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The Future of Human Health, Longevity, and Health Costs*

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Abstract

Medical advances greatly enhance longevity but may threaten the sustainability of health care finance in its current form. In this paper, we investigate the future of human longevity, morbidity and health costs. We propose a novel, multi-period overlapping generations model with endogenous medical R&D and endogenous survival that is closely associated with morbidity. We capture biologically founded ageing based on gerontology research in order to calibrate our model for the UK. Our calibrated model implies substantial future increases in human longevity that are associated with both reductions in morbidity and a rising health expenditure share in GDP. Stabilizing the health expenditure share by extending health care rationing has potentially sizable effects on morbidity and longevity in the longer run, associated with reduced medical R&D incentives. The implied welfare effects may be substantially negative particularly for future generations.

Key words: Longevity; Medical R&D; Morbidity; Health Care; Rationing.

JEL classification: H50; I10; C60.

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1 Introduction

In this paper we propose a new approach to study the interdependence of medical R&D, health expenditure, longevity and the health status of an age-structured population. We develop a dynamic macroeconomic model where endogenous medical progress affects morbidity in interaction with access to health goods. In turn, morbidity affects mortality rates. These features enable us to make inferences about the future development of life expectancy and health expenditure, conditional on the extent of rationing in health care systems.

A salient feature of structural economic development over the last decades is the secular expansion of the health sector. In the U.S., health expenditure per capita grew by on average 4.1% annually since 1970 to a level of about 18% of GDP four decades later (Chernew and Newhouse, 2012; Gaynor et al., 2015). Starting at lower levels, other developed countries experienced similar rates of increase of the health sector such that, across the board, health expenditure increased faster than GDP. The resulting secular growth trends of health expenditure shares (Chernew and Newhouse, 2012) are predicted to continue in the future (e.g. European Union, 2010; OECD, 2016).

Scholars agree that both the rise of health expenditure and improvements in longevity are related to medical technological progress.¹ Recent examples of health innovations include computerized diagnostic tests (e.g. for medical imaging), personalized cancer therapy, and new treatments of virus infections like HIV or Hepatitis C. More generally, and supportive of our model, Lichtenberg (2007) shows that later vintages of pharmaceuticals are more powerful in the reduction of health deficits. Considering the evolution of 92

¹Most studies attribute between 50 and 80 percent of health expenditure growth to technological progress (Chernew and Newhouse, 2012). As argued convincingly by Chernew and Newhouse (2012), the *persistent* increase of health expenditure shares requires at least one other persistently growing explanatory variable (and thus rules out institutional changes like health care reforms and other only occasionally changing variables). Okunade and Murthy (2002) establish a long-run relationship between medical R&D expenditure and health care expenditure. There may be a role for income as a driver of increases health shares, although questioned by some recent studies refuting the luxury good hypothesis of health care by estimating an income elasticity of health expenditure below unity (Acemoglu, Finkelstein and Notowidigdo, 2013; Baltagi et al., 2016).

potentially lethal diseases he finds that conditions experiencing greater pharmaceutical innovation tend to have greater declines in mortality rates.²

Since in most advanced economies provision of salient health goods and services relies on highly regulated health insurance systems, the entailed increasing utilization of medical goods and services raised concerns about fiscal sustainability and, more generally, the overall desirability of these trends. It motivated the discussion of health care rationing as potential remedy to curb further rising expenditure shares (Aaron and Schwartz, 1990; Ham and Glenn, 2003; Singer, 2009). Indeed, health care rationing has become more and more visible in developed countries. For instance, the National Health Service (NHS) – managing tax-financed health care with guaranteed access in the UK – rations hip replacements and knee surgeries.³ In the mandatory German health system, if the amount of external costs attributable to a medical doctor exceeds a threshold per quarter, the doctor has to privately bear the costs above the cap. In addition, many health care systems (like the UK and Switzerland) have severely limited coverage of a novel (albeit expensive) drug that for the first time heals Hepatitis C.⁴

In our setting, rationing care in order to constrain health expenditure growth has – aside from the obviously detrimental effects on health of the current population – severe “side-effects” on future health and longevity via reduced market size for new medical

²A promising example of a potentially powerful future technology is targeted genome editing like the clustered, regularly interspaced, short palindromic repeat (CRISPR) technology. It gives rise to the development of novel molecular therapeutics for human disease. Recent biotechnological R&D also focusses on anti-ageing drugs that would – once effective, safe and covered by health care – be demanded by basically everybody. See The Economist (2016) for an overview on recent developments in the anti-ageing research.

³See Edwards, Crump and Dayan (2015). Contrary to many European health systems, US medicare (health insurance for the elderly) involves a co-insurance rate for pharmaceuticals of 25%. Co-insurance makes demand for pharmaceuticals price-elastic. In fact, in the US prices for pharmaceuticals are little regulated, compared to European health care systems. The fundamental issue of rationed health care provision is nevertheless present as well in the US, albeit in different form.

