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Growth and Welfare under Endogenous Lifetimes*

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Abstract

We study the role of endogenous healthcare choices by households to extend their expected lifetimes on economic growth and welfare in a decentralized overlapping generations economy with annuitized wealth. We characterize endogenous healthcare spending in the decentralized market equilibrium and its effects on economic growth, and we identify the moral-hazard effect in healthcare investments when annuity rates are conditioned on average mortality. In a numerical simulation of our model with OECD data from 2005, we find that the moral-hazard effect can be substantial and implies sizable welfare losses of approximately 1.4–2.8 percent, depending on the share of annuitized retirement wealth.

Keywords: Economic growth; endogenous longevity; healthcare expenditures; healthcare technology; moral hazard

JEL classification: *I*10; *J*10; *O*40

I. Introduction

In recent decades, nearly all countries have experienced a substantial increase in human longevity. At least in the developed world, higher expected lifetimes have been accompanied by a significant increase in healthcare expenditures. For example, life expectancy in the United States rose from 69.8 to 78.6 years between 1960 and 2010, while health

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expenditures, as a share of GDP, surged from 5.2 percent to 16.4 percent (according to OECD data).

How does this increased longevity translate into welfare gains? While the existing literature has approached this question by suggesting extended welfare measures that include longevity, varying exogenous longevity in growth models, and discussing endogenous healthcare choices in macroeconomic social planner models, this paper introduces a new perspective. We develop and analyze an endogenous growth model in which longevity is endogenously determined by households' demand for healthcare services in a decentralized market economy.[1] This perspective allows us to study the general equilibrium effects and macroeconomic repercussions on economic growth – and, consequently, the comprehensive welfare effects – of individual healthcare choices.

As we will show, these individual healthcare choices are not necessarily efficient. We particularly focus on an effect that – while important and most likely involving substantial macroeconomic repercussions – has not yet received much attention in the macroeconomic literature: the moral-hazard effect in healthcare investments arising from annuities. Its importance arises from the fact that nearly all social security systems crucially depend on (mandatory) annuitization, where the annuity premium is not conditional on individual healthcare choices, but only on average mortality rates. As Philipson and Becker (1998, p. 552) have noted, "[p]ublic annuity programs are thus large and growing: in OECD countries they constitute about one-tenth of the gross domestic product, make up more than three-quarters of all social insurance, and have contributed to a quarter of the growth in total public expenditures since 1960." As a consequence, the properties of annuities have recently received considerable attention – for example, Hosseini (2015) focuses on adverse selection, and Reichling and Smetters (2015) consider the role of mortality-related medical costs. While Davies and Kuhn (1992) and Philipson and Becker (1998) provide influential microeconomic (partial equilibrium) analyses of the moral-hazard effect of longevity-increasing healthcare investments, we examine the general equilibrium effects and, in particular, the repercussions on economic growth.

In addition, we use our model to discuss the role of technological progress in healthcare technology for economic growth and welfare. Finally, we simulate our model using OECD data to illustrate the sizes of the growth

[1]There is a substantial body of empirical literature on the relationship between health expenditures and life expectancy that argues that expected lifetime is not given per se but can be influenced by investments in healthcare, such as improving sanitation, buying medication and inoculations, consulting a physician, etc. (Lichtenberg, 2004; Cutler *et al.*, 2006; Hall and Jones, 2007; Caliskan, 2009).

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and welfare effects associated with moral hazard in healthcare spending and how they are affected by technological improvements in the healthcare sector.

From a methodological perspective, our model combines the household side of overlapping generations perpetual youth models in the tradition of Blanchard (1985) with the production side of an endogenous growth model in the style of Romer (1986) amended by a healthcare sector. We first demonstrate the existence of a unique market equilibrium in the steady-state economy and discuss the general equilibrium and growth effects of varying healthcare sector sizes. Then, we characterize and solve the problem of a social planner maximizing the sum of individual lifetime utilities to identify two inefficiencies in the decentralized market equilibrium: the standard learning-by-investing externality (Romer, 1986) and the moral-hazard effect associated with annuities with returns that are conditioned on average mortality.

We then show how the sign and size of the moral-hazard effect in healthcare investments depends on the relative changes in the households' expected consumption paths and expected lifetime wealth. In the steady-state equilibrium, the result ultimately depends on the difference in the growth rate of individual household consumption and the growth rate of the economy as a whole. The difference between the two growth rates originates from the finite lifetimes of the individuals, thereby leading to the corresponding generations turnover term in the growth rate of the economy. We show that if the consumption growth rate of the household is positive and larger than the growth rate of the economy, then individuals over-invest in healthcare in the decentralized market equilibrium with annuities conditioned on average mortality rather than individual health status.

What are the macroeconomic implications of over-investment in healthcare? On the one hand, when households live longer, their propensity to consume out of expected lifetime wealth declines, as saving for old age becomes more valuable. This increases the economy's growth rate. On the other hand, shifting labor from the more capital-intensive consumption good production into the healthcare sector reduces the marginal return on capital. A lower interest rate decreases incentives to save and, as a consequence, implies lower economic growth. We show that the first direct and positive effect of higher longevity on economic growth dominates if the healthcare sector is rather small; however, given a larger health sector, the indirect and negative effect, working through the change in the interest rate, prevails. Accordingly, the households' welfare is affected by over-investments in healthcare, not only by an imbalance between the enjoyment of a longer life and its associated direct healthcare costs, as emphasized in the microeconomic literature, but also by changes to the return on the

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underlying fundamental of the annuities (i.e., the return on capital), as well as the wage rate and the economy's growth rate.

While the theoretical rationale for the importance of examining the general equilibrium effects and macroeconomic implications of moral hazard associated with annuities unconditioned on individual healthcare investment is conclusive, are the implications also quantitatively significant? Simulating our model to OECD data, we argue that most likely they are. We find overall welfare losses due to overspending in healthcare for an average OECD country in 2005 of approximately 1.4–2.8 percent, depending on the share of annuitized retirement wealth. Decomposing the overall welfare effect into its different components, we find that the direct effects due to individual household behavior are rather small while the general equilibrium effects and the effect on the economy's growth rate dominate.

Finally, we investigate the implications of technological improvements in the healthcare sector. We consider two different types of healthcare improvements. The first type decreases baseline mortality, which is independent of individual investments in healthcare. One could think of improvements in the sanitary infrastructure or behavioral changes, such as reduced smoking. The second type increases the marginal productivity of healthcare expenditures. Examples include better medication or therapeutic breakthroughs, such as new diagnostic tools or surgeries.[2] We show that in our model framework both types of health technology improvements increase households' healthcare investments. The resulting increased life expectancy exerts a direct positive effect on the economy's growth rate via a higher incentive to save. However, an associated increase in healthcare spending will have the indirect negative effect of reducing the interest rate. Similar to the growth consequences of overspending in healthcare due to moral hazard with unconditioned annuities, as discussed previously, technological improvements in health increase the growth rate when the healthcare sector is very small, but have negative growth effects when the healthcare sector is sufficiently large. To illustrate the change in the size of the moral-hazard effect from improved technology, we calibrate our model such that it reflects the increase in healthcare investments in the average OECD country between 1980 and 2005. We find that the moral-hazard effect becomes larger if the healthcare technology improves. Thus, our analysis of the macroeconomic repercussions of moral hazard due to unconditioned annuity claims suggests that welfare benefits due to increased longevity might be lower than is often suggested.

[2]Our model emphasizes that increases in healthcare expenditures and longevity are driven primarily by the availability of better healthcare technologies, a view supported, for example, by Newhouse (1992), Cutler *et al*. (2006), Suen (2006), and Fonseca *et al*. (2009).

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The remainder of the paper is organized as follows. In the next section, we relate our paper to the existing literature. In Section III, we introduce the model and provide a detailed discussion of the household's maximization problem with respect to healthcare. In Section IV, we characterize the market equilibrium, derive the dynamics of the aggregate economy, and discuss the role of technological progress in healthcare technology. We identify the inefficiencies in the decentralized market equilibrium in Section V by analyzing the social planner's solution. In addition, we explain in detail the moral-hazard effect in healthcare spending due to annuities when their return is not conditioned on the individual household's health status. Using OECD data, we provide a numerical simulation of our model in Section VI. Finally, we discuss several aspects of our model in relation to the real world in Section VII, and we conclude in Section VIII. The proofs of all propositions are relegated to an Online Appendix.

II. Related Literature

Our main contribution is to develop an endogenous growth model with an endogenous lifetime, in which households determine their healthcare investments in a decentralized market economy. This innovation provides us with the tools to analyze the general equilibrium effects and macroeconomic repercussions of distortions in healthcare investments due to annuitized wealth, as identified in the microeconomics literature. Thus, our paper is related to the following strands of the literature.

In a model that has similarities with our framework, Kuhn and Prettner (2016) examine the channels through which an expanding healthcare sector affects economic growth and welfare. They build on the R&D-based endogenous growth model with horizontal innovation of Prettner (2013) by adding a productive healthcare sector. They find that R&D increases in response to healthcare investments due to a general equilibrium effect that reduces the interest rate and, thus, facilitates financing additional research projects. This positive growth effect can outweigh the negative effect of diverting labor from final goods production when the healthcare sector is small, but for larger health sectors, economic growth will decline in response to higher healthcare investments. In this paper, we find a similar growth reaction to an expanding healthcare sector in a model in which growth is driven by capital accumulation.[3] However, the broader mechanism in our model could be interpreted as resulting from a more

[3]Because of different growth engines, a decrease in the interest rate decreases growth in our model, while it fosters growth in Kuhn and Prettner (2016). The reason is that in our AK-type growth model, physical capital accumulation is the direct driver of growth and more saving

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detailed underlying production side that explicitly includes R&D activities. The main difference between our paper and Kuhn and Prettner (2016) is our endogenous modeling of individual households' healthcare choices that allows us to endogenously determine the size of the healthcare sector and the households' life expectancies. This innovative feature also distinguishes our paper from a large body of other papers considering the growth effects of exogenous variations in longevity, including Kalemli-Ozcan *et al*. (2000), Azomahou *et al*. (2009), de la Croix and Licandro (1999), Boucekkine *et al*. (2002), Echevarría and Iza (2006), and Irmen (2017).[4]

Chakraborty (2004), Chakraborty and Das (2005), Bhattacharya and Qiao (2007), and Leung and Wang (2010) analyze a neoclassical growth model with endogenous longevity, which is determined by either household or government investments in health. While savings and healthcare expenditures compete for the same resources, they are complements in equilibrium. Thus, higher economic development is accompanied by a longer average lifetime. Combining endogenous growth with endogenous longevity, van Zon and Muysken (2001) and Aísa and Pueyo (2006) find non-monotonic relationships between longevity and growth. In these papers, longevity is endogenous but determined via aggregate spending in healthcare by a government or a social planner. In contrast, we develop an endogenous growth model, in which each household's average life expectancy directly depends on the household's investments in healthcare. Jones (2016) develops a growth model with R&D in both the consumption good sector and the healthcare sector, and considers the optimal allocation of investment resources from a planner's perspective in an infinitely lived agent framework, neglecting any externalities. Our paper, by contrast, purposefully includes several realistic features, such as a population structure with overlapping generations and old-age retirement saving in annuities, that reflect the properties of typical social security systems in order to examine their effects on endogenous healthcare choices and economic growth.

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directly induces faster growth. In an R&D-based growth model, as in Kuhn and Prettner (2016), higher savings reduce the interest rate, thereby encouraging more R&D.

[4]More remotely, our paper is also related to the literature on demographic transitions and the literature on the growth effects of epidemics, such as AIDS. The former analyzes the relationship among fertility, mortality, and growth. Longevity is either exogenous (Doepke, 2004; Soares, 2005; Hashimoto and Tabata, 2010; Prettner, 2013), endogenously determined via an externality of aggregate variables, such as average income or human capital (Blackburn and Cipriani, 2002; Kalemli-Ozcan, 2002; Lagerloef, 2003; Cervellati and Sunde, 2005; Hazan and Zoabi, 2006), or endogenously determined by the healthcare investments of the parents (de la Croix and Licandro, 2013). Within the latter, Young (2005) concludes that the AIDS epidemic in South Africa, despite being a humanitarian disaster, has rather positive effects on long-run growth. Bell *et al*. (2006) and Bell and Gersbach (2009) are less optimistic and emphasize that epidemics might lead to poverty traps.

