, consumption will eventually begin to decline and, thus, generate a hump-shaped profile over the life-course. Note, that the temperature $T(t)$ does not affect the growth of consumption over lifetime, but only the level of $c(t)$ through life-budget effects.

The evolution of health care demand is given by

$$\dot{h} = \underbrace{\frac{-1}{\mu_{hh}}}_{<0}\left[\mu_{ha} + \mu_{hT}\dot{T} + \underbrace{\mu_h}_{<0}\left(\frac{\dot{\psi}}{\psi} - \frac{\dot{p_H}}{p_H} - \frac{\dot{\phi}}{\phi}\right)\right]. \tag{4.23}$$

Hence, if the marginal effectiveness of health care increases with age $\mu_{ha} < 0$ or temperature $\mu_{hT} < 0$, health care demand rises with age or the temperature, respectively. Similarly, a rising value of life, a falling price for health care or a reduction in the co-pay rate, results in rising health care demand.

4.4 Macroeconomic Equilibrium

Perfectly competitive firms in the production sector choose labor $L_Y(t)$ and capital $K_Y(t)$ so as to maximize period profit (4.10). The first-order conditions imply

$$r(t) = Y_{K_Y}(t) - \delta \tag{4.24}$$
$$w(t) = Y_{L_Y}(t), \tag{4.25}$$

i.e. the market interest rate is equal to the marginal product of capital net of depreciation; and the wage rate is equal to the marginal product of labor. Assuming a neo-classical technology with constant returns to scale we then obtain

$$\begin{aligned} V_Y(t) &= Y(\Lambda_Y(t), K_Y^*(t), L_Y^*(t)) - w\,(t)\,L_Y^*(t) - \left[\delta + r(t)\right]K_Y^*(t) \\ &= (Y(\Lambda_Y(t), K_Y^*(t), L_Y^*(t)) - Y_{L_Y}(\cdot)L_Y^*(t) - Y_{K_Y}(\cdot)K_Y^*(t)) = 0, \end{aligned}$$

i.e. firms in the production sector make no profit.

Perfectly competitive providers of health care choose the labor $L_H(t)$ and capital $K_H(t)$ so as to maximize period profit (4.11). From the first-order condition we obtain

$$r(t) = p_H(t)F_{K_H}(t) - \delta \tag{4.26}$$
$$w(t) = p_H(t)F_{L_H}(t), \tag{4.27}$$

Analogously to the production sector, profits equal zero in the health care sector if a neo-classical technology with constant returns to scale is assumed. Combining (4.26) and (4.27) with (4.24) and (4.25) we have

$$p_H(t) = \frac{Y_{L_Y}(t)}{F_{L_H}(t)} = \frac{Y_{K_Y}(t)}{F_{K_H}(t)}, \tag{4.28}$$

implying that capital and labor inputs are distributed across the production and health care sector in a way that equalizes the price for health care with the marginal rate of transformation between outputs in each sector. For example, $\frac{Y_{L_Y}(t)}{F_{L_H}(t)}$ measures the relative output gain in production as compared to the output loss in health care from reallocating one labor unit from health care into production. The higher the price for health care, the lower will be F_{L_H} implying that more workers will be allocated to the health care sector. Analogously, a rising price for health care implies a shift of capital used in production to the health care sector. Assuming appropriate Inada conditions, $Y_L(\Lambda_Y, K_Y, 0) = Y_K = (\Lambda_Y, 0, L_Y) = \infty$ and $F_L(\Lambda_H, K_H, 0) = F_K(\Lambda_H, 0, L_H) = \infty$ we always have an interior allocation with $L_H(t) = L(t) - L_Y(t) \in (0, L(t))$ and $K_H(t) = K(t) - K_Y(t) \in (0, K(t))$.

In the numerical simulation of our model we will use Cobb-Douglas specifications for the production functions. In Appendix 4.7.3, we show that the set of prices and market allocations $\{w(t), p_H(t), L_Y(t), K_Y(t)\}$ as well as input and output quantities can be expressed in terms of the interest rate $r(t)$ and temperature deviation $T(t)$. This insight will be used in the numerical solution of the model.

4.5 Numerical Solution

In this section, we present the outcomes of the following numerical experiments. The benchmark scenario features a stylized, small economy that is unaffected by climate change. We then introduce a climate-induced mortality effect that uniformly affects all age-groups in a first experiment (i). Second, we investigate the effects of a varying vulnerability across age-groups (ii). As a third scenario we consider the detrimental effect of climate change on the economy's production (iii). We then continue by modeling a simultaneous mortality and production effect as climate change will likely encompass both impacts (iv). In order to solve the numerical problem we employ the algorithm presented in chapter 2. Due to our exogenous market interest rate, the algorithm used in this article is, however, simplified to the partial equilibrium approach.

Note, that we are considering climate change and the market interest rate exogenous factors in this simulation. We motivate the former and latter by our choice of a small open economy as the subject of our experiments. Such an economy is unlikely able to influence the worldwide temperature development on its own, such as through a reduction in production emissions, nor can it be considered a closed economy but instead depends on an exogenous world market interest rate. Moreover, as climate change is a long-term development, we are interested in its long-term effects and simulate the steady state obtained in the various experimental parameter and model settings. However, in experiment (i) we will additionally consider the immediate impact of an environmental shock that is unanticipated by the individuals and study how the economy dynamically reacts to such new circumstances. Finally, we abstract from economic growth as we are interested in the isolated impacts of climate change on health and the economy.[8]

While our model is not calibrated to a specific country in detail, we nonetheless use empirical data from Taiwan to obtain realistic life-cycle profiles with respect to mortality and labor supply in the numerical simulation of the benchmark scenario. We chose Taiwan because it exhibits a high climate vulnerability and is considered to have relatively strong climate-induced effects on human health, see Su et al. (2016). Furthermore, we roughly match some key macroeconomic variables of Taiwan in the benchmark scenario. This notwithstanding, our main focus lies in identifying the transmission channels of health and economic impacts of climate change rather than offering a quantitative analysis of Taiwan's climate change vulnerability.

4.5.1 Specification of the Numerical Analysis

The main components of our benchmark numerical model are specified as follows.

Demography

The single-year model consists of individuals who enter the model economy at age 20 and can live up to the maximum age 100. In our model, a birth at age 20 implies that $\omega = 80$. The number of births is given as $B(t) = B_0 \exp[\nu t]$ where $\nu = 1.0\%$ and $B_0 = 0.1$. Population growth is, thus, determined through the exogenous number of births but also by endogenous mortality.

Mortality

The force of mortality μ is endogenously determined in the model as given in equation (4.2). In order to obtain a realistic base mortality profile, we chose the mortality rates[9] of Taiwan in 1970 as the base mortality rate. Furthermore, we define the decreasing effectiveness of health care with age as

$$\eta(a) = \left(\frac{a - \omega}{1 - \omega}\right)^{1/4}$$

This parametric setting was chosen, such that optimal investments in health $h(t)$ lower base mortality to an extent that the endogenously determined life-expectancy matches present-day data of Taiwan.

Labor supply

To obtain a realistic labor supply profile over the life-course, we proxy $l(a)$ from equation (4.7) by an age-specific income schedule (see Figure 4.1), constructed from 2015 earnings data, as provided by the National Statistic Bureau in Taiwan. We then normalize the income schedule

[8] Hutton (2011) notes, that studies on climate-induced health expenditures usually avoid considering ongoing economic development as the related estimates about the future are often highly uncertain.

[9] We use single-year age-specific mortality data from the Human Mortality Database (HMD).

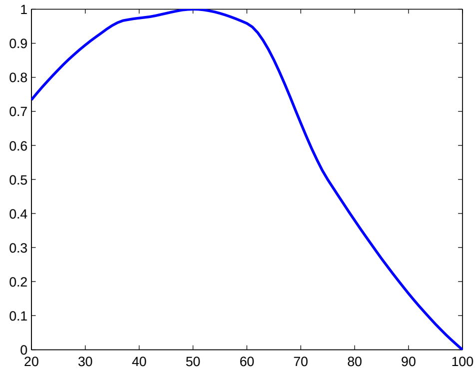


Figure 4.1: Age-specific labor supply

and calibrate the market wage rate $w(t)$ so it matches the maximal life-course income obtained at age 50. We do not model explicitly the pay-as-you-go retirement system of Taiwan due to its rather small replacement rate and, thus, its minor contribution to life-cycle considerations (see Bloom et al. 2007).