⁴See <http://www.hepatitisc.uw.edu/page/treatment/drugs/sofosbuvir-drug>. NHS England has decided to provide treatment only to the 10,000 sickest persons of those being infected per year, a rather small fraction of the estimated 215,000 infected persons in the UK (<https://www.theguardian.com/society/2016/jul/28/nhs-abandoning-thousands-by-rationing-hepatitis-c-drugs>). In Switzerland, patients initially received Hepatitis C treatment only if they had severe liver damage (World Health Organization, 2016). Despite small modifications, rationing remains in place for the bulk of infected persons.

products, in turn suppressing medical R&D. The calibration of our model is consistent with the evolution of survival functions from 1950 until the present. It suggests future demographic change that is associated with significant declines in morbidity and an increase in both the health expenditure share in GDP and the employment share in the health sector by about two percentage points until 2080. We argue that preventing an increase in the health expenditure share would, for instance, reduce life-expectancy of an individual who has reached age 65 in year 2050 by almost 4 years.

Deciding on the trade-off between promoting longevity and limiting increases in health costs is a fundamentally normative issue. We assume that instantaneous utility of surviving individuals depend on their health status and material consumption. Marginal utility from consumption negatively depends on morbidity, in line with empirical evidence (Finkelstein, Luttmer and Notowidigdo, 2013). Our normative analysis suggests that particularly future generations would incur dramatic welfare losses from extending health care rationing that stabilizes the health expenditure share, despite increases in their disposable income. We estimate, for instance, that someone who is 20 years old in 2020 could expect a welfare loss of 14-24 percent from the regime switch. For a 20 year old in 2050 the welfare loss could be 34-48 percent.⁵

Our main contribution is to highlight the interaction between endogenous medical technological progress and longevity as a function of access to health care. Most empirical studies of the determinants of health expenditure estimate medical technological progress as a residual. The study by the European Union (2009), for example, regresses health expenditure against income, the population share above 65, and a time trend, and interprets the time trend (of on average 2 percent annually) as the rate of medical technological progress. Treating medical technological progress as a time trend, however, is problematic when predictions are made on long-run developments of population health

⁵We measure welfare changes from a regime switch in the health care system by an equivalent variation measure. We ask by how much we would have to multiply material consumption levels under the baseline health policy scenario such that the *ex ante* life-time utility of a member of a given generation is the same as after the policy regime switch that forces the health expenditure share to remain at its current level.

and health expenditure under different policy scenarios. Implicitly these predictions assume that health policy does not affect medical progress. In our study we challenge this view by modeling endogenous medical innovation and endogenous population health for different policy scenarios. In particular, we show that limiting the rise in health expenditure has a detrimental effect on health R&D through a market size effect that is associated with the resulting reduction in health care utilization. We thus formalize an idea that goes back to Weisbrod (1991) who argues that the expansion of U.S. health care insurance has induced increasing health R&D and newly developed technologies that, in turn, have driven up health care utilization and costs.⁶ In turn, we show that the resulting decreases in mortality rates (i.e. rising life expectancy) further raise health costs, consistent with empirical evidence (e.g. Zweifel, Steinmann and Eugster, 2005; Bech et al., 2011; Breyer, Normann and Niebel, 2015).

In order to calibrate our model, we employ the *health deficit index* developed by gerontologists (Mitnitski et al., 2000, 2002) and subsequently used in countless empirical studies in the natural sciences for measuring health status and its relation to mortality in an empirically meaningful way. In contrast to health capital (a latent variable popular among economists; Grossman, 1972), health deficits are observed and easily quantifiable. In our model, in line with the conceptualization of morbidity and physiological ageing in gerontology research, individuals accumulate health deficits over the life-cycle which in turn determine mortality rates at a given age. The individual accumulation process of health deficits depends on the interaction between the extent to which individuals are provided with health goods to treat their illnesses and their available quality. Health good quality is endogenously determined by vertical R&D.

Related studies investigated the interaction of health R&D in “reduced form” by either

⁶Testing this hypothesis, Acemoglu et al. (2006) could not show that the introduction of Medicare (the “Social Security Act of 1965” that covered hospital and doctor expenses) increased pharmaceutical demand and pharmaceutical R&D. This finding is not surprising, however, since coverage of pharmaceuticals was not introduced until 2006. Extending the scope of analysis, Acemoglu and Linn (2004), showed large market size effects of the aging baby boomers on the development and market entry of new (age-specific) pharmaceuticals.

assuming a direct utility gain from the consumption of pharmaceuticals (as in Garber, Jones and Romer, 2006, and Grossmann, 2013) or by assuming a direct impact of health goods on the mortality rate of a representative individual (as in Jones, 2016a). Garber et al. (2006) investigate the interaction between medical R&D of a monopolist and the generosity of the health care system, measured by the degree of coinsurance payment of individuals. New generations of pharmaceuticals are assumed to directly raise utility of individuals with the respective disease. Neither health nor longevity are explicitly modeled. Prices of pharmaceuticals are set in private markets (approximating the US health care system). In this setup, lower co-payments lead to higher demand and higher markups charged by drug producing firms.⁷ Consequently, profits of firms may exceed consumer surplus of patients such that, in this sense, there could be too much demand and too much medical R&D. In contrast to that paper, which highlights the problem of moral hazard when prices for pharmaceutical are set on markets, we assume that prices are regulated (approximating the British and German health care system, among others). We then focus on the interaction between health expenditure, medical R&D, morbidity and longevity of an age-structured population in a dynamic macroeconomic model.