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A central focus of our paper is on the moral-hazard effect in healthcare spending associated with old-age and mortality-contingent claims, such as annuities, that are conditioned on average mortality rather than the individual household's health status. This moral-hazard effect is identified in partial equilibrium frameworks by Davies and Kuhn (1992), Philipson and Becker (1998), Sheshinsky (2008), and Kuhn *et al*. (2015), but we examine how it percolates through the economy. We argue that this is of utmost importance as, on the one hand, healthcare expenditures represent a substantial fraction of GDP, with corresponding implications on the aggregate economy, and, on the other hand, old-age saving is, to a large extent, held in annuities. It is also for these two reasons that Reichling and Smetters (2015) study optimal annuitization with correlated medical costs. As large shares of retirement wealth are held in mandatory annuities, Hosseini (2015) examines the welfare benefits of this obligation by avoiding adverse selection in the annuity market.[5] We emphasize that such mandatory annuities entail another distortion, namely the moral-hazard effect in healthcare spending, which we focus on in our paper, with particular emphasis on its general equilibrium effects and macroeconomic repercussions. While the macroeconomic implications of annuities are studied in Heijdra and Mierau (2012) and Heijdra *et al*. (2014), we shift the focus to the macroeconomic implications of annuities when healthcare spending and longevity are endogenous. Taking the moral-hazard effect of annuities on healthcare spending into account together with several other factors, recently a number of authors have argued that the expansion of social security can explain a large part of the surge in healthcare spending over the last few decades (Zhao, 2014; Zhang *et al*., 2006; Yew and Zhang, 2018). Rather than quantifying the effects of expanded social security on healthcare spending, our focus lies on the effects of healthcare spending on the aggregate economy. While Zhao (2014) considers some general equilibrium effects, as well as effects on aggregate savings of the increase of endogenous healthcare spending in response to the expansion of an annuity based social security system, we also consider effects on economic growth.

Moreover, our paper relates to the literature on the welfare consequences of increased longevity – for example, Becker *et al*. (2005) and Jones and Klenow (2010). As in these papers, we employ the utility of a representative individual to derive a welfare measure that includes human longevity. However, we use a comprehensive general equilibrium framework, which is absent from those models. This allows us to identify further channels through which longevity affects welfare.

[5]Further, Caliendo *et al*. (2014) show that when households make bequests a social security system based on annuities might not be welfare-improving.

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Finally, there is also a body of literature that tries to explain the sources of the large increase in health spending over the last decades, with many papers attributing a dominant role to technological change in the healthcare sector; a good overview can be found in, for example, Chernew and Newhouse (2012). A recent contribution by Hall and Jones (2007) argues that preferences can drive the increase in healthcare spending as well. In contrast to these contributions, our paper focuses on the efficiency of healthcare spending and our general results allow for both types of drivers of increased healthcare expenditures.

III. The Model

The model comprises a continuum of households. As in Blanchard (1985), households born at time $s \in (-\infty, \infty)$ face a hazard rate $p(s)$ of dying that is constant throughout the lifetime of each household. In our model, however, the hazard rate can vary across households from different cohorts, as it is determined by the level of medical treatment that the household receives throughout its lifetime. At any time t, a new cohort is born. We abstract from household fertility decisions and assume that cohort size grows at the constant and exogenously given rate ν.[6] We normalize the cohort size at time $t = 0$ to unity.

There are two production sectors in the economy: the consumption good sector and the healthcare sector. We assume that both sectors operate under perfect competition. In addition, there is a financial sector comprising competitive insurance providers offering annuities. A central aspect of the paper is the discussion of the implications of annuity premia being (un)conditioned on individual households' mortality rates.

Healthcare Sector

We consider a representative firm in the healthcare sector that provides medical treatment by solely employing labor.[7] Without loss of generality, we assume that one unit of labor produces one unit of medical treatment.

[6]The parameter ν can be mapped onto the economy's fertility rate, which specifies the average number of children born by each woman (or by our abstract genderless individual). The fertility rate is independent of the size of the actual population.

[7]According to OECD (2015a), the health sector is (and ever has been) a highly labor-intensive sector. "On average, OECD countries invested around 0.45% of their GDP in 2013 in terms of capital spending in the health sector. This compares with 8.9% of GDP on average across the OECD for current spending on healthcare services and medical goods." (OECD, 2015a, p. 174). There is also a literature that empirically demonstrates that due to the healthcare sector's high labor intensity, costs for healthcare services will increase strongly in response to increases in labor productivity in other sectors, for example, due to technological progress or capital accumulation

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In a competitive healthcare sector, medical treatment will be offered at the marginal cost $w(t)$. At time of birth, households choose a level of medical treatment $h(s)$ that is fixed over their entire lifetime, and which determines the hazard rate of dying $p(s)$ via a healthcare technology $H\big(h(s)\big)$:

$$p(s) = H\big(h(s)\big) \equiv p_{max} - \psi[h(s)]^{\beta}. \quad (1)$$

Without medical treatment ($h = 0$) households face the hazard rate of dying $p(s) = p_{max}$. The hazard rate $p(s)$ decreases with (weakly) diminishing returns in the level of medical treatment $h(s)$, the degree of which is determined by the parameter $\beta \in (0, 1)$.[8] The parameter $\psi < p_{max}$ reflects the productivity of (a given level of) healthcare investments and can be interpreted as the quality level of the health system or the state of the art in medical treatment. It denotes the maximum amount by which a household could reduce its hazard rate against p_{max} by spending all wage income on healthcare. While p_{max} reflects, for example, the sanitary infrastructure of the economy, ψ increases with the human capital of physicians, the efficiency of hospitals, and so forth.[9]

The specification of the healthcare technology (1) implies that improvements in the healthcare technology can come in two qualitatively different ways. First, the maximal hazard rate p_{max} may decrease, implying that all households, independent of their levels of healthcare spending, experience a lower hazard rate of dying. In fact, a decrease in p_{max} offers higher life expectancy for free (at least for the individual household). Historical examples in this respect include new knowledge about germ theory leading to better hygienic standards and a change in personal behavior. We also interpret the introduction of most vaccines and drugs as a decrease in p_{max} because these drugs are usually not very expensive. As an example, consider penicillin, which led to substantial declines in mortality in the last century.[10] Second, the state of the art in medical

(Hartwig, 2008; Bates and Santerre, 2013). This phenomenon is often referred to as Baumol's cost disease. Our model also reflects this feature.

[8]We assume a strictly concave healthcare technology in health investments h, as it implies that the marginal productivity of health spending is infinite at the origin $h = 0$. This helps us to keep the focus of our analysis on interior solutions with $h > 0$, whereas with a linear specification (i.e., $\beta = 1$), we would have to carry a possible corner solution $h = 0$ through the entire analysis. As the corner solution would not add much extra insight, we decided to exclude it to make the exposition and analysis as concise and clear as possible.

[9]An alternative and interesting way of modeling health and longevity would be via the accumulation of health deficits over an individual's lifetime, as in Dalgaard and Strulik (2014). Healthcare investments would then slow down health deficit accumulation and, as a consequence, increase longevity. Our qualitative results would remain under such a modeling approach.

[10]Historically, other factors such as work safety regulations and better nutrition have certainly contributed to lower mortality rates as well, next to progress in medical knowledge.

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treatment ψ may increase, implying that the same amount of healthcare spending leads to a higher life expectancy. However, only households with positive healthcare spending benefit from the improved healthcare technology. Consider improvements such as magnetic resonance imaging, coronary heart bypass grafting, and transplantation.[11]

The way we model the healthcare sector is general enough to encompass different theories about the determinants of survival. First, from a macroeconomic point of view, differentiating between p_{max} and ψ allows us to distinguish between longevity increases due to improvements in public health and improvements of medical treatment, two of the historical main factors in driving improvements in longevity (see, e.g., Cutler *et al.*, 2006). Second, from an individual perspective, the costs of healthcare may include direct healthcare costs, such as paying for medical treatment, but may also include indirect or opportunity costs such as physical exercise and a healthy diet that are time-consuming and often associated with a higher probability of better health.

Consumption Good Production

We consider a representative firm in the consumption good sector that produces a homogeneous consumption good via a Cobb–Douglas production technology $Y(t) \equiv K(t)^{\alpha}\left(A(t)L^F(t)\right)^{1-\alpha}$, where $\alpha \in (0,1)$, and $K(t)$ and $L^F(t)$ denote the aggregate amount of capital and labor employed in consumption good production, respectively. Here, $A(t)$ denotes total factor productivity (TFP) – that is, the technological level of the economy, regarding consumption good production – and is taken as given by the representative firm. Capital depreciates at a constant rate δ. Profit maximization of the representative firm yields factor prices equal to their marginal productivities:

$$r(t) = \alpha \left[\frac{A(t)L^F(t)}{K(t)}\right]^{1-\alpha} - \delta, \tag{2a}$$

$$w(t) = (1-\alpha)A(t)^{1-\alpha}\left[\frac{K(t)}{L^F(t)}\right]^{\alpha}. \tag{2b}$$

We specify total factor productivity $A(t)$ as

[11]Although it makes perfect sense to conceptually distinguish the two different channels of improvements in the healthcare technology, we wish to emphasize that most real-world improvements simultaneously affect p_{max} and ψ. For example, knowledge about germ theory led to better hygienic standards not only in everyday life, thereby decreasing p_{max}, but also in medical treatment, which increased ψ.

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$$A(t) \equiv \frac{K(t)}{N(t)}. \tag{3}$$

Our specification implies a standard “learning-by-doing” or “learning-by-investing” externality similar to Romer (1986), where the factor productivity depends on capital per capita. This specification allows us to avoid a strong scale effect in the economy’s growth rate.[12]

The Financial Sector

The financial sector of the economy comprises a representative, fully competitive insurance firm offering actuarial notes as in Yaari (1965). An actuarial note is a “note that consumers can buy or sell and that stays on the books until the consumer dies, at which time it is automatically cancelled” Yaari (1965, p. 140). A household buying an actuarial note is effectively buying an annuity that pays a return a. With respect to the annuities’ returns, we distinguish two cases.

In the first case, the insurance company can learn, at no cost, the average probability of dying $p(s)$ of each cohort, but will not be able to observe individual households’ healthcare investments. Consequently, annuity payments may depend on the cohort and will hence be written as a function of time t and cohort birth date s: $a(t, s)$.[13] Throughout the paper, we refer to this case as annuity claims that are unconditioned on healthcare expenditures or simply unconditioned annuities.

In the second case, the insurance company can observe healthcare investments and individual households’ resulting hazard rates of dying. This allows the insurance company to condition the annuity rate on the healthcare investments of individual households, and we can write $a(t, h)$, where h reflects the household’s level of healthcare spending. While this scenario is unrealistic, it provides an important benchmark scenario in which moral hazard with respect to healthcare investments is absent.[14] We call this case annuity claims conditioned on healthcare investments or, for short, conditioned annuities.

[12]Romer (1986) assumes that $A(t) \equiv K(t)$. Our specification is similar to that introduced by Frankel (1962).

[13]As we consider large cohort sizes (technically represented by a continuum of households in each cohort), such that insurance companies can offer risk-free annuities, perfect competition among insurance companies will lead to fair annuity payments $a(t, s) = r(t) + p(s)$.

[14]We are aware that there exist so-called “enhanced annuities” that pay a higher rate if the annuitant is overweight or smokes regularly (which is self-certified). However, this conditionality of the return depends on some negative health behaviors and serious conditions but does not account for positive measures to improve health and longevity.

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In our standard model framework, we assume that insurance companies can only observe average cohort mortality rates, while we consider the case of annuity claims conditioned on individual households' healthcare investments in Section V.