Health Insurance

We set $\phi(t) = 0.35\ \forall t$ such that 35% of all health expenditures are payed out-of-pocket, whereas the remaining share is payed for by the public health insurance. The medical care subsidies are financed by an income tax and the government's budget is balanced at all times. The value of 35% reflects the out-of-pocket share in the national health insurance plan by the Taiwanese government.[10]

Remaining parameters and functional forms

Table 4.1 and 4.2 show the numerical inputs for the remaining parameters and functional forms of the benchmark model which are mostly based on the values chosen in chapter 2 and reflect in general standard values in the life-cycle literature. Note, that the elasticity of capital in the production sector, α, is higher than in the medical sector, β, implying the assumption that the health care sector is less capital-intensive than the remaining economy.[11] Our values of Λ_0^Y and Λ_0^H were chosen to obtain a realistic GDP per capita as well as health share of the economy.

Note, that the parameter setting differs in the experiments compared to the Benchmark scenario. Temperature deviation $T(t)$ will be modified in each of the experiments, such that the impact of climate change can be studied. Depending on whether we are interested in mortality or production effects, we will further modify $v(a)$ and d that measure the scale of climate-induced effects on mortality and production, respectively.

[10]Data on national health expenditures were taken from the Taiwan Ministry of Health and Welfare, accessible at `http://www.mohw.gov.tw/EN/Ministry/Statistic.aspx?f_list_no=474`.

[11]This assumption is motivated in chapter 2.

Parameter	Description	Value
r	market interest rate	4%
σ	inverse elasticity of intertemporal substitution	1.75
b	constant offset for consumption in utility function	5
ρ	time preference ρ	2%
c_0	subsistence minimum	0.8
ϵ	effectiveness of medical care in μ	0.1
δ	rate of depreciation	5%
α	elasticity of capital in Y	$1/3$
β	elasticity of capital in F	$1/5$
Λ_0^Y	base productivity in production sector	1.6
Λ_0^H	base productivity in medical sector	0.3
d	scale of climate-induced output damages	0

Table 4.1: Parameters

Function	Description
$T(t) \equiv 0$	temperature deviation from baseline climate
$v(a) \equiv 0$	vulnerability to climate-induced health risks
$Y(t) = \Lambda_Y(t) K_Y(t)^\alpha L_Y(t)^{(1-\alpha)}$	production in manufacturing sector
$F(t) = \Lambda_H(t) K_H(t)^\beta L_H(t)^{(1-\beta)}$	production in medical sector
$\eta(a) = \left(\frac{a-\omega}{1-\omega}\right)^{1/4}$	health care effectiveness
$B(t) = B_0 \exp[\nu t]$	Number of births

Table 4.2: Functional forms

4.5.2 Benchmark

The blue (solid line) plots in Figure 4.2 show the benchmark life-cycle profiles of various individual variables. Consumption expenditures exhibit a hump-shaped pattern, reflecting the initial increase in consumption due to rising income and the eventual decline due to the uncertainty in survival to high ages. Savings are accumulated during the working life in anticipation of low old-age labor supply and high old-age health care spending. Capital begins to decline in the second half of the life and falls to zero at the maximum age. In fact, empirical life-cycle profiles exhibit consumption expenditures that are rising until the middle-ages and falling later in life (see Tung (2011) for an international comparison of consumption age-profiles, including Taiwan). Health care expenditures initially rise slowly reflecting the low base mortality at younger ages. From age 50 onwards they increase strongly due to increasing mortality, after which, around age 80, they begin to fall due to a strongly declining value of life. This hump-shaped pattern is reflected by equation (4.23). In the absence of changes in temperature, in the price for health care and in the co-pay rate ($\dot{T} = \dot{p_H} = \dot{\phi} = 0$), the evolution of health care demand over the life-course is shaped by two-factors. First, the effect of age on the marginal effectiveness of medical care μ_{ha} reflects the initially increasing health care demand over the life-course and is driven by the increasing base mortality. By contrast, the decreasing value of life ($\dot{\Psi} < 0$) works to decrease demand for medical care at the highest ages. This health expenditure profile is qualitatively in line with data on medical expenses over the life-course that in general exhibit decreasing health expenditures in the highest age-groups.[12]

As we abstract from economic growth, the macroeconomic variables of the economy are in a steady-state. In particular, the per-capita health expenditures and the GDP share of health expenditures are constant throughout the whole time horizon. Table 4.3 offers information on selected steady-state variables of the benchmark economy.[13]

Variable	Benchmark value
Remaining life expectancy at age 20	60.8 years
Remaining life expectancy at age 65	19.5 years
Share of elderly (65+)	21.5%
Health share of GDP	7.2%
Employment share in production sector	91%
Payroll tax for health care system	8.5%

Table 4.3: Macroeconomic variables

4.5.3 Climate-induced Mortality Risks

In this section we consider two experiments. In experiment (i) we study the impact of a uniform increase in mortality risk regardless of age, while we consider the effect of age-specific vulnerabilities to climate change in experiment (ii).

Uniform increase in mortality risk

In experiment (i), climate change affects mortality for all age-groups with the same multiplicative factor while we neglect any climate-induced impacts on production. This serves the purpose of understanding the pure impact of increased mortality risk on individuals by disentangling them from income-induced effects. However, this simulation can also be interpreted as a more optimistic scenario, in which economic output and, thus, income is not or only to a negligible degree lowered by climate change.

Compared to the numerical specification in section 4.5.1 representing the benchmark scenario, we modify the parameter setting in two regards. First, we assume an increase in temper-

[12]See chapter 2 for a discussion of US data and European Commission (2015) for an overview of the European member countries. We are not aware of a data source providing age-specific health expenditures for Taiwan.

[13]Note, that our economy only considers individuals aged 20 or older, such that the share of elderly (65+) measures the number of people aged 65 or older divided by the number of those aged 20 or older.

ature at all times by three degrees (by setting $T(t) \equiv 3$). Second, we define health vulnerability uniformly as $v(a) \equiv 0.077$ for all age-groups. This model setting, thus, describes a world featuring a higher temperature level that affects individual's mortality with the same intensity regardless of age. The parameter ϕ_f, denoting the mortality responsiveness to temperature, is set to 1.5 reflecting the non-linear relationship between daily temperatures and mortality rates as found in Deschenes and Greenstone (2011).[14]

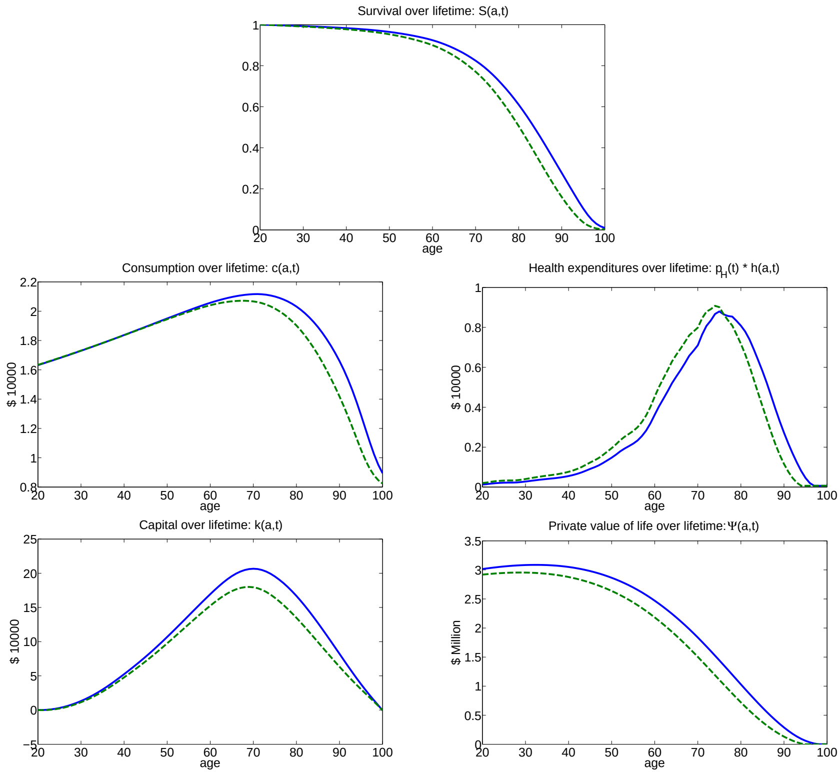


Figure 4.2: Life-course consumption, health expenditures, capital and value of life profiles for benchmark case (blue, solid line), and the climate-induced hight mortality scenario (green, dashed line)

Figure 4.2 shows the individual lifetime variables for the benchmark case (blue, solid line) and the climate-induced high mortality case (green, dashed line). In experiment (i), the increased mortality at all ages results in a lower survival chance at every age. Consequently, life expectancy at age 20 drops by 3.3 years,[15] which has multiple effects on the individual life-cycle. First, we observe, that consumption starts out at an approximately equal level compared to the baseline but lies below it for higher ages. Moreover, the peak of consumption in the life-cycle occurs a

[14] We assume an increase in mean temperatures by about three degrees which reflects a rather high-emission scenario. The impact on mortality rates caused by such an increase in mean temperatures encompassing all direct and indirect climate-induced effects described in the introduction cannot be known precisely, such that an exact calibration is impossible to conduct. Our choice of the parameters $v(a)$ and ϕ_f is, however, motivated by obtaining increases in the mortality rate large enough to have an impact on life-cycle savings as well as on health expenditures.