In another recent study, Jones (2016a) proposes a macroeconomic model with deterministic, horizontal health innovations that affect longevity of a single cohort that privately buys health goods (similar to Grossman, 1972) with a trade-off to material consumption (featuring “love-of-variety” of consumers in both sectors). By investigating the optimal allocation of R&D effort directed towards innovations for health and non-health purposes, it is shown that under a mild condition non-health technological progress may optimally converge to zero growth such that the health expenditure optimally converges to 100 percent. The study makes an important, eye-opening contribution in the debate whether there is too much health care expenditure and it paves the way for our research. Our study, however, focusses on different research questions and shifts from the single-

⁷In a similar vein, Grossmann (2013) relates co-insurance rates to medical R&D incentives. By examining an oligopolistic pharmaceutical market with endogenous firm entry, he also shows that entry deregulation may lead to more pharmaceutical R&D despite lowering profits of pharmaceutical firms.

agent view to a multi-period, overlapping generations model with an explicit health care system and a biologically founded relationship between morbidity and mortality. In particular, we investigate the effects of health care (rationing) on health and longevity of an age-structured population.

In a development context, higher life expectancy may positively affect per capita income (e.g. Cervellati and Sunde, 2011). In fact, investments in human capital or entrepreneurship may be fostered because the gains of economic activity is spread on a longer time horizon. In advanced economies, however, longevity is enjoyed by retirees. Thus, publicly financed policy interventions to promote health good provision and health R&D do not necessarily raise per capita income and consumption levels. Rather there is a fundamental trade-off between longevity and material well-being that we focus on in this paper.

Our paper is also related to a strand of recent studies that utilized the health deficit approach to (re-)investigate the Preston curve (Dalgaard and Strulik, 2014), the role of adaptation for health behavior and health outcomes (Schuenemann, Strulik and Trimborn, 2015), the education gradient (Strulik, 2016), the historical evolution of retirement (Dalgaard and Strulik, 2017), and the optimal design of social welfare systems (Grossmann and Strulik, 2015).⁸

Finally, there is a large literature outside economics that attempts forecasting future life expectancy by estimating statistical time trends. For instance, as acknowledged by Kontis et al. (2017) in widely received paper that accounts for model uncertainty with a Bayesian model averaging approach, the "key limitation" of purely statistical approaches "is the inability to account for [...] changes in the social, technological, and health systems determinants of health" (p. 8). In our economic approach, we endogenize health technology and calibrate health care utilization, analyzing different regimes of future

⁸Grossmann and Strulik (2015) investigate the interaction between increasing health expenditure, which promotes longevity, and a publicly financed pay-as-you-go pension system that is challenged by (endogenously) changing demography. They do not incorporate health R&D or a health good sector, however. Moreover, their analysis is confined to two periods of life (with endogenous lengths).

health care rationing.

The remainder of the paper is organized as follows. Section 2 presents the model. Section 3 provides the positive analysis of health care rationing based on the calibrated model. The normative analysis is presented in section 4. The last section concludes.

2 The Model

Consider the following multi-period overlapping generations model in discrete time, indexed by t , in which individuals age by accumulating bodily impairments (“health deficits”). In line with the evidence on human ageing, on average, individual health deficits correlate exponentially with age and are a highly relevant determinant of the probability of death (e.g. Mitnitski and Rockwood, 2002a, 2002b, 2005). Health goods are provided via a tax-financed health care system without coinsurance, like in the UK and Germany. Improved quality of provided health goods slows down the ageing process. Medical R&D rests on private firms and is competitive. Also the final good sector and factor markets are perfectly competitive, whereas health good providers charge mark-up prices. Mark-up factors can be thought of being determined by negotiations between health care representatives and health good suppliers, again, like in the UK and Germany. There exists a perfect private annuity market. For simplicity, we assume that there is an international capital market that fixes the real interest rate, \bar{r} .

2.1 Households

Each period a new cohort is born. Mortality is cohort-specific and determined by health status, that is measured by the fraction of the health deficits an individual suffers from out of a long list of potential impairments (“health deficit index”), ranging from mild deficits (reduced vision, incontinence) to near lethal ones (e.g. stroke).⁹

⁹According to Rockwood and Mitnitski (2007) and Searle et al. (2008), the exact choice of the set of potential deficits is not crucial, provided that the set is sufficiently large.

Formally, the probability $m_{v,t}$ of a member of cohort v to die between period t and $t + 1$, conditional on having reached age $t - v \geq 0$, is increasing and strictly convex as a function of the health deficit index at that age, $d_{v,t} \in [0, 1]$. There exists a threshold deficit state $d_{\max} \in (0, 1)$ such that no individual survives beyond that state. Moreover, there is a maximum life span (irrespective of health deficits), T . These properties are captured by the parsimonious specification

$$m_{v,t} = \begin{cases} \frac{1 - e^{-\frac{(d_{v,t})^\phi}{\sigma}}}{1 - e^{-\frac{(d_{\max})^\phi}{\sigma}}} \equiv \tilde{m}(d_{v,t}) & \text{if } d_{v,t} < d_{\max} \text{ and } t < v + T - 1 \\ 1 & \text{otherwise,} \end{cases} \quad (1)$$

where we assume $\sigma > 1$ and $\phi \geq (1 - 1/\sigma)^{-1}$, implying $\tilde{m}'' > 0$. Note that $\tilde{m}(0) = 0$ and $\tilde{m}(d_{\max}) = 1$. σ and ϕ will turn out to affect the ‘‘curvature’’ of the mortality function as a function of age. As will become apparent, specification (1) enables us to capture empirically observed survival rates reasonably well with a small set of parameters. By definition, the survival rates and conditional mortality rates are related by

$$S_{v,t} = S_{v,v} \prod_{u=v}^{t-1} (1 - m_{v,u}) \text{ for } t \geq v + 1, \quad (2)$$

i.e., $m_{v,t} \equiv -(S_{v,t+1} - S_{v,t})/S_{v,t}$. The initial cohort size in period v is $S_{v,v}$.