The Households' Optimization Problems

Households exhibit identical *ex ante* preferences and face equal hazard rates for the same levels of medical treatment. Households born at time s maximize expected discounted lifetime utility derived from consumption:

$$U(s) \equiv \int_s^\infty V\big(c(t,s)\big) \exp\big[-\big(\rho + p(s)\big)(t-s)\big]\, dt. \tag{4}$$

Here, $V\big(c(t,s)\big)$ denotes the instantaneous utility derived from consumption $c(t,s)$ at time t of the household born at time s, and ρ is the constant rate of time preference. We impose standard curvature properties on the instantaneous utility function ($V' > 0$ and $V'' < 0$), as well as the Inada conditions $\lim_{c\to 0} V'(c) = \infty$ and $\lim_{c\to\infty} V'(c) = 0$. Our definition of lifetime utility (4) normalizes instantaneous utility of being dead to zero. Hence, we additionally assume a utility representation with $V(c) > 0$ for all $c > 0$, which avoids the possibility of households wishing to be dead rather than alive.[15]

At any time alive, households are endowed with one unit of labor each that they supply inelastically to the labor market at wage $w(t)$. In

[15]Rosen (1988) showed that optimal investments in healthcare crucially depend on two characteristics of the instantaneous utility function: (i) the intertemporal elasticity of substitution and (ii) the difference in instantaneous utility between being alive and dead. One way to ensure positive utility levels is to employ an instantaneous utility function with an intertemporal substitution elasticity $\sigma > 1$. This is the modeling choice we make, following the well-known papers by Murphy and Topel (2003) and Becker *et al*. (2005). Note that with this specification of σ, individuals always enjoy being alive as long as consumption is positive. Parts of the literature capture additional utility elements from being alive besides consumption by including a positive constant λ: $V\big(c(t,s)\big) = c(t,s)^{1-(1/\sigma)}/(1-1/\sigma)+\lambda$ (see, e.g., Rosen, 1988; Becker *et al*., 2005). Hall and Jones (2007) show that there is an income effect driving healthcare expenditures when $\sigma < 1$. In this specification, individuals do not enjoy being alive purely from the consumption utility, but all life value essentially originates from λ, which has to be sufficiently large for a positive overall utility of being alive. Higher consumption simply reduces the absolute value of the consumption utility to be subtracted from λ.
Our general utility formulation $V(c(t,s))$ that we use in our model set-up for the derivation of the households' first-order conditions, the general equilibrium definition as well as the solution of the social planner problem can encompass any of the mentioned utility formulations. As we discuss further in Section VII, the economic channels that we identify in how endogenous healthcare choices affect economic growth and welfare as well as the roots of the market inefficiencies will not depend on which of these utility specifications is chosen.

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addition, households can save and borrow assets $b(t,s)$ at the interest rate $r(t)$. Households are born without assets and can contract against the risk of leaving unanticipated bequests on a perfectly competitive life insurance market, as described previously. In line with Philipson and Becker (1998) and Eeckhoudt and Pestieau (2008), among others, we assume that households take $a(t,s)$ as given, and, in Section V, we contrast it with the case in which insurance companies can condition the annuity premia on a household's health status. As negative bequests are prohibited, households hold their entire wealth in fair annuities. Denoting the costs of healthcare by $M\big(h(s)\big)$, the household's budget constraint is

$$\dot{b}(t,s) = a(t,s)b(t,s) + w(t) - c(t,s) - M\big(h(s)\big), \qquad t \geq s, \tag{5}$$

with $b(s,s) = 0$. Inserting $M\big(h(s)\big) = h(s)w(t)$ into the household's budget constraint (5) yields the following:

$$\dot{b}(t,s) = a(t,s)b(t,s) + \big(1 - h(s)\big)w(t) - c(t,s), \qquad t \geq s. \tag{6}$$

Thus, we can interpret the level of medical treatment $h(s)$ as the fraction of labor income that a household spends throughout its entire life on healthcare services. This implies that $h(s) \in [0,1]$, as households are born without assets and must not be indebted when dying.

Households maximize expected intertemporal utility (4) subject to conditions (6) and $b(s,s) = 0$ by choosing an optimal level of medical treatment $h(s)$ and an optimal consumption path $c(t,s)$. As detailed in the Online Appendix, the necessary conditions for the household's optimum are summarized by the standard consumption Euler equation

$$\dot{c}(t,s) = -\frac{V'(c(t,s))}{V''(c(t,s))}[a(t,s) - (\rho + p(s))], \tag{7}$$

and by the necessary condition for optimal healthcare spending

$$\begin{aligned} -\int_s^\infty & V(c(t,s))H'(h(s))(t-s)\exp[-(\rho+p(s)))(t-s)]dt \\ &= \int_s^\infty V'(c(t,s))w(t)\exp[-(\rho+p(s))(t-s)]dt. \end{aligned} \tag{8}$$

These two conditions, together with the budget constraint (6), the initial condition $b(s,s) = 0$ and the transversality condition for the stock of assets $\lim_{t\to\infty} b(t,s)\exp[-a(s)(t-s)] = 0$, characterize the households' optimal choices. The left-hand side of condition (8) represents the additional utility derived from the increment in expected lifetime associated with a marginal increase in healthcare spending. The right-hand side reflects the marginal costs of such a higher expected lifetime, namely less consumption due to higher healthcare expenses. As the instantaneous utility function satisfies the

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Inada conditions, as does the healthcare production function for $h(s) \to 0$, the optimal amount of $h(s)$ will be an interior solution on $(0, 1)$.[16] Note that $h(s) = 1$ cannot be optimal, as this would imply that the household spent its entire labor income on healthcare, leading to zero consumption at all times it is alive. In this case, the marginal costs in terms of consumption would be infinite, while the expected marginal benefit of healthcare expenditures is bounded from above.

IV. Decentralized Market Equilibrium and Dynamics

We now analyze the decentralized market equilibrium. We demonstrate the existence and uniqueness of the decentralized market equilibrium in the steady state and discuss the resulting steady-state dynamics of the economy. Then, we investigate the effects of improvements in the healthcare technology and show results on the effects of an enlarged health sector on the equilibrium prices and the economy's growth rate. These insights will be important for the subsequent discussions on the growth and welfare consequences of moral hazard in health spending.

We begin by introducing household variables per capita derived by integrating over all living individuals and dividing by the population size of the economy:

$$z(t) \equiv \frac{\int_{-\infty}^{t} z(t, s)N(t, s)\, ds}{N(t)}. \tag{9}$$

Here, $z(t)$ and $z(t, s)$ denote per capita and individual household variables, respectively, and $N(t, s) = \exp[\nu s]\exp[-p(s)(t - s)]$ reflects the size at time t of the cohort born at time s. The population size and, hence, the labor supply at time t are given by $N(t) = \int_{-\infty}^{t} N(t, s)ds$.

The economy consists of five markets: the labor market, the capital market, the consumption good market, the market for annuities, and the market for healthcare. Accordingly, an equilibrium in this economy is defined as follows.

Definition 1 (Market equilibrium). *We define a market equilibrium as (i) an allocation* $\{\{c(t, s), b(t, s), h(s)\}_{s=-\infty}^{\infty}, K(t), L^F(t), L^H(t)\}_{t=-\infty}^{\infty}$ *and (ii) prices* $\{p_c(t)=1, w(t), r(t), \{a(t, s)\}_{s=-\infty}^{\infty}\}_{t=-\infty}^{\infty}$, *such that profits of the firms (consumption good, healthcare, annuity) and utilities of the households are maximized and all markets clear at any time* t:

[16] If the healthcare production function had a finite slope at $h = 0$, the corner solution $h = 0$ might occur.

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capital market,

$$K(t) = \int_{-\infty}^{t} b(t,s)N(t,s)ds; \tag{10a}$$

labor market,

$$L^F(t) + L^H(t) = N(t); \tag{10b}$$

healthcare market,

$$\int_{-\infty}^{t} h(s)N(t,s)ds = L^H(t); \tag{10c}$$

annuity market,

$$\int_{-\infty}^{t} (a(t,s) - r(t))b(t,s)N(t,s)ds = -\int_{-\infty}^{t} b(t,s)\dot{N}(t,s)ds; \tag{10d}$$

consumption good market,

$$\int_{-\infty}^{t} [c(t,s) + \dot{b}(t,s)]N(t,s)ds = Y(t). \tag{10e}$$

The left-hand side of each of the market clearing conditions reflects demand, while the right-hand side represents the supply of the respective good. Our focus will be on the economy's steady state. We refer to a steady state of the economy by the standard definition.

Definition 2 (Steady state). *The economy is in a steady state if consumption per capita, capital per capita, and wages grow at constant rates and the interest rate is constant.*

In our equilibrium analysis of the decentralized economy, we use the following functional form for the individuals' instantaneous utilities:

$$V\big(c(t,s)\big) \equiv \frac{c(t,s)^{1-(1/\sigma)}}{1-(1/\sigma)}, \quad \sigma > 1, \tag{11}$$

which allows for a balanced-growth path, as the following proposition states.

Proposition 1 (Unique steady-state equilibrium). *There exists a unique steady-state equilibrium in which*

(a) *all households choose the same level of healthcare $\bar{h}$, implying mortality rate $\bar{p} = H(\bar{h})$,*

(b) *the interest rate is given by $\bar{r}(\bar{h}) = \alpha \left[1 - \bar{h}\right]^{1-\alpha} - \delta$,*

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(c) *the wage rate is given by* $\bar{w}(\bar{h}, t) = k(t)(1-\alpha)\left[1-\bar{h}\right]^{-\alpha}$*, and*

(d) *the insurance premium is given by* $\bar{p}$*, that is,* $\bar{a}(\bar{h}, \bar{p}) = \bar{r}(\bar{h}) + \bar{p}$.

The unique optimal interior level of healthcare expenditures in the steady-state equilibrium $\bar{h}$ *is implicitly given by*

$$\frac{\sigma}{1-\sigma}\frac{H'(\bar{h})}{x(\bar{h}, \bar{p})} - \frac{1}{(1-\bar{h})} = 0, \tag{12}$$

with $x(\bar{h}, \bar{p}) \equiv (1-\sigma)\bar{a}(\bar{h}, \bar{p}) + \sigma(\rho + \bar{p})$.

The crucial step in the proof (given in the Online Appendix) is to derive the households' optimal healthcare expenditures, provided that the economy is in steady state, and then to show that these healthcare expenditures lead to the presumed steady state. Uniqueness follows from the uniqueness of the prices and allocation for a given level of healthcare expenditures and the fact that, given a constant interest rate and constantly growing wage rate, the households' healthcare investments are unique.

In the proposition and throughout the paper, we indicate steady-state values by a bar. Moreover, we give both h and p as arguments if appropriate rather than just h, as this allows us to separate the effects of h via longevity p from other channels. It enables us to identify and clearly illustrate the different ways that healthcare investments affect the economy. In equation (12), we use the abbreviation $x(\bar{h}, \bar{p}) \equiv (1-\sigma)\bar{a}(\bar{h}, \bar{p}) + \sigma(\rho + \bar{p}) = \bar{r}(\bar{h}) + \bar{p} - \sigma(\bar{r}(\bar{h}) - \rho) > 0$,[17] which represents the household's propensity to consume out of expected lifetime wealth. Using the utility specification (11), the Euler equation (7) identifies the equilibrium growth rate of the household's consumption profile in steady state as $g_{hh}(\bar{h}) \equiv \sigma(\bar{r}(\bar{h}) - \rho)$. Consequently, the second way of writing $x(\bar{h}, \bar{p})$ shows that the propensity to consume $x(\bar{h}, \bar{p})$ reflects the difference between the return on annuities $\bar{r}(\bar{h}) + \bar{p}$ and the growth rate of the household's consumption $g_{hh}(\bar{h})$.

Note that $\dot{N}(t, s) = -p(s)N(t, s)$, and consequently we obtain from (10d) the actuarially fair premium $a(t, s) = r(t) + p(s)$. Focusing on the steady state, in which the equilibrium interest rate is constant, we can neglect the time argument and write $\bar{a}(\bar{h}, \bar{p})$. Moreover, as households are free to choose between working in the healthcare sector and working in consumption good production, each household must earn the same equilibrium wage $w(t)$, as given by equation (2b). Given the consumption good firm's capital demand, as given by (2a), the allocation and prices are determined via the households' supply of capital and demand for healthcare services.

[17] Note that $x(\bar{h}, \bar{p}) > 0$ is necessary for the household's maximization problem to be well defined.

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Equilibrium Dynamics

The following proposition characterizes the resulting steady-state dynamics of the economy.

Proposition 2 (Steady-state dynamics). *The dynamics of the aggregate economy in the steady-state equilibrium is:*

(a) *characterized by*

$$\dot{c}(t) = \sigma\left[\bar{r}(h) - \rho\right] c(t) - x(\bar{h}, \bar{p})(\bar{p} + \nu)k(t), \tag{13a}$$

$$\dot{k}(t) = \left[\frac{\bar{r}(\bar{h})}{\alpha} + \frac{1-\alpha}{\alpha}\delta - \nu\right] k(t) - c(t); \tag{13b}$$

(b) *governed by a unique balanced-growth path with the following growth rate*

$$\bar{g}(\bar{h}, \bar{p}) = \frac{1}{2}\left\{\frac{\bar{r}(\bar{h})}{\alpha} + \frac{1-\alpha}{\alpha}\delta - \nu + \sigma\left[\bar{r}(\bar{h}) - \rho\right]\right\} - \frac{1}{2}\sqrt{\left\{\frac{\bar{r}(\bar{h})}{\alpha} + \frac{1-\alpha}{\alpha}\delta - \nu - \sigma\left[\bar{r}(\bar{h}) - \rho\right]\right\}^2 + 4x(\bar{h}, \bar{p})(\bar{p} + \nu)}. \tag{14}$$

Besides providing a precise description of the economy's balanced-growth path, Proposition 2 conveys two important insights. First, as on the balanced-growth path $\dot{c}(t)/c(t) = \dot{k}(t)/k(t) = \bar{g}(\bar{h}, \bar{p})$, the first equation, showing the evolution of consumption per capita, reveals that the growth rate of the household's consumption profile must be higher than the economy's growth rate on the balanced-growth path. This is evident, as the first term of equation (13a) reflects g_{hh}, from which a second positive term is subtracted. This latter term, which is the difference in consumption levels at any time t between the households just born and the households just dying, reflects the underlying overlapping generations structure of the economy. Second, the economy's growth rate on the balanced-growth path is affected by the size of healthcare investments via two different channels: life expectancy $\bar{p}$ and the equilibrium interest rate $\bar{r}(\bar{h})$. In the following subsection, we examine how these two channels of changes in the size of the healthcare sector influence equilibrium prices and the economy's growth rate.