[15] The decrease in life-expectancy by 3.3 years is not to be understood as a prediction but serves to illustrate the economic consequences of such a rather strong impact on longevity.

few years earlier. This is due to diminished survival chances and, hence, a lower weighting of utility at high ages. Second, health expenditures rise above the benchmark level until about age 70, a direct response to the higher base mortality rate. Somewhat surprisingly, however, medical expenses are lower for the highest age-groups as compared to the baseline, which we will discuss further below. Third, individual assets are reduced for all age-groups as a consequence of a lower incentive for old-age saving. Fourth, the value of life, that is determined by the consumption levels over the remaining life-course, is lower compared to the baseline throughout the whole life-cycle as a result of lower consumption at higher ages.

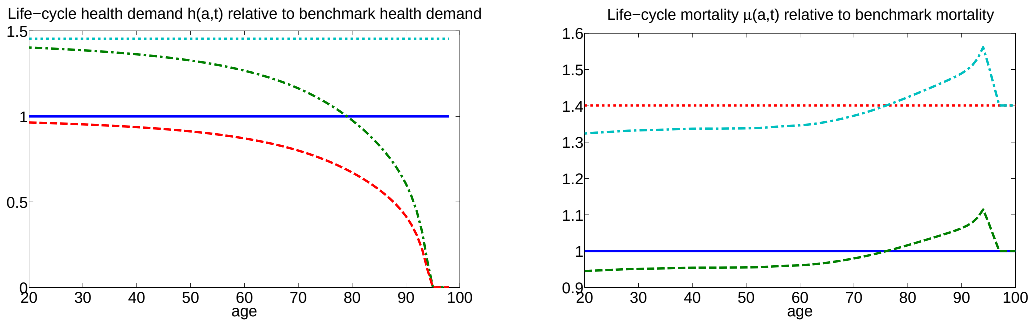
We now want to shed light on the question why health expenditures respond differently at varying ages relative to the baseline. Inspecting equation (4.21), we note that

$$\left(\frac{\tilde{\mu}(a)\eta(a)\epsilon(a)}{\phi(t)p_H(t)}\right)^{\frac{1}{1-\epsilon}}$$

is identical in the benchmark scenario and experiment (i). The differences in health care demand solely result from changes in $\Psi(a,t)f(a,T)$.[16] Thus, we observe two competing impacts on health care demand in experiment (i) relative to the baseline. While, the decreased value of life exerts downward pressure, the increased mortality risk induces an upward force on health care demand. This is illustrated in Figure 4.3a, which shows the health care demand in different scenarios relative to the health care demand in the baseline. Naturally, the blue, solid baseline plot is simply constant and of value one. The cyan, dashed-dotted line reflects the relative increase of health care demand for younger cohorts and reduction for the elderly in experiment (i), as already seen in Figure 4.2. The remaining two plots show two counter-factuals, that serve the purpose of decomposing and illustrating the isolated effects of the value of life (VOL) and climate-induced mortality risk, respectively. Evaluating equation (4.21) using the VOL from the benchmark case and f from experiment (i) (depicted by the red, dotted plot) we observe, that the induced mortality risk increases health care demand uniformly for all age-groups if the VOL channel is shut down. Conversely, ignoring this additional mortality risk and (counter-factually) considering only the effect on the VOL leads to a decrease in health care demand that intensifies with age, shown by the green, dashed plot. The differential effect on health care expenditures for different age-groups is, thus, explained by the fact, that at lower ages the increased mortality risks dominate, whereas at higher ages, the diminished value of life overcompensates the additional mortality risk induced by climate change.

In a similar fashion one can decompose the effect on age-specific mortality attributable to a) the climate-induced health risk and b) shifted age-specific medical care spending, which we illustrate in Figure 4.3b. Again we are considering the effect on mortality relative to the benchmark case. Keeping health care demand unchanged with respect to the benchmark case, the climate-induced health risk increases mortality uniformly (see red, dotted plot). If we consider, however, the altered health care demand while shutting down the effect of f, we can observe,

[16] The price for health care, p_H, is determined by the fixed interest rate r as well as by Λ_H and Λ_Y, see Appendix 4.7.3. Due to our negligence of production impacts in this experiment, the price of health care does in consequence not change in experiment (i) compared to the benchmark.



(a) Benchmark (blue, solid)
High mortality case (cyan, dashed-dotted)
Benchmark VOL (red, dotted)
Benchmark f (green, dashed)

(b) Benchmark (blue, solid)
High mortality case (cyan, dashed-dotted)
Benchmark h (red, dotted)
Benchmark f (green, dashed)

Figure 4.3: Decomposition of life-cycle health care demand and mortality

that younger individuals lower their mortality rate while the elderly allow for a even higher mortality risk (illustrated by green, dashed plot). Hence, in total, the increased health care spending among lower age-groups dampens the climate-induced mortality increase, while at higher ages, the reduced health care spending amplifies the mortality risk, as illustrated by the cyan, dashed-dotted plot for experiment (i). Indeed, longevity losses induced by climate change are greatest among older cohorts,[17] contributing to the stronger relative effect for the elderly on the value of life. Hence, in addition to the direct effect of climate change on mortality, the reduced value attached to lives might further deteriorate health, particularly among vulnerable groups such as the elderly. This represents an adverse complementarity between health risks caused by climate change and behavioral shifts towards lower health investments and stands in contrast to the favorable complementarity described by Dow et al. (1999) and Murphy and Topel (2006) in which cause-specific mortality reductions increase the incentives to invest in health care affecting mortality from other causes.

Notably, this result is consistent with empirical evidence linking health behavior to remaining life expectancy and the value of life. For example, Oster (2012) finds that health behavior response to HIV is stronger among individuals who have a higher life-expectancy. In another study, Oster et al. (2013) show that individuals diagnosed with Huntington's disease, that considerably lowers life expectancy, have riskier health behavior and smaller investments in health compared to those individuals that have been diagnosed negatively. While the first study was implemented in developing countries, the second study shows that the link between health behavior and remaining life expectancy also holds in richer countries, indicating that this relationship is universal to life-cycle planning.

As already mentioned, savings are reduced in the considered experiment. This is due to the diminished life-expectancy and the resulting smaller incentive for old-age savings, a mechanism in line with theoretical and empirical findings established by Bloom et al. (2003) and in

[17] The remaining life expectancy of a 20-year-old falls by 5% compared to 13% for an individual aged 65.

particular with Lee et al. (2000) who examined the relationship between life expectancy and savings in Taiwan. However, one would expect that the higher health expenditures might in fact also induce the opposite, hence a positive effect on savings, as individuals need to accumulate financial cushions in order to provide for higher health expenditures (see De Nardi et al. 2010). However, this is not the case in our setting due to the fact that the bulk of the additional health expenditures accrue while individuals are still working. At very old ages, health expenditures are actually reduced as already noted and this, in fact, works to diminish savings additionally.

In Table 4.4, we report the macroeconomic effects of experiment (i). Health expenditures per capita in our model economy rise as the increase of health care demand among the young dominates the decrease within the group of the elderly. As a consequence individuals decrease consumption expenditures on average in order to cover the higher health expenditures. This economic-wide shift of consumption towards health care is also reflected by an increased health share of GDP and the employment share in the health sector.

Variable	**Change rel. to benchmark**
Life expectancy	-3.3 years
Health care expenditures per capita	$+7.3\%$
Consumption expenditures per capita	-1.1%
Health share of GDP	$+0.4$ pp
Employment share in health care sector	$+0.5$ pp

Table 4.4: Macroeconomic variables

So far, we have looked at the long-term impact of climate-induced health risks (while neglecting production effects) and observed a reallocation from consumption to health, with the exception of the most elderly individuals who tend to decrease health care demand in the face of high mortality risk. While this is an interesting insight into the longterm life-cycle effects of increased mortality, an important question is how individuals react to climate-induced effects on health if these arrive as a shock. To answer this question, we now alter the parameter setting of experiment (i) such that there is an unanticipated temperature, and hence, mortality increase at $t = 200$, i.e.

$$\begin{aligned} T(t) &= 0 \;\; \forall t \in [0, 200] \\ &= 3 \;\; \forall t > 200. \end{aligned}$$

Figure 4.4 illustrates the impact of climate change on individuals aged 80 at the time of shock.[18] Contrary to the long-run steady-state, the elderly increase their health spending as

[18]Note, that we implement the shock in our numerical simulation by restricting individuals to differ from their benchmark life-cycle allocation until the shock arrives.

an immediate response to an unanticipated negative shock to mortality. An analogous decomposition method as above (not shown here) reveals that again increased mortality risk tend to increase health care demand and a diminished value of life lowers it. However, the reduction in the value of life is dampened as individuals shift consumption that was originally planned for the late stages of their life towards the closer future.