Each individual works for R periods and inelastically supplies one unit of labor in working age (and no labor afterwards).¹⁰ We thus implicitly assume that, conditional on survival, labor supply is independent of health status.¹¹ The total units of labor supplied to the economy in period t are given by $L_t = \sum_{u=t-R+1}^t S_{u,t}$.

Households have preferences over material consumption and health status. They choose the consumption path that maximizes expected life-time utility. Because the

¹⁰Allowing for a positive elasticity of labor supply with respect to net wages rather than assuming exogenous labor supply would be conflict with the evidence that hours worked have declined over a longer time horizon in many growing economies (e.g. Lee, McCann and Messenger, 2007).

¹¹In fact, at the individual level, a decline in health status does not seem to have a large effect on labor supply (see e.g. Jaeckle and Himmler, 2010, as well as Hokayem, and Ziliak, 2014). Introducing age-dependent labor supply or varying the retirement age does not affect the main insights of our analysis.

interest rate is fixed, saving decisions of households do not interact with R&D decisions of firms and physical capital input. We thus first analyze the supply side and introduce life-time utility later to analyze welfare implications of our model.

2.2 Firms

There is a standard numeraire goods sector, producing a standard final good, and a health sector.

2.2.1 Numeraire Good Sector

The final good is chosen as numeraire. It is produced under perfect competition according to

$$Y_t = (K_t^Y)^\alpha (A_t L_t^Y)^{1-\alpha}, \quad (3)$$

$\alpha \in (0, 1)$, where K_t denotes the physical capital input in period t , L_t^Y is the amount of labor in the consumption goods sector, and A_t is a measure of non-health knowledge. Its level is initially given by $A_0 > 0$ and exogenously grows over time with constant rate $g > 0$. Physical capital depreciates at rate $\delta^K \geq 0$. Thus, the user cost per unit of capital is given by $\bar{r} + \delta^K$. It is equal to the marginal product of capital, $\bar{r} + \delta^K = \alpha (A_t L_t^Y / K_t^Y)^{1-\alpha}$. The wage rate, w_t , equals the marginal product of labor, i.e. $w_t / A_t = (1 - \alpha) (A_t L_t^Y / K_t^Y)^{-\alpha}$. Thus,

$$\frac{w_t}{A_t} = (1 - \alpha) \left(\frac{\alpha}{\bar{r} + \delta^K} \right)^{\frac{\alpha}{1-\alpha}} \equiv \omega. \quad (4)$$

2.2.2 Health Good Producers

Health Technology and Health R&D There is a continuum of potential illnesses that are represented by the unit interval, indexed by $j \in [0, 1]$. The health sector provides patentable health goods (and services) like pharmaceuticals to treat illnesses. For each illness, there is a competitive R&D sector aiming to advance the treatment quality. A successful innovator provides a quality level that is by an amount $\gamma > 0$ higher than

the quality without innovation. An innovator is formally awarded an infinitely-lived patent. As will become apparent, however, patent holders will frequently be driven out of business by future innovators. The quality of the latest vintage of health good j available in period t is denoted by $q_t(j)$. The quality of all health goods (including older vintages) may deteriorate over time at rate $\delta^Q \in (0, \gamma)$. In the case of pharmaceuticals, depreciation of quality captures mutations of bacteria and viruses, with resistance of antibiotics being a prime example.

Denoting by $\mu_{t+1}(j)$ the probability of a successful innovation to treat illness j that can be commercialized in $t + 1$, the quality of health good j thus evolves according to

$$q_{t+1}(j) = \begin{cases} (1 - \delta^Q)q_t(j) + \gamma & \text{with probability } \mu_{t+1}(j), \\ (1 - \delta^Q)q_t(j) & \text{otherwise.} \end{cases} \quad (5)$$

Hence, the expected quality of a health good targeted to illness j in period $t+1$, $\mathbb{E}[q_{t+1}(j)]$, is given by

$$\mathbb{E}[q_{t+1}(j)] = \mu_{t+1}(j) [q_t(j)(1 - \delta^Q) + \gamma] + (1 - \mu_{t+1}(j))q_t(j)(1 - \delta^Q). \quad (6)$$

Let $l_t(j)$ denote the amount of labor devoted by a representative R&D firm in health sector j at t and assume that the perceived probability of a successful innovation is proportional to it:

$$\tilde{\mu}_{t+1}(j) = \tilde{\xi}_t l_t(j), \text{ with } \tilde{\xi}_t \equiv \xi \cdot (L_t^Q)^{-\vartheta}, \quad (7)$$