Equilibrium and Growth Effects of the Size of the Health Sector

The discussion in this subsection will provide the basis for the following main results on the growth and welfare effects of endogenous health

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spending choices by households. Before considering the effects of the size of the healthcare sector on the economy, we first consider the healthcare technology as one central reason of why different countries have different levels of healthcare spending.

Recall that the healthcare technology (1) exhibits two parameters that influence the hazard rate p of households. A decline in the parameter p_{max} reduces the hazard rate that households face without investments in healthcare. An increase in the parameter ψ increases the reduction of the hazard rate that is purchased for any given healthcare investment h. As stated in the following proposition, an improvement in the healthcare technology, either via a decrease in p_{max} or an increase in ψ, leads to higher equilibrium healthcare investments, independent of whether annuity rates are conditioned on healthcare expenditures.

Proposition 3 (Role of the healthcare technology for longevity). *The following conditions hold in the steady-state market equilibrium:*

$$\frac{d\bar{h}}{dp_{max}} < 0, \quad \frac{d\bar{p}}{dp_{max}} > 0, \quad \frac{d\bar{h}}{d\psi} > 0, \quad \frac{d\bar{p}}{d\psi} < 0.$$

A better healthcare technology affects the equilibrium hazard rate of dying $\bar{p}$ in two ways. First, there is a direct effect. *Ceteris paribus*, a decrease in p_{max} or an increase in ψ lowers the hazard rate $\bar{p}$. Second, an improvement in the healthcare technology induces higher healthcare expenditures. This is also the case for a decrease in p_{max}, although p_{max} enters p in an additively separable way. The reason is that the marginal effect of a decrease in p is proportional to the discount factor $\exp[-p(t-s)]$. As a consequence, any decrease in p – for whatever reason – will trigger higher healthcare expenditures.[18] Note that, in our model, the direct effect of a marginal decrease in p_{max}, reflected by the partial derivative $\partial p/\partial p_{max}$, is equal to one. A marginal increase in the productivity of healthcare spending ψ implies a direct effect of h^{β}. Because $h^{\beta} < 1$, the increase in expected lifetime that comes for "free" is larger when p_{max} marginally declines compared to a marginal increase in ψ. As a consequence, if a marginal decrease in p_{max} and a marginal increase in ψ lead to the same reduction in the hazard rate of dying, the decline via the increase in the productivity of health spending ψ is accompanied by higher healthcare expenditures.

The following proposition states how a marginal increase in healthcare expenditures affects the steady-state equilibrium and balanced-growth path of the economy.

[18]This is a standard feature of life-cycle models (see, e.g., Murphy and Topel, 2006).

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Proposition 4 (Equilibrium and growth effects of healthcare investments).
(a) *An increase in steady-state healthcare investments* $\bar{h}$ *increases the equilibrium wage rate and decreases the equilibrium interest rate:*

$$\frac{d\,\bar{w}(\bar{h},t)}{d\,\bar{h}} > 0 \ \ and \ \ \frac{d\,\bar{r}(\bar{h})}{d\,\bar{h}} < 0.$$

(b) *If* $\alpha < 1/\sigma$, *the growth rate of the economy increases with the interest rate, while the difference between the growth rate of the households' consumption profiles and the economy's growth rate decreases with the interest rate:*

$$\frac{d\,\bar{g}(\bar{h},\bar{p})}{d\,\bar{r}(\bar{h})} > 0 \ \ and \ \ \frac{d\left(g_{hh}(\bar{h}) - \bar{g}(\bar{h},\bar{p})\right)}{d\,\bar{r}(\bar{h})} < 0.$$

(c) *If* $\alpha < 1/\sigma$, *the direct effect of a larger healthcare sector on the economy's growth rate is positive (via increased longevity), while the general equilibrium effect via the interest rate is negative:*

$$\frac{d\,\bar{g}(\bar{h},\bar{p})}{d\,\bar{h}} = \underbrace{\frac{\partial \bar{g}(\bar{h},\bar{p})}{\partial \bar{p}}\frac{d\,\bar{p}}{d\,\bar{h}}}_{>0 \text{ dir. effect}} + \underbrace{\frac{\partial \bar{g}(\bar{h},\bar{p})}{\partial \bar{r}(\bar{h})}\frac{d\,\bar{r}(\bar{h})}{d\,\bar{h}}}_{<0 \text{ indir. effect}}$$

An increase in healthcare investments increases the growth rate if the healthcare sector is sufficiently small and decreases the growth rate if the healthcare sector is sufficiently large.

A rise in healthcare expenditures re-assigns labor from consumption good production to the healthcare sector. This contraction of labor supply in manufacturing increases the equilibrium wage rate. In turn, the marginal productivity of capital declines, as labor is shifted away from the more capital-intensive sector.

In Proposition 4(b), we examine what such a change in the interest rate implies for economic growth. In line with economic intuition, we find that an increase in the interest rate positively affects economic growth by increasing households' savings. Consequently, a lower interest rate due to higher healthcare expenditures implies a negative effect on economic growth. Moreover, the growth rate of the household's consumption profile is positively related to the interest rate. Hence, both the consumption growth rate of the households and the economy's growth rate decline in response to an expansion of the healthcare sector, and we find that the difference between the two growth rates widens as a result. That is, the economy's growth rate has a steeper slope in r than does the household's consumption growth rate. The qualifier $\alpha < 1/\sigma$ constitutes a sufficient but not necessary

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condition for the result to hold. In our case, the intertemporal elasticity of substitution σ ranges between one and two, which implies an upper bound on the capital share in consumption good production α between $1/2$ and one. Typical values for α are in the range of $1/3$ to $1/2$ and, therefore, do not challenge the condition.

Last but not least, Proposition 4(c) describes the growth effects of a larger healthcare sector, which operate via two channels: (i) longevity and (ii) the equilibrium effects due to changes in the interest rate. With respect to the former channel, we find that the propensity to consume declines when households expect to live longer. This implies an increase in savings and, thereby, exerts a positive effect on the economy's growth rate. This channel is represented by the term $x(\bar{h}, \bar{p})(\bar{p}+\nu)$ (see Online Appendix A6), which is sometimes referred to in the literature as the "generations turnover" term. The second channel via the interest rate has already been discussed in Proposition 4(a) and (b).

The relative sizes of these two effects with opposite signs drive the last result stated in Proposition 4. When the healthcare sector is small, the increase in longevity from a marginal increase in healthcare spending is very high according to our specification of the healthcare production function, but the effect on the interest rate is rather small and bounded from above. Due to diminishing returns in health production, the direct effect of longevity and growth decreases when health investments are already substantial. However, shifting additional labor from manufacturing to healthcare implies huge costs in terms of capital productivity when only few households are employed in consumption good production.

Finally, we return to considering the effect of health technologies on growth and welfare. By increasing longevity for given healthcare investments $\bar{h}$, technological improvements in the healthcare sector increase the economy's growth rate. As better technology in the healthcare sector also increases health spending, it further involves the equilibrium and growth effects of an expansion of the healthcare sector, as discussed in Proposition 4. Therefore, relative to the results provided in Proposition 4, technological improvements in healthcare exert an additional positive, but limited in size, effect on longevity in addition to that operating through an increase in healthcare investments. Consequently, when the healthcare sector is small, technological improvements in the healthcare sector positively affect economic growth. However, the negative effects on economic growth stemming from a declining marginal productivity of capital, as labor is re-assigned to the healthcare sector, will dominate when the healthcare sector is sufficiently large. Thus, technological improvements in healthcare increase economic growth when the healthcare sector is small and decrease

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growth when the healthcare sector is large.[19] From this discussion we can further infer that there is a maximum long-run growth rate that can be achieved with the right healthcare technologies. Such growth maximizing healthcare technologies can be characterized as those sets (p_{max}, ψ, β) that lead to the growth maximizing healthcare investments.[20]

V. Inefficiency of the Market Equilibrium

Thus far, we have characterized the decentralized, steady-state market equilibrium and identified how increasing healthcare expenditures affect the equilibrium prices and the steady-state dynamics of the economy. Yet, a central innovation in our model is that healthcare investments are endogenously determined by the households' choices on healthcare expenditures. In the following, we analyze whether these household choices are efficient and discuss the general equilibrium and macroeconomic consequences of such inefficiencies.

The Social Planner's Solution

To identify potential market failures associated with the households' choice of healthcare expenditures, we compare the decentralized equilibrium allocation to the allocation that a social planner maximizing utilitarian welfare would choose.[21] Welfare is defined as the weighted sum of the utilities of all households alive from time $t = 0$ to infinity. The social planner's weight on the lifetime utilities of different cohorts is equal to the time preference rates of the households. This implies that the lifetime utility of a household born at time s will be discounted to time 0 with the time preference rate $\rho^s = \rho$.[22]

[19]It would also be interesting to know how the size of the moral-hazard effect is affected by improvements in the healthcare technology. However, from a theoretical perspective, the effect is ambiguous, and thus, the answer to this question depends on the values of the exogenous parameters of the model. We will, however, examine the change in the size of the moral-hazard effect in our numerical simulations in Section VI.
[20]We note however that the healthcare investments leading to maximal growth may not be unique.
[21]As our focus is on moral hazard originating from unconditioned annuities, we could simply identify their effect at the macro level by including annuities conditioned on individual household mortality in the decentralized equilibrium. While not trivial, we nevertheless solve the social planner's problem to be transparent with respect to all market inefficiencies and potential interactions of other inefficiencies with the moral-hazard effect.
[22]For a discussion of the effects of the relationship between individual time preference rates and that of the social planner on the allocation of consumption across different age cohorts see, for example, Schneider *et al*. (2012).

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Then, the planner's problem is given by

$$\max_{\{\{c(t,s)\}_{t=0}^{\infty},h(s)\}_{s=0}^{\infty}} \int_0^{\infty} \mathcal{V}(t)dt,$$

where

$$\begin{aligned}
\mathcal{V}(t) &= \int_{-\infty}^{t} V(c(t,s)) \exp[-(\rho + p(s))(t-s)] \exp[\nu s] \exp[-\rho^s s] ds, \\
\text{s.t. } p(s) &= H(h(s)), \\
N(t) &= \int_{-\infty}^{t} \exp[\nu s - p(s)(t-s)] ds, \\
L^H(t) &= \int_{-\infty}^{t} h(s) \exp[\nu s - p(s)(t-s)] ds, \\
L^F(t) &= N(t) - L^H(t), \\
C(t) &= \int_{-\infty}^{t} c(t,s) \exp[\nu s - p(s)(t-s)] ds, \\
\dot{K}(t) &= F(K(t), L^F(t), L^H(t)) - \delta K(t) - C(t),
\end{aligned}$$

and initial conditions specifying $\{h(s)\}_{-\infty}^{s=0}$ and $K(0)$ and $N(0)$. Here, $\mathcal{V}(t)$ represents aggregate welfare at time t (i.e., the sum of instantaneous utilities of all households alive at time t). Despite assuming $\rho^s = \rho$, we include the planner's time preference rate ρ^s in the welfare specification for clarity of expression. The first constraint represents the healthcare technology, while the second reflects the economy's population size at time t by summing up the still living individuals of all cohorts born at the different birth dates $s \leq t$. For reasons of comparability with the decentralized solution, the planner determines one unique level of healthcare $h(s)$ for the households in the cohort born at time s that is fixed throughout their lifetimes. Consequently, the demand for healthcare at time t, $L^H(t)$, sums the individual healthcare demands of all households alive at time t. The remaining share of the population works in the consumption good sector. The last two constraints specify aggregate consumption and the equation of motion of the aggregate capital stock.