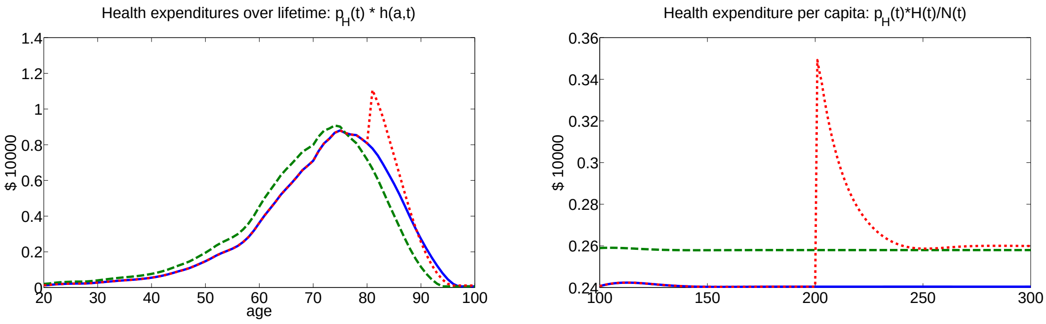


Figure 4.4: Individual health expenditures (left) and health expenditures per capita (right) in the benchmark scenario (blue, solid line), steady-state effect of experiment (i) (green, dashed line) and shock effect of experiment (i) (red, dotted line)

This initial, strong increase in health investments is observed among all age-groups, such that average health expenditures rise strongly above the long-term value at the time of the shock at $t = 200$, as shown in the right panel of Figure 4.4. This is consistent with several studies (see Anderson et al. 2013, Michelozzi et al. 2009, Semenza et al. 1999, Åström et al. 2013) finding evidence that heat waves, that usually pose an unanticipated threat to health and even life, increase the short-term demand for health care significantly. In the long-run, however, and if climate change permanently increases mortality, this analysis implies that the impact on health expenditures could vary by age. In particular, less medical care could be demanded by the elderly who shift health expenditures to earlier stages of their life. Such a shift of medical care could also be a consequence of change in behavior by health professionals, namely by investing more attention and medical resources into those patients with a higher remaining life-expectancy. Such a rationale would be in line with the Eubie-Blake effect by Breyer et al. (2015), see also its discussion in the introductory chapter 1.

Age-specific increase in mortality risk

We now consider experiment (ii) in which climate change affects different age-groups to a varying degree and focus only on the steady-state outcomes. In subexperiment (iia), we assume, that vulnerability $v(a)$ grows linearly with age, where $v(a) = \left(\frac{a}{\omega}\right) v_{\max}$. We choose parameter $v_{\max}$ in such a way that life expectancy at age 20 is reduced to the same extent as in experiment (i), namely by 3.3 years.[19] Figure 4.5 shows survival over lifetime for experiment (i) (uniform increase in mortality) and experiment (iia) relative to the benchmark case.[20] Survival is below the

[19] Setting $v_{\max} = 0.137$ reduces life-expectancy by that extent.

[20] Throughout this article we restrict the plots showing variables relative to the benchmark case until age 90. This is due to the fact that relative differences rise strongly with age due to the fact that survival falls exponentially with

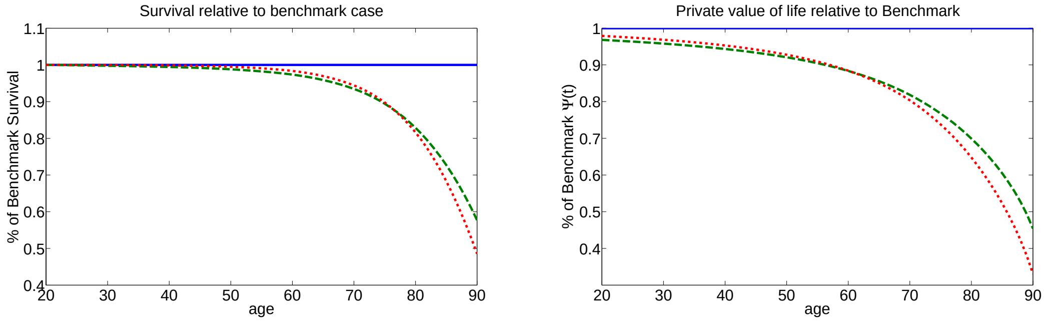


Figure 4.5: Survival and the value of life relative to the benchmark case in experiment (i, age-independent mortality effect, green-dashed line) and experiment (iia, increasing vulnerability with age, red-dotted line)

benchmark level at any age in both experiments, however, for the age-independent increase of climate change risk on mortality (green, dashed plot) survival falls faster until age 70 and slower afterwards compared to experiment (iib) where vulnerability to climate-induced health effects are taken into account (red, dotted plot).[21] Hence, the age-specific vulnerabilities result in a differential effect on survival prospects of different age groups. A similar picture emerges for the value of life (VOL), see right panel of Figure 4.5. While younger individuals posses a higher willingness to pay for survival relative to experiment (i), the VOL of the elderly is even further reduced. This observation is in line with the health expenditures of the elderly in experiment (iia), shown in Figure 4.6, that drop even below the level of experiment (i) despite the increase in climate-induced health vulnerability they face. Apparently, the further increase of mortality in these age-groups is outweighed by the even larger reduction in the VOL. Younger individuals, however increase health expenditures to a lesser extent relative to the benchmark scenario as compared to experiment (i) due to their lower vulnerability to climate-induced mortality risks.

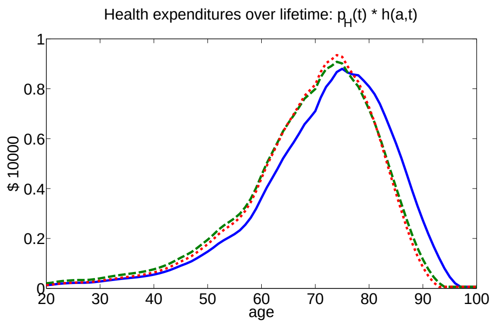


Figure 4.6: Health expenditures for benchmark case (blue, solid line), the climate-induced high mortality scenario (green, dashed line) and age-increasing vulnerability scenario (red, dotted line)

mortality rates. Hence, the large relative differences at high ages would make the changes at the more relevant, younger ages less apparent in the graphs.

[21]This is also reflected by the remaining life expectancy at age 70, which is 4% lower in experiment (ii) compared to (i).

In Figure 4.7, we show the effect of the increased mortality risk on further individual life-cycle variables. The decreased life-expectancy results, analogous to experiment (i), in an overall reduction and front-loading of consumption expenditures. However, individuals can sustain higher consumption for a longer time during their life compared to experiment (i) as they face lower health expenditures at younger ages. At very high ages, consumption falls below the level of experiment (i) as individuals discount old-age consumption to an even greater extent. The negative savings incentive due to the diminished longevity appears to be stronger in experiment (iia). In particular, the onset of dissaving within the life-cycle happens at a younger age. While the overall reduction of life expectancy is identical in experiment (i) and (iia), the survival changes of younger (older) individuals are greater (smaller) in the former experiment. As savings are mainly accumulated for the provision of financial resources at high ages when labor income is low, the old-age saving incentive is, thus, weaker in experiment (iia).

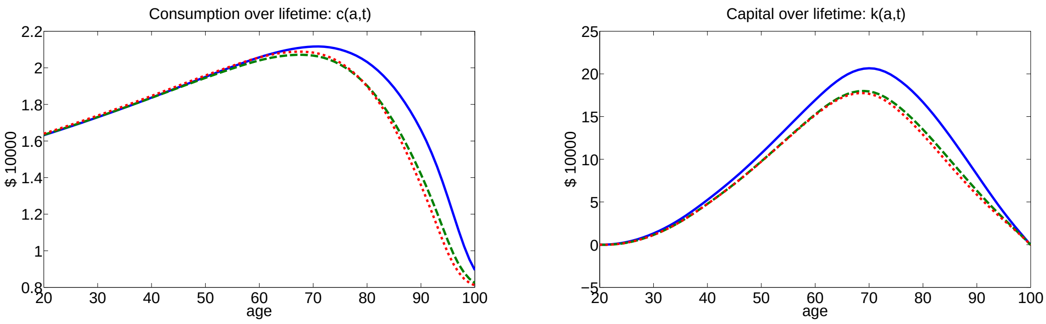


Figure 4.7: Life-course consumption, health expenditures and capital profiles for benchmark case (blue, solid line), the climate-induced high mortality scenario (green, dashed line) and age-increasing vulnerability scenario (red, dotted line)