$\xi > 0$, $\vartheta \in (0, 1)$, where L_t^Q is the aggregate amount of health R&D labor in t . $\tilde{\xi}_t$ is taken as given in the decision of R&D firms and captures a negative R&D ("duplication") externality: $\vartheta > 0$ implies a wedge between the private and social return to R&D that may arise because firms do not take into account that rivals may work on the same idea such that, from a social point of view, some of the R&D is duplicated.¹² In a symmetric

¹²For $\vartheta \rightarrow 1$, social returns to medical R&D investment approach zero. The argument is analogous to that in Jones and Williams (2000) for a non-health R&D context.

equilibrium, where $l_t(j) = L_t^Q$ for all $j \in [0, 1]$, we obtain $\tilde{\mu}_{t+1}(j) = \tilde{\mu}_{t+1} = \xi \cdot (L_t^Q)^{1-\vartheta}$ for all j .

There also may be innovations that occur unintentional or are commercialized by non-profit innovators like public research institutions.¹³ They become effective in $t + 1$ with probability $\bar{\mu}_{t+1}$. Let $Q_t \equiv \int_0^1 q_t(j) dj$ denote the average quality of the latest vintages of health goods ("stock of medical knowledge"). We assume that there is an intertemporal spillover of the form

$$\bar{\mu}_{t+1} = \eta Q_t, \quad (8)$$

$\eta \in [0, \delta^Q/\gamma)$. Thus, the total probability of medical progress in any sector is given by

$$\mu_{t+1} \equiv 1 - (1 - \bar{\mu}_{t+1})(1 - \tilde{\mu}_{t+1}) = \eta Q_t + (1 - \eta Q_t) \cdot \xi \cdot (L_t^Q)^{1-\vartheta}. \quad (9)$$

By the law of large numbers, there is no aggregate risk. Thus, $\int_0^1 \mathbb{E}[q_{t+1}(j)] dj$ is deterministic and equal to Q_{t+1} . According to (6), it evolves as

$$Q_{t+1} = \gamma \mu_{t+1} + (1 - \delta^Q) Q_t, \quad (10)$$

where initial level $Q_0 > 0$ is given. Substituting (9) into (10), we obtain

$$\frac{Q_{t+1} - Q_t}{Q_t} = \frac{\gamma(1 - \bar{\mu}_{t+1})\tilde{\mu}_{t+1}}{Q_t} - \delta^Q = \frac{\gamma(1 - \eta Q_t)\xi(L_t^Q)^{1-\vartheta}}{Q_t} - \delta^Q, \quad (11)$$

$\tilde{\delta}^Q \equiv \delta^Q - \gamma\eta > 0$. Thus, the growth rate of Q is a declining function of its level, becoming negative without intentional R&D (i.e. $Q_{t+1} < Q_t$ if $L_t^Q = 0$).

Marginal Costs of Health Goods and Price-Setting Production of one dose of a health good in period t requires $\chi > 0$ units of labor. Thus, marginal production costs in period t are χw_t . The price mark-up of health goods can be thought of as an outcome

¹³The inventions of Penicillin and Viagra are prime examples of major breakthroughs that were not intended to treat the health problems they target today.

of negotiations between the government as health insurer and (a representative body of) health good providers like pharmaceutical companies.¹⁴ For instance, in the UK, prices for pharmaceuticals are regulated and based on a non-contractual agreement between the UK Department of Health and the Association of the British Pharmaceutical Industry. Similarly, in Germany, health care suppliers negotiate with pharmaceutical companies the maximum price covered by the mandatory health insurance.

Suppose the government bids down suppliers of older vintages to their marginal costs and pays to the industry leader a mark up factor that is increasing in his quality advantage vis-à-vis previous vintages. Denote by $\mathbf{q} > 0$ the (absolute) quality advantage of the industry leader over the competitor with the second-highest quality product in the same market. We assume that the mark up factor is given by $1 + f(\mathbf{q})$, where f is an increasing and strictly concave function that fulfills $f(0) = 0$. It captures the price setting power of health good providers as a function of its quality advantage in the market. If the leading firm is one step ahead of the closest competitor (i.e. $\mathbf{q} = \gamma$), it gets a profit per unit sold that is equal to $f(\gamma)\chi w$, whereas the previous innovator receives zero profit. If the leading firm is two steps ahead of the closest competitor (i.e. $\mathbf{q} = 2\gamma$), it gets a profit per unit equal to $f(2\gamma)\chi w$. The profit increase for the industry leader by innovating, i.e. becoming two steps rather than one step ahead, is $[f(2\gamma) - f(\gamma)]\chi w$. Since strict concavity of f and $f(0) = 0$ imply $f(2\gamma) < 2f(\gamma)$, we have $[f(2\gamma) - f(\gamma)]\chi w < f(\gamma)\chi w$. Thus, it does not pay off for the leader to innovate. The incumbent firm would strictly prefer to invest in R&D in a second market rather than advancing its latest vintage.¹⁵ Consequently, the incumbent is driven out of business when there is an innovation in the market it leads and leader's quality advantage to the closest competitor is exactly $\mathbf{q} = \gamma$.

¹⁴Pharmaceutical companies may draw their negotiation power via lobbying and marketing that influences government negotiators and public opinion, respectively, on the merits of pharmaceuticals. For instance, interest groups representing the pharmaceutical sector strongly argue that they need to earn high profits enabling them to conduct R&D and therefore have to charge high prices that should be covered by health insurance.