To solve the planner's problem, we apply a two-step procedure. First, we solve the "inner problem", in which the social planner allocates a given amount of consumption across all generations alive in a period t. Our assumption $\rho^s = \rho$ implies that it is optimal for the social planner to distribute consumption equally such that every household enjoys consumption $c(t,s) = \hat{c}(t) = C(t)/N(t), \forall s$. Second, by inserting this into the objective function, we obtain the "outer problem" of finding the optimal path $C(t)$ and $h(t)$. We solve this outer problem by setting up the Lagrangian

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and interchanging the order of integration of the constraints such that we are able to use the calculus of variations to derive necessary conditions for an optimum. The detailed solution to the planner's problem is provided in the Online Appendix. For the necessary conditions for a welfare maximum, we obtain the familiar expressions for the optimal path of consumption and capital:

$$\dot{\hat{c}}(t) = -\frac{V'(\hat{c}(t))}{V''(\hat{c}(t))}\left(\frac{\partial F(K(t), L^H(t), L^F(t))}{\partial K(t)} - \delta - \rho\right), \tag{15}$$

$$\dot{k}(t) = F(k(t), l^H(t), l^F(t)) - \delta k(t) - \frac{\dot{N}(t)}{N(t)}k(t) - \hat{c}(t). \tag{16}$$

Here, $l^F(t) = L^F(t)/N(t)$ and $l^H(t)$ denote the shares of labor in manufacturing and healthcare, respectively. The main novelty of our approach lies in the characterization of the optimal levels of healthcare. We obtain the following necessary condition that the level of healthcare of any generation born at time $s \geq 0$ satisfies in the social planner's optimum:

$$\begin{aligned}
&-\int_s^\infty V(\hat{c}(t))H'(h(s))(t-s)\exp[-(\rho+p(s))(t-s)]dt \\
&\quad -\int_s^\infty w^H(t)V'(\hat{c}(t))\exp[-(\rho+p(s))(t-s)]dt \\
&= -\int_s^\infty V'(\hat{c}(t))\hat{c}(t)H'(h(s))(t-s)\exp[-(\rho+p(s))(t-s)]dt \\
&\quad -\int_s^\infty w(t)V'(\hat{c}(t))h(s)H'(h(s))(t-s)\exp[-(\rho+p(s))(t-s)]dt \\
&\quad +\int_s^\infty w(t)V'(\hat{c}(t))H'(h(s))(t-s)\exp[-(\rho+p(s))(t-s)]dt.
\end{aligned} \tag{17}$$

We denote by $w(t)$ the marginal product of labor in the consumption good sector, which reflects the wage rate in the decentralized market equilibrium. In addition to the planner's uniform distribution of consumption, conditions (15)–(17) reveal three differences from their counterparts in the decentralized market economy, which we discuss in the following.

Externalities in the Market Equilibrium

Comparing the social planner's solution with the decentralized market equilibrium, as defined in Definition 1, we identify two market failures: the learning-by-investing externality (Romer, 1986) and moral hazard in healthcare investments.

We identify the standard learning-by-investing externality by comparing the consumption Euler equation of the social planner (15) with the household's (7) in equilibrium, where $a(t, s) = r(t) + p(s)$, according

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to equilibrium condition (10d). Consequently, the difference in the consumption path of the households in the decentralized equilibrium relative to that in the social planner's optimum originates from the difference in the return on capital. The social rate of return

$$\frac{\partial F(K(t), L^H(t), L^F(t))}{\partial K(t)} - \delta = \left[\frac{A(t)L^F(t)}{K(t)}\right]^{1-\alpha} - \delta$$

is larger than the private return $r(t) = \alpha(A(t)L^F(t)/K(t))^{1-\alpha} - \delta$ because firms take the technological level $A(t)$ of the economy as given, neglecting the positive spillovers that the employment of capital exerts on the economy's manufacturing output $Y(t)$ via an increase in the technological level.[23] As is well known, this leads to an inefficiently low level of asset holdings that could be corrected, for example, by subsidizing household savings.

The other inefficiency is associated with healthcare expenditures. The two expressions on the left-hand side of equation (17) are familiar from the household's first-order condition (8). They reflect the additional utility obtained directly from a higher expected lifetime and the direct healthcare costs arising from higher labor input in the healthcare sector at the expense of labor in consumption good production. Comparing the social planner's optimality condition (17) and the household's first-order condition (8), we notice one important difference: The terms on the right-hand side of the social planner's optimality condition with respect to healthcare investments (17) do not appear in the corresponding first-order condition (8) of the household in the decentralized economy. This represents the moral-hazard effect with respect to healthcare spending, as households take annuity rates as given. This effect comprises three parts, as indicated by the three integrals on the right-hand side of equation (17). The first term represents the utility loss from lower consumption at each point in time, as consumption has to be spread out over a longer expected lifetime. The second term captures the additional costs of healthcare that accrue during the expected additional lifetime of the individual. Third, the additional expected lifetime also allows an individual to earn additional

[23]Note that $\hat{c}(t)$ in the planner's solution reflects each household's consumption level at time t and, thus, also the level of consumption per capita. The two consumption levels would differ if the planner's intra-generational distribution of consumption were not uniform, as is the case in the decentralized economy, where the disparity between $c(t, s)$ and $c(t)$ reflects the difference between the high consumption levels of those dying at t and the low consumption levels of those born at t. As $\hat{c}(t)$ reflects consumption per capita, the law of motion of the per capita capital stock in the social planner's solution (16) is equivalent to that in the decentralized equilibrium, which can be derived by applying equation (9) to equation (5) while considering equilibrium condition (10a).

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labor income, thereby increasing total labor wealth. Consequently, the sign of the moral-hazard effect depends on the relative sizes of the marginal losses due to lower consumption and increased healthcare expenditures and the marginal benefits from higher labor wealth. Although the sign of the moral-hazard effect is generally ambiguous, the moral-hazard effect leads to over-investments in healthcare in the steady-state equilibrium, as we show below.

While we believe that, in reality, the spillover effects of capital investment on the economy's productivity in manufacturing are present and important in decentralized market economies, our focus in this paper is on the inefficiency resulting from moral hazard in healthcare spending when annuity rates are not conditioned on individual mortality rates, as in typical social security systems in most developed countries. Therefore, we now contrast the outcome of the decentralized equilibrium without conditioned annuities with its hypothetical counterpart when annuities conditioned on health status can be supplied by the insurance firm and, thus, no moral-hazard effect arises.

Market Equilibrium without Moral Hazard

We now assume that insurance companies can observe and condition annuity rates $a(t, h)$ on the individual household's healthcare investment. As a consequence, a household increasing its healthcare investments will face a lower annuity rate. As all households of the same cohort s face the identical optimization problem, all households of a given cohort s will choose the same level of healthcare investments $h(s)$. Thus, we can still represent the cohort born at time s by a representative household. To minimize notation, we again write the annuity rate as a function of s, $a(t, s)$, with the difference being that now $\partial a(t, s)/\partial h(s)$ is no longer zero but negative. Given fair annuity rates, as will arise in the market equilibrium with perfect competition, $\partial a(t, s)/\partial h(s)$ will amount to the marginal productivity of the healthcare technology $H'(h(s))$.

For the representative household's optimization problem, this implies that a marginal increase in healthcare investments affects the budget constraint not only via the direct costs but also via changes in the annuity rate. The household's forward budget constraint (see Online Appendix A1) reveals that the household's lifetime consumption stream must be financed by the expected lifetime labor income:

$$b(s, s) = \int_s^\infty [c(t, s) - (1 - h(s))w(t)] \exp\left[-\int_s^t a(t', s)dt'\right] dt. \tag{18}$$

A decline in the annuity rate $a(t, s)$ due to a reduction of $p(s)$ will increase the expected net present value of both the consumption stream

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to be financed and the wealth from lifetime labor income. This reflects the additional consumption needed for the additional expected lifetime and the extra labor income from a longer expected work life, resembling the respective expressions in the social planner's solution. Whether a decline in $a(t, s)$ places additional pressure on the budget constraint or relaxes it depends on the trajectories of consumption and wage rates over time t and, hence, on their initial values at birth date s and their growth rates over time t. Consequently, the sign of the effect depends on the equilibrium dynamics of the economy, which, as shown in Proposition 4, are also influenced by aggregate health expenditures.

To determine the sign and size of the moral-hazard effect, we begin by deriving the household's necessary conditions for a utility maximum. While the optimality conditions with respect to savings and consumption take the same form as presented in Section III, the first-order condition with respect to healthcare (8) becomes

$$
\begin{aligned}
&-\int_s^\infty V(c(t,s))H'(h(s))(t-s)\exp[-(\rho+p(s)))(t-s)]dt \\
&\qquad -\int_s^\infty V'(c(t,s))w(t)\exp[-(\rho+p(s))(t-s)]dt \\
&= \quad -\int_s^\infty V'(c(t,s))\,c(t,s)\frac{\partial a(t,s)}{\partial h(s)}(t-s)\exp[-(\rho+p(s))(t-s)]dt \\
&\qquad +\int_s^\infty V'(c(t,s))(1-h(s))w(t)\frac{\partial a(t,s)}{\partial h(s)}(t-s)\exp[-(\rho+p(s))(t-s)]dt.
\end{aligned} \tag{19}
$$

The left-hand side of equation (19) is identical to the first-order condition when households take the annuity rate as given. The right-hand side of equation (19) presents the additional terms reflecting the consequences of health investments that reduce the annuity rate. It reflects the influence on the household's budget constraint, as discussed above, evaluated in terms of marginal utility. As noted above, given fair annuity rates $a(t, s) = r(t) + p(s)$ we obtain $\partial a(t, s)/\partial h(s) = H'(h(s))$, thereby resembling the right-hand side of the social planner's optimality condition for healthcare investments (17). As already conjectured, the expression on the right-hand side of equation (19) reveals that the sign of the first term is positive, while the sign of the second term is negative. Consequently, the effect of conditioned annuity contracts on healthcare investments is, in general, ambiguous. Relative to the solution in which annuity rates are taken as given, an individual will spend more (less) on healthcare if the additional labor income wealth exceeds (is smaller than) the additional consumption requirements.

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We define the market equilibrium analogously to Definition 1, with the sole difference being that the insurance firm can now verify healthcare investments at the individual household level. Again, perfect competition in the financial sector ensures fair annuity rates.[24] In the following proposition, we show that when the households' utilities take the form as in equation (11), there exists a steady-state equilibrium with conditioned annuity contracts that is unique under a plausible condition.

Proposition 5 (Steady-state equilibrium without moral hazard). *Suppose that annuity rates can be conditioned on individual healthcare investments. Then, there exists a steady-state market equilibrium in which all prices are characterized as in Proposition 1(b)–(d), and all households invest the same amount in healthcare. The interior level of healthcare expenditures in the steady-state equilibrium $\bar{h}$ is implicitly given by the equation*

$$\frac{\sigma}{1-\sigma}\frac{H'(\bar{h})}{x(\bar{h},\bar{p})} - \frac{1}{(1-\bar{h})} = -H'(\bar{h})\left(\frac{1}{x(\bar{h},\bar{p})} - \frac{1}{y(\bar{h},\bar{p})}\right). \tag{20}$$

The equilibrium is unique if

$$\frac{d[x(\bar{h},\bar{p})/y(\bar{h},\bar{p})]}{d\bar{h}} < 0.$$

We employ the abbreviation $y(\bar{h},\bar{p}) = \bar{r}(\bar{h}) + \bar{p} - \bar{g}(\bar{h},\bar{p})$ to denote the difference between the equilibrium annuity rate $\bar{a}(\bar{h},\bar{p}) = \bar{r}(\bar{h}) + \bar{p}$ and the economy's steady-state growth rate. The condition for uniqueness of the steady-state equilibrium given in the proposition is a sufficient but not a necessary condition. More generally, the steady-state equilibrium is unique if the increase in the relationship between the households' propensity to consume out of wealth and the difference between the annuity rate and the economy's growth rate with respect to $\bar{h}$ is sufficiently small. In the following, we assume a unique equilibrium.[25]

The right-hand side of equation (20) collects the additional terms entering the first-order condition due to conditioned annuity claims and, thus, is the steady-state equivalent of the right-hand side of equation (19). In fact, computing the integrals using steady-state values, the right-hand side of equation (19) yields

[24] Fair annuity rates result from perfect competition, as a lower than fair annuity rate leading to profits for an insurance firm can profitably be overbid by competitors. Offering higher than fair rates for some levels of healthcare spending means cross-subsidization is necessary from households with other healthcare levels. Cross-subsidization will not be possible, as other firms can profitably overbid the excessively low annuity rate at a particular healthcare spending level.