In a further variation of experiment (ii), we now reverse age-specific vulnerabilities, such that

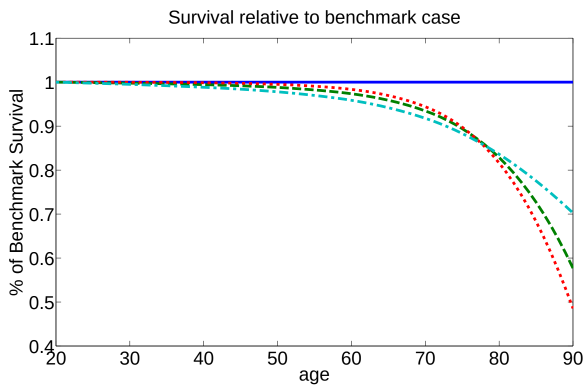


Figure 4.8: Survival relative to the benchmark case as shown in Figure 4.5 including experiment (iib, decreasing vulnerability with age) shown by the cyan dashed-dotted line

Variable	cons. Vuln. (i)	increasing Vuln. (iia)	decreasing Vuln. (iib)
Life expectancy	-3.3 years	-3.3 years	-3.3 years
Health care exp. p. cap	$+7\%$	$+4\%$	$+12\%$
Health share of GDP	$+0.4$ pp	$+0.1$ pp	$+0.7$ pp
Health income tax	$+0.4$ pp	$+0.2$ pp	$+0.9$ pp
Consumption exp. p. cap.	-1.1%	-0.5%	-2.1%
Savings per capita	-13.8%	-14.6%	-12.9%

Table 4.5: Macroeconomic variables

the young bear the largest adverse impacts of climate-induced health effects.[22] In Figure 4.8, we plot survival relative to the benchmark scenario. Compared to the case, where vulnerability is increasing with age, the opposite picture emerges. The young face diminished survival prospects relative to experiment (iia), while the elderly are less severely hit by climate change. While this differential effect on survival might seem obvious considering the assumed vulnerability-age link, it has important implications for the aggregate health care demand and the economy. To see this point, we report a selection of macroeconomic variables in Table 4.5. Despite the identical impact on overall life expectancy, health expenditures per capita react to strongly varying degrees across the experiments. In the case of an age-independent effect on mortality (experiment (i)), health expenditures per capita rise by 7 % relative to the benchmark scenario. In experiment (iia), where vulnerability increases with age, they rise by only 4% while in experiment (iib), featuring decreasing age-specific vulnerability, they exhibit a much stronger increase by 12 %. As we have seen in the previous experiments, the younger age-groups tend to increase health-spending in the light of mortality increases whereas higher age-groups tend to decrease medical expenditures in the long-run. Thus, climate-induced health affecting predominantly the young will increase health-spending to a greater extent than in the scenario where the elderly are most harmed.[23] This pattern is also dominant when considering the economy's health share and income tax. Consumption, as expected, behaves inversely to health expenditures, as consumption is reduced most in the scenarios where health expenditures rise to the largest extent. Interestingly, the aggregate effect on average savings in the population shows a distinctly different behavior across the experiments. While savings, as already discussed, decrease as a result of a lower saving-incentive, the effect is weakest in (iib). This is due to the fact, that individuals who survive into ages with low labor supply experience a greater remaining life expectancy as those in experiment (i) and (iia). Hence, the old-age saving incentive is stronger in this scenario, resulting in a lower decrease in savings.

[22] Vulnerability $v(a)$ now falls linearly with age, with $v(a) = \left(1 - \frac{a}{\omega}\right) v_{\max}$. We set $v_{\max} = 0.19$ as this parameter value results in the identical loss of overall life expectancy of 3.3 years.

[23] The demographic structure also influences the increase in health expenditures across the experiments. Given that our model features a population with a rather large share of elderly, the gap between experiments (iib) and (iia) might even be larger in the case of a younger population.

4.5.4 Climate-induced Losses to Production

We will now consider scenario (iii) in which losses to production are caused through climate change as described in section 4.2.5. To do so, we set $T(t) = 3$ for all times analogous to experiments (i) and (ii). However, we neglect any effect on mortality ($f(a, T) = 1$) and focus solely on production effects. By setting $d = 0.0024$, we model a reduction of approximately 3% in GDP relative to the benchmark scenario.[24] Again, we are only focusing on the long-term impacts on life-cycle allocations and macroeconomic outcomes of a climate-induced output damages.

Figure 4.9 shows the impact on life-cycle allocations. As income has been reduced (see Table 4.6), individuals reduce consumption and savings over the life-course. While these reductions appear to be strongest within the middle-aged groups in absolute terms, they are fairly constant over the life-cycle relative to their age-specific levels. As a result of diminished investments into health, life expectancy drops below the baseline by about 0.2 years. Due to the diminished consumption, the effect on the value of life is negative for all ages.

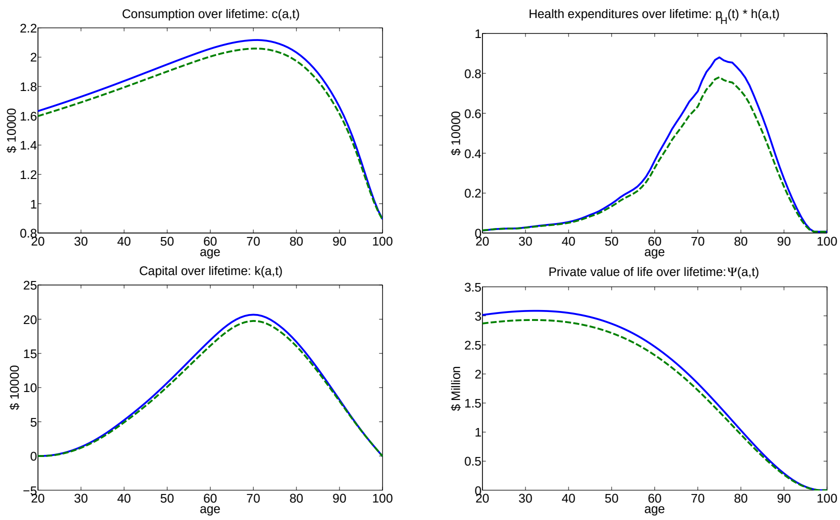


Figure 4.9: Life-course consumption, health expenditures, capital and value of life profiles for benchmark case (blue, solid line), and the production losses scenario (green, dashed line)

The macroeconomics shifts relative to the benchmark scenario are shown in Table 4.6. As expected, wage falls as a response to diminished output. In consequence, the price of health care is reduced due to the fact, that the medical sector is relatively more labor intensive compared to the final good sector. This effect is very weak as seen in Table 4.6 and would, in fact, work towards an expansion of health care demand. Consequently, the negative effect on health care demand, that we observe in Figure 4.9, is caused predominantly by diminished incomes and only slightly dampened by the simultaneous decrease in the price for medical care.

[24] Our choice of d is close to the value assumed in Nordhaus (2014). However, as Pindyck (2013) points out, d is a rather speculative parameter as scientists are not able to quantify the impact of unprecedented temperature levels on economic output based on empirical estimates.

Considering the life-cycle effects, it comes as no surprise that consumption, health care expenditures and capital per capita fall below the benchmark level. Interestingly however, the share of GDP of the health care sector is reduced as well, indicating that the reduction in health care spending has been stronger in relative terms compared to the decline in consumption expenditures. While the economy shrinks we can, thus, observe a structural change towards the production sector. This is in line with Hall and Jones (2007), who have shown, that using standard economic assumptions, rising incomes generate a rising health expenditure share as the marginal utility of consumption falls rapidly whereas the marginal utility of life extension, by means of health expenditures, does not decline. Conversely, falling incomes must lead to a reduced share of health expenditures.

Variable	Change rel. to benchmark
Wage	-3.2%
Price for health care	-0.4%
Health care expenditures per capita	-11%
Consumption expenditures per capita	-2.5%
Health share of GDP	-0.6 pp
Employment share in health care sector	-0.7 pp

Table 4.6: Macroeconomic variables for experiment (iii)

4.5.5 Climate-induced Combined Effect on Mortality and Production

It is rather unlikely that countries will be affected by climate change through one single channel such as losses in income or increases in health risks, but rather will be subject to both effects. Thus, we now consider experiment (iv), which represents the combined impact of experiments (i) and (iii), such that climate change simultaneously increases mortality, uniformly for all age-groups, and reduces incomes through output losses.

Figure 4.10 illustrates how the combined scenario affects life-cycle decisions. Consumption is lower over the whole life-cycle in scenario (iv) compared to the benchmark run. Furthermore, the decrease is strongest among the elderly and weakest among the young, even in relative terms. This is consistent with experiments (i) and (iii), where in the former higher health expenditures decreased consumption expenditures and in particular pushed them towards earlier ages due to the strongly diminished life-expectancy, and in the latter, reduced incomes decreased consumption uniformly across the life-cycle.