¹⁵See Grossman and Helpman (1991) for a similar argument in a context of Bertrand competition.

Hence, the price p_t of each health good is given by

$$p_t = \Gamma \chi w_t = \Gamma \chi \omega A_t, \tag{12}$$

where $\Gamma \equiv 1 + f(\gamma)$ is the mark-up factor.

2.3 Health Care Provision

In many advanced countries, the bulk of individuals exclusively rely on a highly regulated health system with compulsory contributions (e.g. Germany and Switzerland) or is tax-financed like the National Health Service (NHS) in the UK. For simplicity, we assume that it is the only provider of health goods. There may be rationing in health care provision. As formally introduced below, rationing is defined as falling short of the maximally health-effective provision of health goods for a given state of technology.

We do not consider the possibility of "out-of-pocket" health payments or coinsurance. Although the absence of these features are limitations of our analysis, we capture reasonably well the health system of the UK, to which we calibrate our model. In NHS, like in the mandatory German health system, coinsurance is absent. "Out-of-pocket" health expenditure as fraction of total health expenditure have been around 10 percent in the 2000s (OECD, 2016) and also private health insurance coverage has been at a modest level (10.5 percent in the year 2014). Many salient health goods, like surgeries treating orthopedic deficits or drugs for treating cancer and virus infections, may indeed be unaffordable for the bulk of individuals (presumably those who do not have private insurance in the UK either), if not covered by NHS.

2.4 Health Deficit Accumulation

We assume that physiological ageing starts when individuals become economically active, i.e. consume and supply labor.¹⁶ Modern gerontology describes ageing as an accumulation

¹⁶We will calibrate the model such that the initial period for each cohort member is at the age of 20.

of health deficits (e.g. Mitnitski and Rockwood, 2002a, 2002b, 2005). The evidence suggests that individual health deficits grow exponentially with age in advanced countries (e.g. Mitnitski et al., 2002; Harttgen et al., 2013). Thus, we assume that the change in the deficit index of a member of cohort ν between period t and $t + 1$ is increasing in the deficit index accumulated until period t . The accumulation process is slowed down by receiving health input, $E_{v,t}$, conceptualized below. The health deficit index evolves according to

$$d_{v,t+1} - d_{v,t} = \begin{cases} \varrho d_{v,t} - \kappa E_{v,t} & \text{if } E_{v,t} < \frac{\varrho}{\kappa} d_{v,t}, \\ 0 & \text{otherwise,} \end{cases} \quad (13)$$

$\kappa > 0$, $\varrho > 0$, with initial value $d_{\min} \equiv d_{v,v} > 0$. Parameter ϱ is the growth rate of the health deficit index in absence of health interventions. It can be interpreted as the physiological “force of ageing”.¹⁷ κ is a shift parameter we employ to calibrate the model, as the effective health input will turn out being a latent variable, because it depends on the (latent) medical knowledge stock Q .

We conceptualize health input, $E_{v,t}$, as total health good consumption to treat illnesses that are caused by existing health deficits, weighted by the quality of the consumed health goods. We thereby capture that health deficits derive from past, not fully cured or not fully curable illnesses. For illustration, consider two health deficits are within the set of potential health deficits to calculate the deficit index in the empirical gerontology literature that motivates our modeling approach. First, the physical difficulty to move is known to contribute to developing cardiovascular diseases. If not treated properly, these lead to further health deficits. Second, feeling lonely may cause major depressive disorder. Again, without treatment, further health deficits develop.

Formally, an individual born in v acquires a set $\mathcal{I}_{v,t} \subset [0, 1]$ of illnesses in period $t \geq v$ with measure equal to the current deficit index, $|\mathcal{I}_{v,t}| = d_{v,t}$. We normalize the maximally effective consumption per health good, per individual and per period, to

¹⁷Health deficit accumulation would cease if the effective health input became sufficiently high. Although this may not pure utopia but conceivable with further biotechnological advances (De Grey and Rae, 2007), we will not consider the case in this paper.

unity. For instance, in the case of pharmaceuticals there is an optimal dose. We capture under-utilization of health care by allowing the actual consumption per health good, per period and per individual, to be smaller than unity, lowering the effective health input accordingly. The “health care provision wedge” in t is parameterized by $\varphi_t \in [0, 1]$. One major cause of under-utilization is institutionally caused health care rationing. Full utilization is possible only without rationing. In this case, $\varphi = 0$, whereas $\varphi = 1$ holds in absence of a health system or full exclusion from it. By the law of large numbers, suffering from a set of illnesses $\mathcal{I}_{v,t}$ of measure $d_{v,t}$ in $t \geq v$, an individual born at v thus experiences the effective health input

$$E_{v,t} = (1 - \varphi_t) \int_{j \in \mathcal{I}_{v,t}} q_t(j) dj = (1 - \varphi_t) d_{v,t} Q_t. \quad (14)$$