[25] We obtain unique equilibria throughout our numerical illustration (see Section VI and Online Appendix A9).

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$$-c(s, \bar{h}, \bar{p})^{-1/\sigma} H'(\bar{h}) \left[\frac{c(s, \bar{h}, \bar{p})}{[x(\bar{h}, \bar{p})]^2} - \frac{(1 - \bar{h}) w(s, \bar{h})}{[y(\bar{h}, \bar{p})]^2} \right], \tag{21}$$

where $c(s, \bar{h}, \bar{p})^{-1/\sigma}$ is the marginal utility of consumption at birthdate s and $-H'(\bar{h})$ denotes the increase in longevity and, simultaneously, the reduction in the annuity rate for a marginal increase in healthcare expenditures. The term in brackets is the difference between the additional consumption needed for the additional lifetime and the additional wealth in terms of labor income net of extra healthcare costs. Thus, the term in brackets echoes the increased pressure (or release of pressure) on the budget constraint (18) from a marginal increase in longevity increasing healthcare investments. The sign and size of this effect are determined by the difference between $x(\bar{h}, \bar{p})$ and $y(\bar{h}, \bar{p})$, which reflects the difference between the growth rate of the household's consumption profile $g_{hh}(\bar{h}) = \sigma(\bar{r}(\bar{h}) - \rho)$ and the growth rate of the economy in steady state $\bar{g}(\bar{h}, \bar{p})$, as well as by the relationship between the level of initial consumption by the household $c(s, \bar{h}, \bar{p})$ and the level of net labor income at date s $(1 - \bar{h})w(s, \bar{h})$. In addition to $x(\bar{h}, \bar{p})$ and $y(\bar{h}, \bar{p})$, the equilibrium level of initial consumption $c(s, \bar{h}, \bar{p})$ is also affected by the equilibrium interest rate and the economy's growth rate, as it depends on the household's net present lifetime wealth. As a consequence, both the size and sign of the moral-hazard effect in general equilibrium are *ex ante* ambiguous.

The solution to the household's utility maximization problem provides a link between the initial wage rate and initial consumption $c(s, \bar{h}, \bar{p})$. In steady state, we obtain $c(s, \bar{h}, \bar{p}) = (1 - \bar{h})W(s, \bar{h}, \bar{p})x(\bar{h}, \bar{p})$, where $W(s, \bar{h}, \bar{p}) = w(s, \bar{h})/y(\bar{h}, \bar{p})$ denotes the net present value of the household's lifetime labor income. Inserting into equation (21) yields, after some transformations, the right-hand side in the household's first-order condition (20) in the steady-state equilibrium. This indicates that the sign of the moral-hazard effect is determined by the relationship between the growth rate of the household's consumption profile, which is part of $x(\bar{h}, \bar{p})$, and the growth rate of the economy, as in $y(\bar{h}, \bar{p})$. As we have shown, $g_{hh}(\bar{h}) > \bar{g}(\bar{h}, \bar{p})$ and, consequently, $y(\bar{h}, \bar{p}) > x(\bar{h}, \bar{p})$, implying that the right-hand side of equation (20) is positive. Therefore, in the steady-state market equilibrium with conditioned annuity rates, households' healthcare spending is lower than in the steady-state equilibrium with unconditioned annuity rates. This result is summarized in the following proposition.

Proposition 6 (Over-investment in healthcare). *In the steady-state equilibrium with mortality contingent annuity claims, households invest less in healthcare than in the steady-state equilibrium where annuity rates cannot be conditioned on individual healthcare investments.*

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VI. Numerical Simulations

We illustrate our theoretical findings via a numerical simulation to get an idea of the quantitative relevance of the moral hazard effect in healthcare spending. In line with our model, we assume that increases in average lifetime stem from the interplay of improvements in the healthcare technology and the endogenous choice of healthcare spending. This implies that the growth and interest rates of the economy depend on the healthcare technology and the healthcare expenditures. In order to apply our stylized life-cycle model to real world data, several important obstacles have to be addressed.

First, our model analysis focused on steady-state economies in which, due to a given and constant healthcare technology, healthcare expenditures and thus also mortality are equal among all living individuals. Obviously, this is a simplification of real-world affairs. However, it is consistent with the index we utilize for mortality (i.e., life expectancy at birth), which is defined as the hypothetical life expectancy of a newly born infant, given that mortality rates remain constant over the entire lifetime. Thus, we calibrate a hypothetical average OECD country to 2005 data, assuming a steady-state economy and a constant healthcare technology consistent with 2005 mortality and health expenditure data. We explore the welfare loss due to unconditioned annuity claims and the effects of a change in the steady-state healthcare technology.

Second, our model assumes that all household wealth is held in annuities. While there is evidence that retirement wealth is increasingly annuitized, still sizable fractions of wealth are invested in other assets (see, e.g., Pashchenko, 2013); see also our discussion in Section VII. Thus, if we assumed that all wealth is held in annuities, we are likely to overestimate the moral-hazard effect of healthcare spending. Yet, as we have shown in Proposition 5, the distortion from moral hazard arises not from annuities per se, but from annuities that are unconditioned on healthcare investments. While we argue that almost all real world annuities are unconditioned, the distinction between conditioned and unconditioned annuities provides a parsimonious way to account for limited annuitization, at least with respect to the moral-hazard externality of healthcare investments. Thus, for our numerical illustration, we assume that households hold some fraction $\lambda \in [0, 1]$ of their wealth in unconditioned annuities, while the remainder $1-\lambda$ is held in conditioned annuities. As shown in the Online Appendix, this leads to the following implicit equation for the optimal choice of healthcare investments in the steady state $\bar{h}$:

$$\frac{\sigma}{1-\sigma}\frac{H'(\bar{h})}{x(\bar{h},\bar{p})} - \frac{1}{(1-\bar{h})} = -(1-\lambda)H'(\bar{h})\left(\frac{1}{x(\bar{h},\bar{p})} - \frac{1}{y(\bar{h},\bar{p})}\right). \qquad (22)$$

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As the share of annuitized wealth of the retired population varies significantly across countries (see our discussion in Section VII), we run three calibrations for the share of unconditioned annuities λ equaling 0.5, 0.75, and 1.

To illustrate the effect of changes in the healthcare technology, for each value of λ, we investigate two different scenarios: (i) an economy with the healthcare technology of 1980 and (ii) an economy with the healthcare technology of 2005. To concentrate on the effects of the healthcare technology, we assume that all other aspects of the economy, such as the consumption good production technology and the initial capital endowment per capita, are the same.[26] For reasons of data availability we employ 2005 data to calibrate the model (apart from data on the healthcare technology). We also note that the scenarios do not intend to compare the expected lifetime utilities of different cohorts born in 1980 and 2005, but our focus is on the role of the healthcare technology.

For both scenarios, we analyze two different annuity regimes. In regime 1, which we consider to be the status quo, we assume that the fraction λ of wealth is invested in annuities that cannot be conditioned on healthcare choices. Thus, only the fraction λ of wealth gives rise to the moral-hazard externality of healthcare spending. In regime 2, which we consider to be the counterfactual scenario, we assume that all annuity payments are conditioned on healthcare expenditures and, thus, the moral-hazard effect vanishes.

Third, while there is no doubt that investments in healthcare (at least on average) positively affect longevity, to what extent healthcare investments decrease mortality strongly depends on numerous socio-economic factors that can differ across countries. To abstract from country-specific peculiarities, particularly in the healthcare system, to the greatest extent possible, we construct a hypothetical country, which resembles the OECD average with respect to all relevant characteristics, in particular longevity and healthcare expenditures. Among all OECD countries for which data were available in 1980, average lifetime at birth increased from 69.7 years in 1980 to 76.7 years in 2005.[27] Over the same time horizon, the average healthcare spending as a percentage of GDP increased from 6.1 percent to 8.7 percent. The growth rate of our average OECD country was

[26]Note, however, that steady-state population size depends on the expected lifetime, as the cohorts' initial sizes when born are fixed and constant.

[27]We average life expectancy at birth and healthcare expenditures for all OECD countries for which data are available in both 1980 and 2005. In particular, this excludes Chile, the Czech Republic, Estonia, Greece, Hungary, Israel, Italy, Luxembourg, Mexico, Poland, the Slovak Republic, Slovenia, and Sweden. See also Online Appendix A9 for details on the numerical illustration.

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$g = 2.02$ percent per year on average between 2002 and 2008, and wage income in 2005 was $w = 41597.7$ USD.[28]

Consistency of our hypothetical average OECD country with our model implies that the healthcare technology is such that (i) healthcare spending of our hypothetical average OECD country leads to the observed life expectancy and (ii) the optimality condition of healthcare spending (22) holds. As our healthcare technology (1) is characterized by three parameters, p_{max}, ψ, and β, imposition of the two aforementioned conditions still leaves one parameter undetermined. To fix the last degree of freedom, we exploit the variations of longevity and healthcare expenditures among OECD countries. We assume that differences in healthcare expenditures explain $\kappa = 50$ percent of the differences in longevity among the OECD countries.[29] To lend further credibility to the calibration of our healthcare technology, we calculate the implied value of a statistical life under regime 1 in scenario (ii), which ranges from 4.17 to 4.21 million (2015 PPP) USD, for λ between 0.5 and 1, and lies very well within the empirically determined range for OECD countries (see, e.g., OECD, 2012).

For the intertemporal elasticity of substitution σ, we follow Murphy and Topel (2003), who suggest a value of $\varepsilon = (u'(c)c)/u(c) = 0.346$, which is also used by Becker *et al.* (2005). For our instantaneous utility function (11), this translates to $\sigma = 1.529$, which we round to $\sigma = 1.5$. The utility discount rate is set to $\rho = 2$ percent and the capital depreciation rate to $\delta = 7$ percent. The economy-wide capital share is set to $1/3$. Together with the healthcare expenditures of 8.7 percent of GDP in 2005 and assuming, in line with our theoretical model, that healthcare is produced by labor alone, we derive the capital share of the consumption good sector $\alpha = 36.5$ percent. In addition, we abstract from population growth (i.e., $\nu = 0$), as we employ data in per capita terms. In our model, we express healthcare expenditures as a share of labor income. Thus, we derive healthcare expenditures h by dividing observed healthcare expenditures as a percentage of GDP by the economy wide labor share of $2/3$. Table 1 summarizes the model parameters used in the numerical simulation.

To compare the expected lifetime utilities of two individuals under two different regimes, we calculate the compensating variation, that is, the percentage increase in consumption that an individual under the first regime had to enjoy to experience the same expected lifetime utility as the individual would under the second regime. Comparing regimes

[28] We calculate yearly averages of our average OECD country for GDP per capita and wage income per capita in 2015 PPP USD.

[29] The calibration procedure is detailed in Online Appendix A9. Sensitivity analyses for the impact κ of healthcare variations on variations of longevity show that our results are highly insensitive to variations in κ.

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Table 1. *Summary of the model parameters used in the numerical illustration*

Symbol	Description	Value
λ	Share of unconditioned annuities	0.5, 0.75, 1 (share of annuitized wealth)
ρ	Time preference rate	2%
δ	Capital depreciation rate	7%
ν	Growth rate of cohort size	0%
σ	Intertemporal elasticity of substitution	1.5 (Murphy and Topel, 2003)
α	Value share of capital in consumption good production	36.5% (calibrated to 2005 data)
β	Curvature parameter of healthcare technology	Calibrated to 1980 and 2005 data
p_{max}	Hazard rate of dying without healthcare	Calibrated to 1980 and 2005 data
ψ	Marginal impact of healthcare spending on longevity	Calibrated to 1980 and 2005 data
h	Share of labor income spent on healthcare	Calculated from 1980 and 2005 data
T	Life expectancy	Calculated from 1980 and 2005 data

1 and 2 in both scenarios, the difference ΔU in expected lifetime utilities is due to the moral hazard induced by unconditioned annuity claims.

The results are shown in Table 2. In scenario (i), the healthcare technology has been calibrated to resemble the life expectancy (69.7 years) and healthcare expenditures (6.1 percent of GDP) of the average OECD country in 1980, while in scenario (ii), the healthcare technology mimics the life expectancy (76.7 years) and healthcare expenditures (8.7 percent of GDP) of the average OECD country in 2005. Comparing the calibrated healthcare technologies, we observe that for all three values of λ the hazard rate for mortality without healthcare treatment p_{max} has declined and the marginal productivity of the healthcare technology ψ has improved while the curvature of the healthcare production function β remained almost constant. This implies that in scenario (ii), individuals live – on average – longer than in scenario (i) even without any healthcare expenditures, and each percentage point of wage income spent on healthcare in scenario (ii) reduces mortality to a greater extent than in scenario (i). As a result of the improved healthcare technology, individuals spend a higher percentage of their wage income on healthcare in scenario (ii): h increases from 9.13 to 13.05. This has implications for the steady-state equilibrium of the economy. The interest rate decreases from 3.75 percent to 3.45 percent, and the growth rate declines from 2.44 percent to 2.01 percent.