Health expenditures are subject to two opposing forces. The income losses exert downward pressure on health care demand of all age groups, whereas the increased mortality pushes the demand in the opposite direction, at least for young age-groups. The combined effect, thus, results in an ambiguous impact on health care demand, its sign depending on the relative strength of each effect. The very old reduce health expenditures considerably as their value of life does not only fall due to the diminished life expectancy and consequently because of the reduction of consumption allocated to these higher age-groups but also due to lower income and, thus, less

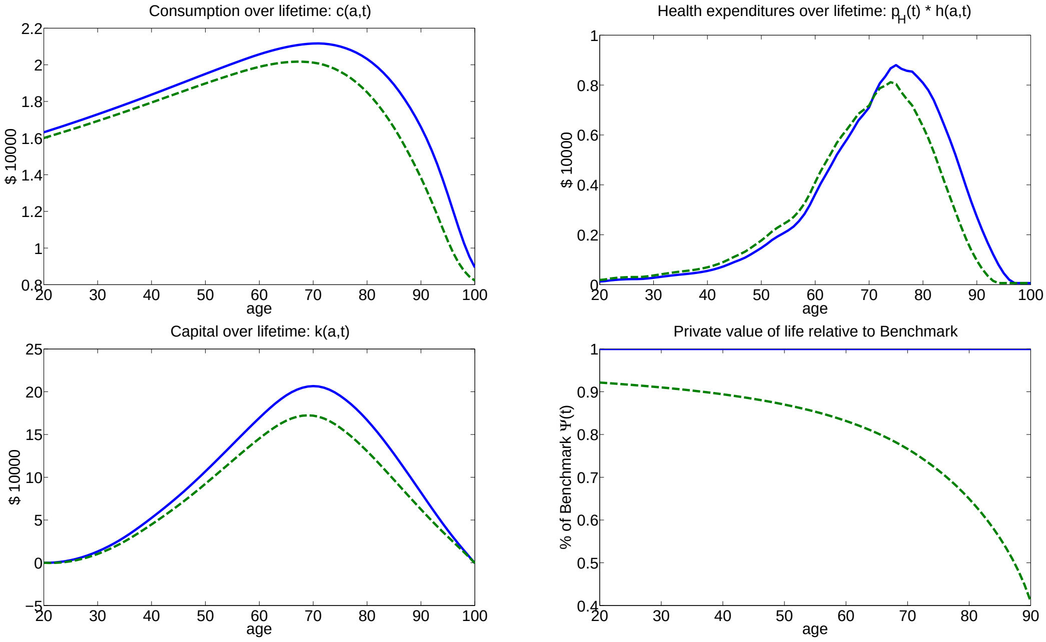


Figure 4.10: Life-course consumption, health expenditures, capital and value of life profiles where the blue (solid) line denotes the baseline, the green (dashed) line experiment (iv)

consumption in general. Hence, the reductions in medical expenses in experiment (i) and (iii) reinforce each other for these older age-groups. Younger individuals, instead, increase health care expenditures in the light of higher mortality risk, despite the reduced income. With regard to their impact on savings and the value of life, both effects that we considered, the lowered income and the higher mortality risk reinforce each other, leading to a considerable reduction for all age-groups.

Table 4.7 reports how the macroeconomic variables respond to the climate-induced combined effect on mortality and production. Life expectancy in experiment (iv) falls due to mortality increases as seen in scenario (i) but also, to a smaller extent, through reductions in income (scenario (iii)), resulting in less demand of medical care that would otherwise work to reduce mortality. With regard to health expenditures we see that the increase of health expenditures in experiment (i) has been reversed by the income effect presented in experiment (iii). A similar picture emerges with respect to the health expenditure share of GDP and the health income tax. However, a precise calibration with respect to the expected effects on mortality and production would need to be conducted to make predictions about the magnitude and sign of the total effect on health expenditures of a given country or region. Yet, such an undertaking would likely fail due to the large uncertainty in estimates on mortality and income effects of climate change. Nonetheless, the implication of this numerical exercise is, most importantly, that health expenditures under climate change will be determined by two impact channels working in opposite directions. Regions that experience strong mortality effects with modest production losses will likely experience higher health care demand whereas other regions with predominantly income effects will decrease health spending.

Variable	Incr. in mortality (i)	Prod. losses (iii)	Combined (iv)
Life expectancy	-3.3 years	-0.2 years	-3.5 years
Health care exp. per capita	$+7\%$	-11%	-4%
Health income tax	$+0.4$ pp	-0.7 pp	-0.2 pp
Health share of GDP	$+0.4$ pp	-0.6 pp	-0.2 pp

Table 4.7: Macroeconomic variables

4.6 Conclusion

In this article, we have developed a life-cycle framework to analyze the effects of climate change on individual consumption and medical expenditure decisions as well as on the aggregate health care demand. While predictions of the exact magnitude of these effects is subject to a calibration of expected (and often unknown) impacts on production and mortality of a specific economy, our model can shed light on the qualitative nature of climate change effects, some of which we summarize in the following.

First, there is an ambiguous climate-induced effect on health expenditures and the health share of a country. On the one hand, climate change lowers income, leading to a reduction in consumption and health expenditures. Due to a higher marginal utility of consumption at lower levels, health expenditures are more strongly reduced such that the health expenditure share falls. On the other hand, the increased base mortality induces individuals to spend, on average, more on health expenditures. Hence, a trade off between the reducing effect of lower income on health expenditures and the boosting effect of higher mortality arises.
Second, the highest age-groups tend to reduce their health expenditures in the long run when facing higher mortality risks, even in the absence of a negative income effect. This is the result of relatively strongly diminished remaining life expectancy at high ages and a subsequent reduction in the value of life. Climate change, hence, might disproportionately affect the remaining life-expectancy and well-being of the elderly, an effect not caused but exacerbated by additional age-specific vulnerability to climate-induced mortality risks. However, in the short-term and when climate change impacts are unanticipated, individuals of all age-groups react to a higher mortality risk by investing additional resources into health care. The impact of climate change on health expenditures might, thus, vary strongly across different time scales.
Third, climate change is likely to have a negative effect on the value of life. This can imply an increase in risky or unhealthy behavior and lower incentives for protective investments, such as those relating to housing, working places and transport systems. Such an shift away from healthy behavior would present an indirect channel through which health is further deteriorated as a consequence of global warming. This can be interpreted as an adverse complementarity analogous to the favorable complementarity in the spirit of Murphy and Topel (2006) and Dow et al. (1999) where reductions in mortality for one cause increase the incentives to invest in health care affecting mortality from another cause.
Fourth, aggregate health care demand is subject to various forces and is crucially linked with

life-cycle effects, the demographic structure of the population and the age-specific vulnerability profile of climate-induced health effects. Increases in aggregate health care demand are likely to be strongest when the young are predominantly affected by health risks and their population share is large. If the mortality of primarily higher age-groups is raised or the population is relatively old, smaller increases in health expenditures are to be expected. Health care demand can even fall in the presence of climate-induced mortality risk, if income losses are sufficiently strong.

This article, thus, stresses the importance of considering life-cycle impacts in the estimation of the climate change effect on health care expenditures. Failing to account for the age-heterogeneity of health care demand or the linkage of income and health care demand via the value of life might bias these forecasts strongly. For example, the rise in health expenditures might be strongly overestimated when income effects are neglected or the negative effect of higher mortality on the value of life and, hence, the willingness to pay for survival is ignored. Studies that attempt to quantify climate-induced health costs should, thus, aim for a life-cycle perspective in their estimates, rather than relying on the static assumption, that rises in mortality and morbidity proportionally increase health spending. Moreover, our analysis suggests that aggregate health expenditure effects will be shaped by the age-vulnerability profile of climate-induced mortality impacts. Our insights into the mechanisms with which vulnerabilities across the population translate into a differential effect on health spending can be used in studies to better estimate aggregate effects and to identify particularly susceptible regions or populations.

In this article, we are focusing on an open economy model, where the economy is assumed to be small enough such that is has no significant influence in the worldwide GHG emissions. Thus, an interesting extension of the model would consider a closed and emission-rich economy such as China or the US (or the world itself). In such a model one can examine the effects of taxation for the purpose of financing climate change mitigation as opposed to financing health care subsidies. Climate-induced health effects could, thus, not only be dealt with by adaption through medical care but also by mitigating increases in temperatures in the first place.