It depends on the interaction between the contemporaneous health care utilization ($1 - \varphi_t$), the current deficit state ($d_{v,t}$) and the average quality of health goods (Q_t). Substituting (14) into (13), the growth rate of the health deficit index is deterministic and independent of the deficit state. For $t \geq v$ it is given by¹⁸

$$\frac{d_{v,t+1} - d_{v,t}}{d_{v,t}} = \begin{cases} \varrho - (1 - \varphi_t) \kappa Q_t & \text{if } Q_t < \frac{\varrho}{\kappa(1 - \varphi_t)} \equiv \bar{Q}_t, \\ 0 & \text{otherwise.} \end{cases} \quad (15)$$

Each surviving member of cohort v in period t consumes

$$h_{v,t} = (1 - \varphi_t) S_{v,t} d_{v,t} \quad (16)$$

units per health good from the latest vintages (i.e. an average dose $1 - \varphi_t$ for any member of cohort v and for each illness $j \in \mathcal{I}_{v,t}$), and nothing from the older vintages of the health

¹⁸If the economy reached a quality level of health goods $Q_t \geq \bar{Q}_t$ in finite time \bar{t} and $\varphi_t \leq \varphi_{\bar{t}}$ for all $t \geq \bar{t}$, all individuals born in $v \geq \bar{t}$ would remain with $d_{v,t} = d_{\min}$ for all $t \geq \bar{t}$. The case does not arise in our calibrated model, but would be implied by assuming zero depreciation of health good quality ($\delta^Q = 0$).

good. Total demand for each selected vintage of a health good in period t is given by the summing up $h_{v,t}$ over all cohorts with living members:

$$H_t = \sum_{v=t-T+1}^t h_{v,t} = (1 - \varphi_t) \sum_{v=t-T+1}^t d_{v,t} S_{v,v} \prod_{u=v}^{t-1} (1 - m_{v,u}), \quad (17)$$

where we used (2) and (16) for the latter equation. Thus, more rationing in health care provision (a higher φ) saves health costs by reducing health good consumption, all other things being equal. However, a higher φ has two detrimental effects on health status and life expectancy. First, according to (15), it speeds up the evolution of health deficits for a given stock of medical knowledge, Q . Second, according to (17), it lowers market size for health goods, H , in turn reducing incentives for health innovations.

3 Positive Analysis

We first highlight some equilibrium conditions and then conduct a supply-side analysis of the calibrated model.

3.1 Equilibrium Conditions

Denote by π_t the instantaneous profit of health good producers, which are all identical *ex ante* and thus also *ex post*. Ruling out bubbles and arbitrage possibilities in the financial market and accounting for the probability μ_u that health good producers are driven out of business in period $u \geq t + 1$, the value of a vertical innovation in the health sector created in t reads as

$$V_t \equiv \pi_t + \sum_{u=t+1}^{\infty} \frac{\prod_{s=t+1}^u (1 - \mu_s) \pi_u}{(1 + \bar{r})^{u-t}}. \quad (18)$$

Labor market clearing implies that

$$L_t^Y + L_t^H + L_t^Q = L_t, \quad (19)$$

where $L_t^H \equiv \chi H_t$ denotes total employment in health goods production. For later use, denote employment shares by $\ell_t^Y \equiv L_t^Y/L_t$, $\ell_t^H \equiv L_t^H/L_t$ and $\ell_t^Q \equiv L_t^Q/L_t$, i.e. in equilibrium, $\ell_t^Y + \ell_t^H + \ell_t^Q = 1$.

As implied by the assumption that the interest rate is exogenous, consumer choices (introduced in section 4) do not play a role for the allocation of labor, health contribution rates, longevity and morbidity. The dynamical system, including the long run equilibrium, is summarized in Appendix A.

For later use, denoting the gross domestic product (GDP) by $GDP_t \equiv Y_t + p_t H_t$, the health expenditure share reads as

$$\mathfrak{s}_t \equiv \frac{p_t H_t}{GDP_t} = \frac{p_t H_t}{Y_t + p_t H_t}. \quad (20)$$

Moreover, the inverse of the probability of an incumbent to be driven out of the market is the effective patent length (*EPL*), i.e.

$$EPL_t \equiv \frac{1}{\mu_{t+1}}. \quad (21)$$

Finally, let us define the "dependency ratio", *DPR*, as the ratio of retirees to workers. Denoting the size of the retired (old-aged) population by $O_t \equiv \sum_{u=t-T+1}^{t-R} S_{u,t}$, we have

$$DPR_t \equiv \frac{O_t}{L_t} = \frac{\sum_{u=t-T+1}^{t-R} S_{u,t}}{\sum_{u=t-R+1}^t S_{u,t}}. \quad (22)$$

3.2 Calibration

We dynamically calibrate the model to endogenous observables in the UK whenever available; otherwise we use North American data. We first consider the output elasticity of labor, $1 - \alpha = wL^Y/Y$. According to Karabarounis and Neiman (2014, "CLS KN merged"), the arithmetic average for the period 1987-2011 of the UK corporate labor share in total income has been 62 percent (which is also the 2011 value). Thus, we set

$\alpha = 0.38$. For the real interest rate we choose the typical value $\bar{r} = 0.05$. For the depreciation rate of physical capital we follow Grossmann and Steger (2016) who argue that $\delta^K = 0.07$. The growth rate of wage rates is set equal to the annual growth rate of income per capita in the UK for period 1960-2011, $g = 0.02$ (Jones, 2016b).