First, we analyze what would have happened in scenarios (i) and (ii) if annuity claims were not only partly but fully conditioned on healthcare expenditures, while all other fundamentals of the economy (including

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Table 2. *Utility gains (compensating variation) for a hypothetical average OECD country*

	$\lambda = 0.5$		$\lambda = 0.75$		$\lambda = 1$	
	Scenario (i) 1980 HCT	Scenario (ii) 2005 HCT	Scenario (i) 1980 HCT	Scenario (ii) 2005 HCT	Scenario (i) 1980 HCT	Scenario (ii) 2005 HCT
Healthcare technology						
p_{max} (%)	1.5307	1.4490	1.5302	1.4482	1.5296	1.4475
ψ (%)	0.8299	0.9048	0.8253	0.9001	0.8207	0.8954
β	0.8997	0.8998	0.8997	0.8998	0.8997	0.8998
Regime 1						
h (%)	9.13	13.05	9.13	13.05	9.13	13.05
T (years)	69.7	76.7	69.7	76.7	69.7	76.7
r (%)	3.75	3.45	3.75	3.45	3.75	3.45
g (%)	2.44	2.01	2.44	2.01	2.44	2.01
Regime 2						
h (%)	8.79	12.70	8.62	12.53	8.46	12.36
T (years)	69.6	76.5	69.5	76.4	69.4	76.3
r (%)	3.78	3.48	3.79	3.49	3.80	3.51
g (%)	2.48	2.05	2.50	2.07	2.52	2.09
Comparison of regimes 1 → 2						
$\Delta U_{1\rightarrow 2}$ (%)	1.37	1.41	2.05	2.11	2.73	2.82
ΔU_{direct} (%)	0.0031	0.0031	0.0068	0.0070	0.0120	0.0123
ΔU_{equil} (%)	−0.06	−0.07	−0.09	−0.11	−0.11	−0.13
ΔU_{growth} (%)	1.45	1.50	2.17	2.25	2.90	3.01

Notes: Utility gains (compensating variation) for a hypothetical average OECD country from switching from a regime 1 with fraction λ of unconditioned annuities to a regime 2 of perfectly conditioned annuity claims given 1980 (scenario (i)) and 2005 (scenario (ii)) healthcare technologies (HCT).

the healthcare technology) remained unchanged. We find that steady-state healthcare expenditures in both scenarios decrease, while the interest and growth rates increase. In scenario (i), healthcare investments are reduced from 9.13 percent to between 8.79 percent ($\lambda = 0.5$) and 8.46 percent ($\lambda = 1$), resulting in a lower life expectancy of 69.6 ($\lambda = 0.5$) to 69.4 ($\lambda = 1$) years (a decrease of approximately one to four months). However, the interest rate increases from 3.75 percent to a range of 3.78 percent ($\lambda = 0.5$) to 3.80 percent ($\lambda = 1$), and the growth rate rises from 2.44 percent to a range of 2.48 percent ($\lambda = 0.5$) to 2.52 percent ($\lambda = 1$). Similarly, healthcare expenditures in scenario (ii) decline from 13.05 percent to between 12.70 percent ($\lambda = 0.5$) and 12.36 percent ($\lambda = 1$), resulting in a decline in life expectancy from 76.7 years to 76.5 years ($\lambda = 0.5$) and 76.3 years ($\lambda = 1$), respectively (a decrease of approximately two to five months). The interest rate increases from 3.45 percent to a range between 3.48 percent ($\lambda = 0.5$) and 3.51 percent ($\lambda = 1$), and the growth

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rate of the economy rises from 2.01 percent to a range of 2.05 percent ($\lambda = 0.5$) to 2.09 percent ($\lambda = 1$).

Second, we compare regimes 1 and 2. We find that expected lifetime utility levels are higher under regime 2 with fully conditioned annuity claims. Individuals under regime 1 would have to enjoy a consumption level that is between 1.37 percent and 2.82 percent higher (depending on share of unconditioned annuities λ and scenario) throughout their entire lifetime to reach the expected lifetime utility under regime 2. The welfare loss in regime 1 grows proportionally with the share of unconditioned annuities λ. To understand how conditioned annuity claims affect the expected lifetime utility, we first write expected lifetime utility in the steady state as follows (see also Online Appendix A9):

$$U(s) = \frac{\sigma}{\sigma - 1} c(s, \bar{h}, \bar{p})^{(\sigma-1)/\sigma} \frac{1}{\bar{x}(\bar{h}, \bar{p})}. \tag{23}$$

Here, $\bar{x}(\bar{h}, \bar{p})$ denotes the propensity to consume in the steady-state equilibrium and $c(s, \bar{h}, \bar{p})$ is a household's consumption at birth, which is given by

$$c(s, \bar{h}, \bar{p}) = W(s, \bar{h}, \bar{p})\bar{x}(\bar{h}, \bar{p})(1 - \bar{h}). \tag{24}$$

Differentiating with respect to the steady-state healthcare expenditures $\bar{h}$ yields the following:

$$\begin{aligned} \frac{dU(s)}{d\bar{h}} &= U(s)\left\{\frac{\sigma - 1}{\sigma}\left[-\frac{1}{1 - \bar{h}} + \frac{d\bar{x}(\bar{h}, \bar{p})/d\bar{h}}{\bar{x}(\bar{h}, \bar{p})}\right.\right. \\ &\quad \left.\left. + \frac{dW(s, \bar{h}, \bar{p})/d\bar{h}}{W(s, \bar{h}, \bar{p})}\right] - \frac{d\bar{x}(\bar{h}, \bar{p})/d\bar{h}}{\bar{x}(\bar{h}, \bar{p})}\right\}. \end{aligned} \tag{25}$$

Thus, changes in steady-state healthcare spending $\bar{h}$ affect utility either via a change in the growth rate of individual consumption (last term) or via the initial consumption level at birth (first three terms), which itself depends on the direct costs and benefits of healthcare expenditures (first and second terms in brackets) and changes in the net present value of lifetime earnings $W(s, \bar{h}, \bar{p})$ (third term in brackets).

We further decompose the difference in expected lifetime utility into three components. The first component ΔU_{direct} consists of all changes in expected lifetime utility at the microeconomic level of the individual due to a direct change in healthcare spending $\bar{h}$ or a corresponding change in the mortality rate $\bar{p}$. Thus, ΔU_{direct} is the difference in expected lifetime utilities due to switching from regime 1 to regime 2 if the individual's $\bar{h}$ changes from 9.13 percent (13.05 percent) to a value between 8.79 percent ($\lambda = 0.5$) and 8.46 percent ($\lambda = 1$) (12.70–12.36 percent) and, as a consequence, the life expectancy decreases from 69.7 (76.7) to a range

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of 69.6 ($\lambda = 0.5$) to 69.4 ($\lambda = 1$) (76.5–76.3) years, but the wage, interest rate, and the growth rate of the economy remain at regime 1 values.

The second component ΔU_{equil} isolates the effect of changes in the equilibrium wage rate and interest rate but leaves healthcare spending, expected lifetime, and the economy's growth rate at the levels of regime 2. The last component ΔU_{growth} elicits the difference in expected lifetime utilities that stems from the change in the economy's growth rate while leaving healthcare spending, life expectancy, and wage and interest rates unchanged.[30]

We find that the direct effect at the individual household level of a change from the annuity regime 1 to regime 2 is positive. This is to be expected, as regime 2 completely eliminates the moral-hazard incentive for individual households to over-invest in healthcare because they do not take into account the repercussions of higher healthcare spending, respectively higher life expectancy, on the equilibrium annuity rate. This effect is well understood and documented in the literature (see, e.g., Philipson and Becker, 1998). Yet, we find that this direct effect at the individual household level is very small (between 0.0031 and 0.0123 percent depending on scenario and the value of λ).

The isolated effect on the wage and interest rate ΔU_{equil} is negative. This implies that with respect to wage and interest rates, households are better off under regime 1 with moral hazard than under regime 2 without moral hazard. The reason is that the wage rate increases with increasing healthcare spending, while the interest rate decreases (see Proposition 4(a)). This leads to a higher net present value of lifetime earnings. In Online Appendix A9, we show that the effect on the initial consumption level at birth, as given by equation (24), is unambiguously positive. However, the propensity to consume $\bar{x}(\bar{h}, \bar{p})$ increases, and thus the total effect on lifetime utility, as given by equation (23), is ambiguous. For our numerical simulation, we find that the positive effect on initial consumption outweighs the negative effect on the growth rate of individual consumption, rendering the total effect of an increase in healthcare spending on lifetime utility positive. As healthcare investments are lower in regime 2, this leads to the observed decrease in expected lifetime utility in the range of 0.06–0.13 percent (depending on the scenario and the value of λ).

[30]Note that the decomposition of the total effect is somewhat arbitrary. We select this particular (hypothetical) decomposition to clearly distinguish among the different channels by which increased longevity affects expected lifetime utility and to clearly identify the magnitude of each of these channels. Obviously, other decompositions of the different channels (e.g., incremental or hierarchical decompositions) are conceivable. Note further that the decomposed utility differences do not add up to the total utility difference, as the decomposition is only equivalent to the total derivative for a marginal change in the healthcare technology.

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Finally, a change in healthcare expenditures also affects the growth rate of the economy. According to Proposition 4(c), an increase in $\bar{h}$ leads to an increase in the growth rate for small values and to a decrease for high values of $\bar{h}$. ΔU_{growth} isolates the impact of a change in the growth rate on expected lifetime utility. For all values of λ, we find that in both scenarios a switch from regime 1 to regime 2 reduces healthcare expenditures and increases the economy's growth rate. Accordingly, we observe an increase in expected lifetime utility between 1.45 and 3.01 percent (depending on the scenario and the value of λ).

In summary, we find clear evidence that the moral-hazard incentives of unconditioned annuity claims have a sizable effect on individual expected lifetime utility. We find that expected lifetime utility would increase by approximately 1.4–2.8 percent if annuity claims could be conditioned on healthcare expenditures, depending on the degree of annuitization of retirement wealth.[31] Interestingly, the direct microeconomic effect of moral hazard in our model is rather small. In fact, the negative effect of moral hazard is predominated by a macroeconomic repercussion of healthcare expenditures on the economy's growth rate. In addition, we find that the negative effect of moral hazard is larger under a healthcare technology that resembles the average OECD country in 2005 compared with a healthcare technology consistent with the average OECD country in 1980. Thus, both improving healthcare technology and increasing unconditioned annuitization of retirement wealth might further increase the negative effect of moral hazard due to unconditioned annuity claims in the future.

VII. Discussion

In the following, we relate our model framework and the obtained results to different aspects of the real world.

Annuities

The most important argument for the relevance of our analysis stems from the prevalence of unconditioned annuity claims throughout the developed world. In fact, the typical pension system within OECD countries rests on three pillars: the first pillar is a public pension system, the

[31] These results are very robust to reasonable variations in the exogenously set parameters σ, ρ, and δ. While variations in δ between 0.05 and 0.1 have hardly any effect, variations of σ between 1.25 and 1.75 and variations of ρ between 0.01 and 0.04 result in moral-hazard effects between 0.5 and 2 percent ($\lambda = 0.5$) and 1 and 4 percent ($\lambda = 1$), respectively. The overall effect scales linearly with the share λ of unconditioned annuities.