4.7 Appendix

4.7.1 Optimal solution to the Individual Life-cycle Problem

Following the age-structured maximum principle, the individual's life-cycle problem, i.e. the maximization of (4.4) subject to (4.6) and (4.7) can be expressed by the Hamiltonian

$$\mathcal{H} = uS - \lambda_S \mu S + \lambda_k \left[rk + lw - c - \phi p_H h - \tau + s \right],$$

leading to the first-order conditions

$$\begin{aligned} \mathcal{H}_c &= u_c S - \lambda_k = 0, && (4.29) \\ \mathcal{H}_h &= -\lambda_S \mu_h S - \lambda_k \phi p_H = 0, && (4.30) \end{aligned}$$

and the adjoint equations

$$\begin{aligned} \dot{\lambda}_S &= (\rho + \mu)\, \lambda_S - u, && (4.31) \\ \dot{\lambda}_k &= (\rho - r)\, \lambda_k. && (4.32) \end{aligned}$$

Evaluating equation (4.29) at two different ages/years (a, t) and $(\widehat{a}, t + \widehat{a} - a)$, equating the terms and rearranging gives

$$\begin{aligned} \frac{u_c\left(\widehat{a}, t + \widehat{a} - a\right)}{u_c\left(a, t\right)} &= \frac{\lambda_k\left(\widehat{a}, t + \widehat{a} - a\right)}{\lambda_k\left(a, t\right)} \frac{S\left(a, t\right)}{S\left(\widehat{a}, t + \widehat{a} - a\right)} \\ \Leftrightarrow \frac{u_c\left(\widehat{a}, t + \widehat{a} - a\right)}{u_c\left(a, t\right)} &= \exp\left\{ \int_a^{\widehat{a}} \left[\rho + \mu\left(\widehat{\widehat{a}}, t + \widehat{\widehat{a}} - a\right) - r\left(t + \widehat{\widehat{a}} - a\right) \right] d\widehat{\widehat{a}} \right\} \\ \Leftrightarrow \frac{u_c\left(c\left(a, t\right)\right)}{e^{-\rho(\widehat{a} - a)} u_c\left(c\left(\widehat{a}, t + \widehat{a} - a\right)\right)} &= \exp\left\{ \int_a^{\widehat{a}} \left[r\left(t + \widehat{\widehat{a}} - a\right) - \mu\left(\widehat{\widehat{a}}, t + \widehat{\widehat{a}} - a\right) \right] d\widehat{\widehat{a}} \right\} \end{aligned}$$

which equals equation (4.16).

In order to obtain a solution for λ_S, we integrate (4.31) which gives

$$\lambda_S\left(a, t\right) = \int_a^{\omega} u\left(\widehat{a}, t + \widehat{a} - a\right) \exp\left[-\int_a^{\widehat{a}} \left(\rho + \mu\right) d\widehat{\widehat{a}} \right] d\widehat{a}.$$

Using the definition of the value of life, see (4.17), we can express it analogously as

$$\psi\left(a, t\right) := \frac{\lambda_S\left(a, t\right)}{u_c\left(a, t\right)} = \int_a^{\omega} \frac{u_c\left(\widehat{a}, t + \widehat{a} - a\right)}{u_c\left(a, t\right)} \frac{u\left(\widehat{a}, t + \widehat{a} - a\right)}{u_c\left(\widehat{a}, t + \widehat{a} - a\right)} \exp\left[-\int_a^{\widehat{a}} \left(\rho + \mu\right) d\widehat{\widehat{a}} \right] d\widehat{a}.$$

Substituting from the Euler equation (4.16) and rearranging we obtain equation (4.18).

Inserting (4.29) into (4.30) allows to rewrite the first-order condition for health care as

$$-\mu_h\left(a, t\right) \psi(a, t) = \phi\left(t\right) p_H\left(t\right).$$

which gives equation (4.20).

4.7.2 The evolution of consumption and health expenditures over the life-course

Total differentiation of (4.29) with respect to time gives

$$\begin{aligned} & u_{cc}S\dot{c} + u_c\dot{S} - \dot{\lambda}_k \\ = \; & u_{cc}S\dot{c} - u_c\mu S - (\rho - r)\lambda_k \\ = \; & u_{cc}S\dot{c} - [\rho - r + \mu]\, u_c S = 0. \end{aligned}$$

From this we obtain the dynamics of consumption given in equation (4.22). Total differentiation of (4.20) with respect to time gives

$$-\left(\mu_{hh}\dot{h} + \mu_{ha} + \mu_{hT}\dot{T}\right)\psi - \mu_h\dot{\psi} - \dot{\phi}p_H - \phi\dot{p_H} = 0$$

from which we obtain the dynamics for health care as,

$$\dot{h} = \frac{-1}{\mu_{hh}}\left(\mu_{ha} + \mu_{hT}\dot{T} + \frac{\dot{\phi}p_H + \phi\dot{p_H} + \mu_h\dot{\psi}}{\psi}\right),$$

which is easily transformed into equation (4.23).

4.7.3 Equilibrium Relationships with Cobb-Douglas Technologies

In the numerical simulation of our model we will use Cobb-Douglas specifications for the production functions. In the following, we show that the set of prices and market allocations $\{w(t), p_H(t), L_Y(t), K_Y(t)\}$ can be expressed in terms of the interest rate $r(t)$ and temperature deviation $T(t)$. This insight will be used in the numerical solution of the model.

Consider the Cobb-Douglas-specifications

$$Y(t) = \Lambda_Y(t)K_Y(t)^{\alpha}\left[L_Y(t)\right]^{1-\alpha} \tag{4.33}$$
$$F(t) = \Lambda_H(t)K_H(t)^{\beta}\left[L_H(t)\right]^{1-\beta}, \tag{4.34}$$

with $\alpha, \beta \in [0, 1]$.

From the first-order conditions (4.24), (4.25), (4.26) and (4.27) we then obtain the factor demand functions

$$K_Y^d(t) = \frac{\alpha Y(t)}{r(t) + \delta}, \tag{4.35}$$
$$L_Y^d(t) = \frac{(1-\alpha)\,Y(t)}{w(t)}, \tag{4.36}$$
$$K_H^d(t) = \frac{\beta p_H(t)F(t)}{r(t) + \delta}, \tag{4.37}$$
$$L_H^d(t) = \frac{(1-\beta)p_H(t)F(t)}{w(t)}. \tag{4.38}$$

Combining (4.35) with (4.36) and (4.37) with (4.38) we obtain the equilibrium capital intensity

$$k_Y^*(t) := \quad \frac{K_Y^d(t)}{L_Y^d(t)} = \frac{\alpha}{1-\alpha}\frac{w(t)}{r(t)+\delta}, \tag{4.39}$$

$$k_H^*(t) := \quad \frac{K_H^d(t)}{L_H^d(t)} = \frac{\beta}{1-\beta}\frac{w(t)}{r(t)+\delta}. \tag{4.40}$$

and, thus, $K_Y^d(t) = k_Y^*(t)L_Y^d(t)$. Using $k_Y^*(t)$ in (4.33) to rewrite $Y(t) = \Lambda_Y(t)L_Y^d(t)\left(k_Y^*\right)^\alpha$ and inserting this in (4.36) we can solve for the equilibrium wage:

$$w^*(t) = (1-\alpha)\,\Lambda_Y(t)\left[\frac{\alpha}{r(t)+\delta}\right]^{\frac{\alpha}{1-\alpha}}.$$

Note, that $\Lambda_Y(t)$ is determined by Temperature $T(t)$ as well as by other exogenously given parameters. Hence, we can determine the wage rate based on the market interest rate $r(t)$ and the temperature deviation. The wage rate can now be used to determine the capital intensities $k_Y^*(t)$ and $k_H^*(t)$. Using the market clearing condition $F(t) = H^d(t)$ and (4.37) and (4.38) we obtain the general equilibrium price for health care as

$$p_H^*(t) = \frac{1}{\Lambda_H(t)}\frac{(r(t)+\delta)^\beta w(t)^{1-\beta}}{\beta^\beta(1-\beta)^{1-\beta}}.$$

Using (4.38) we can determine the optimal labor demand in the health care sector, $L_H^*(t)$. The labor market equilibrium then determines

$$L_Y^*(t) = L(t) - L_H^*(t)$$

and the macroeconomic allocations are fully characterized.

CHAPTER 5

Conclusion

In this final section of the thesis, a brief summary and discussion of the findings is provided. Furthermore, future research plans connected to the topic of this thesis are presented.

5.1 Summary and discussion of findings

This thesis has discussed various determinants of health care expenditure growth. Moreover, the joint dynamics of health expenditures with the economy, the age structure of the population as well as the welfare consequences have been analyzed.