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second is a funded system that recipients and employers pay into, and the third is voluntary privately funded accounts. Typically, the first two pillars comprise mandatory annuities. According to OECD data (OECD, 2015b), in 2011 public pension expenditures in the OECD amounted, on average, to approximately 10 percent of GDP and to 18 percent of total government spending. Between 1990 and 2011, the increase in public pension expenditures outpaced the increase in GDP by 28 percent. Furthermore, in 2014, mandatory social insurance contributions and mandatory private pension contribution rates for employees and employers for a private-sector worker earning the average wage were approximately 20 percent (OECD, 2015b).[32]

Rusconi (2008) provides an overview of the annuity markets and pension systems across OECD countries and classifies countries into two categories: "life-long annuity predominated" versus those predominated by "alternative forms of income". While a number of countries, such as Germany, the United Kingdom, the Netherlands, and Italy, predominantly employ life-long annuities, some countries, such as the United States, use predominantly alternative forms of income. As a consequence, sources of income of retired individuals vary significantly across countries. In Hungary and Belgium, 89 percent and 85 percent, respectively, stem from annuitized mandatory and occupational social security and pension systems, while this fraction is below 50 percent only in four OECD countries (Turkey, New Zealand, Canada, and Mexico; OECD, 2015b).[33]

Depending on the country, the types of annuities in the pension system and those offered in the private market can differ. The OECD categorizes them into immediate, deferred, and other annuities. Cannon and Tonks (2008) provide a good overview of different annuity types. In essence, they all share the central characteristics captured by the actuarial notes we employ in our analysis. Furthermore, the fair rate of return of the annuity depends on average individual longevity, but annuity contracts do not typically condition on health factors: The overwhelming share of annuitized wealth from the public pension system and mandatory second-pillar contributions does not condition on the health status of the annuitant. There are so-called "enhanced annuities", which pay higher rates when a person has some particular health conditions or is a regular smoker. However, they only play a marginal role in overall annuitized retirement

[32]Note that while technically in our analysis we consider reversible annuities, our central focus is on the distortions annuities involve when it comes to endogenous healthcare investments. In this respect, the reversible annuities are similar to the typically irreversible annuities of the pension systems.

[33]Hosseini (2015) also reports for the United States an average fraction of retirement wealth that is annuitized of approximately 50 percent for individuals older than 60 years.

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wealth and only condition on very specific health characteristics. In summary, annuities play a central role in old age retirement wealth, and also the share varies significantly across countries. To accommodate this heterogeneity, we ran numerical simulations for 50 percent, 75 percent, and 100 percent of unconditioned annuitized wealth.

Length of Working Life

In our model, we find that whether the moral-hazard effect in healthcare investments leads to over- or under-investment depends on whether the expected additional consumption exceeds the expected additional wealth for a marginal increase in the household's life expectancy due to increased healthcare investments. It is rather intuitive that a longer life implies financing a stream of consumption over a longer time horizon. Yet, it is less obvious how it might lead to higher expected labor income wealth because, in reality, the average person no longer works at the age of average life expectancy of approximately 80 years. However, life-extending healthcare measures not only play a role at the very end of life, but they also extend an individual's expected working life via three different channels: (i) later death during the regular working life, (ii) later or no early retirement based on health issues, and (iii) fewer unemployment spells due to poor health. In fact, ill health was the most commonly cited reason for early retirement among both men and women according to several studies.[34] In addition to the expected extension of the household's working life, the expected additional labor income wealth also depends on the wage rate and on the growth rate of wages (which, in steady state, is also the growth rate of the economy). As we have shown, the growth rate of the economy is either positively or negatively affected by a marginal increase in healthcare investments, depending on the initial size of the healthcare sector.

Also, in our model, we assume that households inelastically supply one unit of labor as long as they are alive. Thus, we abstract from a retirement phase at the end of a household's lifetime. How would the explicit consideration of a retirement phase change our results concerning under- or over-investment in healthcare due to moral-hazard effects from unconditioned annuity claims? As outlined above, over-investment occurs if the costs to finance consumption over a longer life expectancy outweigh the increase in the net present value of expected lifetime labor income due to a marginal increase in healthcare expenditures. While a retirement phase has

[34]See, for example, Disney *et al*. (2006) and references therein. In addition, Dwyer and Mitchell (1999) report that men in poor health are expected to retire one to two years earlier. Further evidence for substantial effects of health on labor market participation are reported by Garcia-Gomez *et al*. (2010), van den Berg *et al*. (2010), and Brown *et al*. (2010).

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little impact on the need to finance consumption over a longer time horizon, it clearly limits the possibilities for increases in lifetime labor income.[35] As a consequence, we expect that, in reality, over-investment in health is even larger than suggested by our model.[36] To better estimate the size of the moral-hazard effect, a quantitative exercise with richer detail on retirement and age-dependent mortality and health status over the life cycle would be a desirable next step.

Role of the Intertemporal Elasticity of Substitution

We set up our model framework with a general strictly concave utility formulation. With this general utility function, we derive the solution to the households' maximization problem for given prices and the social planner's solution. For analytical tractability when characterizing the steady-state equilibrium of the economy, we use a constant relative risk aversion (CRRA) utility function, as specified in equation (11), and we follow the literature around Murphy and Topel (2003) and Becker *et al*. (2005) in choosing an intertemporal elasticity of substitution $\sigma > 1$. Hall and Jones (2007) argue that, with a preference specifications of $\sigma < 1$, rising healthcare expenditures can be explained through rising incomes only. Our general set-up and social planner solution encompasses such a specification and it is only with respect to the steady-state equilibrium that we employ an intertemporal elasticity of substitution larger than one.[37] With an intertemporal elasticity of substitution smaller than one,

[35]Yet, it is certainly true that people in good health expecting to live longer might consider extending their working life if doing so were to positively affect their wealth. In fact, Kuhn *et al*. (2015) examine the relationship between the endogenous choices of healthcare and retirement age in a partial equilibrium analysis and find that moral hazard due to unconditioned annuities leads to both excessive healthcare expenditures and an excessive duration of the working life. In addition, the official retirement age might also increase with higher average life expectancy.

[36]This is particularly true if pension systems rely on unconditioned annuity claims. Zhao (2014) shows in a quantitative general equilibrium neoclassical growth model calibrated to US data that one-third of the increase in US healthcare expenditures between 1950 and 2000 can be attributed to the increase in social securities over the same time horizon.

[37]To derive a steady state in the economy, we have to resort to a particular utility specification for tractability. As our focus is on the market inefficiencies with endogenous healthcare spending, we aim for a specification allowing for best analytical tractability of the long-run steady state. In addition, our specification ensures we stay on the conservative side with respect to the incentives for healthcare spending (i.e., we avoid creating the impression that large inefficiencies might be driven or at least exaggerated by our modeling choices). We believe that our utility specification appropriately balances these desiderata for our analysis. Not denying that there is additional value to life beyond consumption and that part of the health expenditure might additionally be driven by increases in income, we acknowledge that steady-state health spending in our model is likely to be on the lower side.

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the equilibrium dynamics would change such that the healthcare sector would grow to dominate the entire economy with consumption good production growing positively but at a lower rate. Similarly, we would obtain equilibrium dynamics with an ever-growing healthcare sector if we included continuous technological improvements in healthcare (see, e.g., Jones, 2016). However, such changes to our model will not negate the channels identified in the previous analysis through which endogenous healthcare expenditures affect the economy. The role of healthcare investments in extending the households' lifetimes will increase their propensity to save, the longer lifetimes will deliver direct welfare from living longer to the households, and healthcare investments will lower the labor supply in the consumption good production sector and, hence, will lower the return to capital, which, as a consequence, will also exert a negative incentive on saving via this channel. These economic channels are not affected by whether σ is greater or smaller than one. Similarly, the identification of the inefficiencies regarding health investments and the determinants of the sign and the size of the moral-hazard effect from annuities unconditioned on individual household mortality are not affected by the precise value of σ. However, the size of the health expenditures, and consequently how quantitatively strong these economic forces and effects are, would depend on the particular preference specification. Our specification implies rather conservative predictions with respect to healthcare investments.

Improvements in the Healthcare Technology

We discussed in Section IV, and showed in our numerical simulations, how differences in the healthcare technology lead to different sizes of the healthcare sector, growth, and welfare in the steady-state equilibrium. This comparison can refer either to two countries with different healthcare technologies, but otherwise similar, or to the same country that, after experiencing a phase of improvements in the healthcare sector, has approached a new steady state with this better healthcare technology. The steady state with better healthcare technology would involve higher health expenditures and, in this way, reflects the literature emphasizing technological progress in the healthcare sector as one central reason for the increase in healthcare spending (Chernew and Newhouse, 2012).

The technological improvements in the healthcare technology that we discussed in this model are exogenous, and we compared the steady-state equilibria before and after the technological improvements. While this can provide interesting insights into how the economy can be affected by better healthcare, it would be intriguing to include endogenous technological progress in healthcare, for example, depending on the amount of healthcare investment.

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If we assume that healthcare investments trigger an increase in ψ, the parameter reflecting the efficiency with which healthcare expenditures translate into extra lifetime, and/or a decrease in p_{max}, the baseline mortality without healthcare expenditures, then our findings suggest that such improvements would lead to even higher healthcare expenditures. This in turn would further increase expected lifetimes. With respect to output growth, the trade-off between the positive effect from higher lifetimes and the negative effect due to a larger share of the labour force working in the healthcare sector remains. Depending on which of the effects dominates, growth will increase or decrease in response. The moral-hazard effect with respect to healthcare investments remains as long as annuity rates condition on average mortality of each cohort.

We expect the long-run dynamics to depend on the assumptions regarding the maximum lifetimes of humans. If the biologically achievable maximum age is finite (e.g., 150 or 200 years), then it will be necessary to assume that the increments of technological progress decline and there would be a technological limit in how low p_{max} and how large ψ can be. In fact, our present model can then inform about the long-run steady state the economy is approaching with such maximal technology and marginally small/negligible improvements in the healthcare technology.

By contrast, it might be that healthcare technology can extend lifetimes without bound if there is no given biological limit to the lengths of human lifetimes. Then, it would be interesting to explore if and under which conditions an economy with endogenous healthcare technology improvements will approach a balanced-growth path with a long-run level of healthcare expenditures $h < 1$ or instead experience unbalanced growth where the size of healthcare sector increases step by step towards $h = 1$, dominating the economy in the long run. In any of these cases, we can tell that the upper bound for the long-run growth rate in output in such an economy will be the growth rate we obtain if we were simply to consider infinitely lived households (without healthcare spending) in our current framework.

VIII. Conclusion

In this paper, we have examined the role of households' endogenous healthcare choices to extend their expected lifetimes on economic growth and welfare in a decentralized, overlapping generations economy with the realistic feature that households' savings are held in annuities. While it is well known that annuities that do not fully condition their returns on individual households' health statuses induce moral-hazard effects in health spending, how this effect plays out in general equilibrium and the

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macroeconomic repercussions it implies for the economy's growth prospects is the central contribution of our analysis.

An increase in healthcare spending that causes households to live longer will reduce the equilibrium return on annuities. We find that this lowers the discount rate in the household's budget constraint on future consumption and future labor income, the latter of which is typically neglected in the literature. Another interpretation is that the increase in healthcare spending implies, on the one hand, that additional consumption needs to be financed for the increase in lifetime but, on the other hand, that additional income might also be earned during the additional lifetime. Neglecting the effect of healthcare spending on annuity rates by taking the latter as given leads households to over-invest in healthcare if the extra lifetime consumption exceeds the extra lifetime income, and vice versa. We show that households will over-invest in the steady-state equilibrium. Under-investment can only occur if the health investment has an additional large and positive (side) effect of increasing the households' wage rates.

We further show that, in macroeconomic terms, increased health investments boost economic growth when the healthcare sector is small but curtail growth when the healthcare sector is already sizable. The latter case additionally amplifies the neglect of the quality of life in terms of consumption in favor of the quantity of life resulting from over-investment in healthcare, as emphasized in the microeconomic literature. In fact, our simulations using OECD data suggest that the growth effect of over-investment in healthcare is negative. Moreover, we find that the welfare losses resulting from over-investment in healthcare are substantial and approximately 1.4–2.8 percent, depending on the share of annuitized retirement wealth. In particular, the numerical results highlight the importance of the general equilibrium effects and, especially, the growth effects for the welfare impacts of the moral-hazard effect. In addition, our simulations suggest that technological improvements in the healthcare sector tend to increase the welfare losses from moral hazard in healthcare investments.

The policy implications that can be drawn from our analysis clearly indicate that attempts should be made to condition annuity payments in social security systems to a far greater extent on health status than is currently done. In practice, this might be a difficult task in terms of measurement, and it might also be a contentious issue politically. Yet, the rewards in the event of success are sizable gains in expected lifetime utility.

In this paper, we analyze the complex interplay among endogenous longevity, endogenous economic growth, and welfare in a model that abstracts from various issues that deserve further scrutiny. To be able to analytically investigate the aggregate economy, we employ a rather simplistic household model. Interesting extensions in this direction include

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age-dependent mortality, retirement decisions, and endogenous fertility. At the level of the aggregate economy, we have shown that the decentralized market solution exhibits several externalities that call for government action. Augmenting the model with realistic features of national health systems would allow future researchers to examine their effects on growth and welfare and to evaluate potential policy interventions. Finally, we have only considered exogenous improvements in the healthcare technology. Endogenizing these improvements is a further challenge for future research.

Supporting Information

Additional supporting information may be found online in the Supporting Information section at the end of the article.

Online Appendix

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