With respect to health expenditure growth, we have examined the role of medical progress, income growth and insurance expansions in the US. First we have demonstrated that the general equilibrium perspective matters strongly with respect to the role of medical progress in health expenditure growth. Much of the increase associated with medical innovations is dampened, in the medium and long-run, by the increase in the price for medical care arising through shifts in the structure of the economy and higher savings in the population. Second we have argued, that medical progress is not to be viewed solely as an exogenous trend but itself determined by the dynamics in the health care sector. We have demonstrated that a considerable share of medical progress that took place in the US in the second half of the 20th century was the result of expanding insurance systems. It thus becomes a question of accounting whether insurance expansions as the distant effect or medical progress as the immediate effect are assigned the causal role of spending growth. Third, the analytical and numerical results of our model indicate that medical progress, income growth and health insurance do not independently drive health care spending but exhibit strong complementarities. Notably, this implies that residual approach estimates of the role of medical progress should be cautiously interpreted, as complementarities are likely to be picked up. Fourth, in a more forward-looking perspective, the thesis has shown that the impact of climate change on health spending is ambiguous and depends not only on the direct climate-induced mortality impacts but also on the more generally adverse effects on the economy. On the macroeconomic level, it has been shown that the population structure matters strongly when assessing the aggregate effect on health expenditures induced by climate change. A discussion of health expenditure growth alone is unrewarding, as more important questions arise in the same context. These questions pertain to the implications of health care sector expansion on the rest of the economy and particularly on the welfare of individuals. We have shown that medical progress has an ambiguous effect on economic output as it increases the dependency ratio in the economy but, at the same time, also boosts the capital stock per capita. The former effect is likely to be present in many countries due to the fact that so far only few governments have implemented a sufficient increase in the retirement age to counterbalance the increase in life-expectancy. The latter effect, the impact on savings, however, hinges on the strength of the welfare state. If old-age consumption and health care is financed through intergenerational transfers only, a saving incentive following medical innovations is not likely to materialize or will at least be weaker. The impact of health care expansion on the economy is thus dependent on the institutional setting in a country. With respect to the welfare implications, medical progress unambiguously improves welfare as individuals take advantage of more effective health care to enjoy longer lives, implying that the shifting of resources from consumption towards health care is efficient. In contrast, insurance expansions introduce an inefficiency in the individual trade-off between consumption and health care through the subsidization of medical care and the associated moral hazard effect. Abstracting from the favorable risk-sharing effects of insurance, this implies a drag on welfare. However, the insurance expansion as observed in the US was indeed welfare improving according to our simulation, as the favorable effect of induced medical progress by far compensated the adverse effect through moral hazard. Climate change is by assumption welfare-decreasing, due to its negative impact on mortality as well as on economic performance. However, if income losses are sufficiently small, a shift from consumption away to health expenditures can dampen the adverse welfare impact.

5.2 Outlook on future research

While this thesis has shed some light on the various determinants of health care expenditures and its implications for longevity, welfare and the economy, it has not accounted for population heterogeneity other than age. However, in real populations, individuals do not only differ by age, but in many other dimensions of which education is especially important for health and economic outcomes. A large and well-known literature has evolved showing that education is associated with a range of different life-cycle outcomes. Important within the context of this thesis is the observation, that in many developed countries, disparities in longevity across educational groups exist and have increased over the last decades.

While there is no consensus on the drivers of the underlying health-related disparities, several studies point to the role of medical progress as a possible contributor to longevity inequality. This literature argues that individuals from higher socioeconomic groups tend to be able to utilize medical advances quicker and more effectively in lowering mortality. This can have important implications for the analysis of medical progress. In particular, medical progress might improve longevity and welfare of high-education individuals, while affecting other individuals adversely through the upward pressure on medical prices induced by medical progress. Furthermore, following Baumol's theory, productivity gains in capital-intensive sectors cause not only income to grow but also production costs in labor-intensive sectors, such as the health care sector, to soar. Income growth might, however, disproportionately affect high-education individuals, whereas the price for health care rises for the whole population.

In future work, we plan to develop a theory on the differential impact of medical progress on heterogeneous individuals by expanding the model framework described in this thesis. To do so, individuals will differ not only in age but also in educational level, giving rise to a difference in income and in the ability to use medical technology effectively to improve survival chances. Retaining the general-equilibrium structure of the model will allow for an analysis of the described macroeconomic feedback channels and their relevance with respect to mortality inequality.

Beside this analysis of mortality inequality, the thesis will be used as a starting point for several other extensions planned for the future. As already noted the effects of medical progress and other determinants of health expenditures might have different impacts in economies with stronger public health care and pension systems such as in the European welfare states. Thus, there is currently work undergoing to develop a model adaptation to public health care systems in which the consumption of health care is not determined privately but rather depends on the quantity of health care and level of medical technology approved by the public authority. Moreover, the role of exogenous demographic trends, such as the emergence and aging of the baby-boomers (in the US and elsewhere) can be analyzed very effectively within the model framework of this thesis. In particular we plan to explore the role of baby-boomers in aggregate health spending over time, in medical progress aimed at individuals of particular age groups and for the sustainability of public health and pension systems.

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Curriculum Vitae

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Personal Information
Born: 28th December 1987 in Sarajevo
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Work Experience

Junior Researcher, Vienna Institute of Demography, Vienna, Austria — Oct. 2014 – present

- MEDPRO-Project: Study of the nexus of population ageing, health expenditure and medical progress
- Organized biweekly colloquia with international guest researcher

Data Systems Programmer, The Sphere Institute, Burlingame, USA — Sep. 2013 – Aug. 2014

- Developed numerical and statistical programs for US health care policy analysis

Education

Doctoral program in Mathematical Economics, Technical University, Vienna — Oct. 2014 – present

- Research in the field of health expenditures and its implications for the economy and welfare, Supervisor: Prof. Dr. Alexia Fürnkranz-Prskawetz and Dr. Michael Kuhn
- Coursework Grade: 1.08 (on scale from 1=best to 5=worst)

Master Thesis Research, University of California, Berkeley, United States — 2012 – 2013

- Research in the field of tumor growth modeling in collaboration with the Lawrence Berkeley National Laboratory
- Coursework GPA: 4.0 (on scale from 4.0=best to 0.0=worst)

Master of Science, Regensburg University, Germany — 2011 – 2013

- Major in Mathematics, Minor in Computational Science, Grade 1.0 (on scale from 1=best to 5=worst)
- Thesis: Finite Element Methods for Evolving Surfaces in Tumor Modeling, Supervisor: Prof. Dr. Harald Garcke

Bachelor of Science, Regensburg University, Germany — 2007 – 2011

- Major in Mathematics, Minor in English Philology, Grade 1.1 (on scale from 1=best to 5=worst)
- Thesis: Mathematical Modeling of Pattern Formation in Biological Systems with Reaction Diffusion Systems, Supervisor: Prof. Dr. Harald Garcke

Research

Published Paper:

- Daniel Croner and Ivan Frankovic, forthcoming (2018), **A Structural Decomposition Analysis of Global and National Energy Intensity Trends**, Energy Journal.

Published Working Papers:

- Ivan Frankovic, 2017, **The Impact of Climate Change on Health Expenditures**, TU Vienna Working Paper, 02/2017.
- Ivan Frankovic, Michael Kuhn and Stefan Wrzaczek, 2016**, Medical Care within an OLG economy with realistic demography**, TU Vienna Working Paper, 02/2016.

In Progress:

- Special Report on Climate Change and Health, financed by the Austrian Panel on Climate Change
- "Health insurance, endogenous medical progress, and health expenditure growth" (with M. Kuhn)
- "The Impact of Medical Progress on Health Inequality" (with M. Kuhn)
- "Congestion in Public Health Care Systems" (with M. Kelly)
- "The International Trade of Workplace Risk" (with M. Kuhn)
- "Using vintage structure for a multi-stage optimal control model with random switching time" (with S. Wrzaczek and M. Kuhn)

Conference presentations

Tagung des Vereins für Socialpolitik, Vienna, Austria	Sep. 2017
International Health Economics Association Conference, Boston, USA	Jul. 2017
EAERE Conference, Athens, Greece	Jun. 2017
NOeG Conference, Linz, Austria	May 2017
Internationale Energiewirtschaftstagung, Vienna, Austria	Feb. 2017
European Economic Association Conference, Geneva, Switzerland	Aug. 2016
European Health Economics Association Conference, Hamburg, Germany	Jul. 2016
RES Symposium of Junior Researches, Brighton, UK	Mar. 2016
RGS Doctoral Conference, Bochum, Germany	Feb. 2016

Summer schools

Economics of Health Inequality, Rotterdam, Tinbergen Institute	Jul. 2016

Scholarships & Awards

Delegate to the **Lindau Nobel Meeting 2017**	2017
Admitted to the **German Association of Mathematicians** (DMV)	2013
Graduate Fellowship, **University of California, Berkeley**	2012 – 2013
Scholarship, **German Academic Exchange Service** German National scholarship granted in a national competition	2012 – 2013
Scholarship, **e-Fellows** European scholarship for business and academic elite of tomorrow	2011 – 2013

Scholarship, **Max-Weber-Program** 2010 – 2013
German national scholarship awarded in a statewide competition

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Place and Date Ivan Frankovic