We assume that individuals become economically active at age 20 and live for a maximum of 100 additional years (i.e., nobody reaches age 121); thus, $T = 101$. In fact, for modern times, 120 years seems to be the maximum life-span, irrespective of increasing life-expectancy in the last decades. The retirement age is reached after $R = 43$ working years (i.e. at age 63).¹⁹

We set d_{\min} equal to the average health deficit index for a 20 year old in recent times. Using Canadian data, Mitnitski et al. (2002a) suggest $d_{\min} = 0.03$. Empirical evidence also suggests that the deficit state that leads to death for sure approximately is about two thirds (e.g. Harttgen et al., 2013); thus, $d_{\max} = 0.67$.

The remaining parameters are the mortality rate curvature parameters (σ, ϕ), the labor requirement per unit of health good (χ), medical R&D technology parameters (ξ, δ^Q, ϑ), innovation step size (γ), the strength of the intertemporal innovation spillover (η), the price mark-up (Γ), health deficit accumulation parameters (ϱ, κ), the initial quality index of health goods (Q_0), the time path of the health care wedge, $\{\varphi_t\}_{t=0}^{\infty}$, the time path of initial survival rates, $\{S_{v,v}\}_{v=0}^{\infty}$, and health deficits of all cohorts with living members in the initial period (denoted by vector \mathbf{d}_0).²⁰ They are chosen to simultaneously match (i) empirical UK survival rates for ages 20-100 and periods 1950, 1970, 1990, 2010, (ii) the UK ratio of health expenditure to GDP (\mathbf{s}_t) between 1980-2010, (iii) the recent average rate of change of the health deficit index ($d_{v,t}$) in the cross-section of Canadian cohorts, (iv) the UK employment share in the health sector (ℓ_t^H).

We shall emphasize that empirical survival rates for a year at a given age are computed

¹⁹In the UK, the average age of withdrawal from the labor market is around 64 for males and slightly below 62 for females in the 2000s (Mitchell and Guled, 2010).

²⁰Initial labor productivity, A_0 , does not enter the dynamical system for the positive analysis (Appendix A).

by employing the mortality rates (up to that age) that are observed for that year. Thus, the survival rates are inferred from mortality rates of the cross-section of living cohorts rather than following cohorts over time. It is thus different to $S_{v,t}$ in the theoretical model. The displayed survival functions throughout this paper are computed analogously for being able to compare them with the empirical data. They would be equal to $S_{v,t}$ only if age-specific mortality rates remained constant over time.

To match UK survival rates from year 1950 onwards (www.mortality.org), as $T = 101$, we need to specify initial conditions for the deficit index of all cohorts with living members in year 1850, i.e. we choose 1850 as initial period ($t = 0$). Suppose initial deficit states, \mathbf{d}_0 , result from a policy regime in which a health care system has never existed (i.e. $\varphi_0 = 1$).²¹ According to (1) and (15), given \mathbf{d}_0 and d_{\min} , the evolution of survival functions is exclusively driven by the exogenous time paths $\{\varphi_t\}_{t=0}^{\infty}$ and $\{S_{v,v}\}_{v=0}^{\infty}$, and the endogenous time path of medical knowledge, $\{Q_t\}_{t=0}^{\infty}$. Matching them turns out to require that φ_t is gradually declining and $S_{v,v}$ is non-decreasing over time.²² The assumed time path of $S_{v,v}$ is plausible as it reflects decreases over time in both child mortality and fatal accidents for young individuals. The assumed time path of φ_t is roughly consistent with the historical improvements in the British health care system (e.g. Stewart, 2015).²³ Advanced country health systems are at present still characterized by under-utilization in various forms. First, the density of physicians is much lower in rural areas than in urban areas, suggesting that access to health care is limited in rural regions (OECD, 2015, Fig. 7.10). Second, there is health care rationing, for instance, through waiting lists for orthopedic surgeries and other forms (OECD, 2015, Fig. 7.11-7.13). Some rationing measures have been introduced in the UK only recently (Edwards et al., 2015). We assume as the baseline calibration that future urbanization and better information about

²¹Formally, denote by $\mathfrak{d}_{\mathbf{a},0}$ the deficit index of a surviving individual of age \mathbf{a} in period 0. According to (15), we have $\mathfrak{d}_{\mathbf{a},0} = d_{\min}(1 + \varrho)^{\mathbf{a}}$ for all $\mathbf{a} \in [0, \bar{\mathbf{a}}_0]$, where $\bar{\mathbf{a}}_0$ is the maximum age in period 0. Thus, $\mathbf{d}_0 = (\mathfrak{d}_{1,0}, \mathfrak{d}_{2,0}, \mathfrak{d}_{3,0}, \dots, \mathfrak{d}_{\bar{\mathbf{a}}_0,0})$.

²²Figure A.1 in Online-Appendix shows the exact time paths for the baseline calibration.

²³For the past, innovations associated with health improvements may not exclusively be interpreted as being associated with the health sector but include better sanitation and better environmental conditions that more individuals received access to over time.

treatment possibilities of patients will continue to lead to improve health care usage over time. That is, we assume for the baseline calibration that φ_t moderately decreases for the coming decades (from about 0.15 in 2010 to 0.05 in year 2080). We assume for the baseline scenario that changes in the health care wedge are anticipated by economic subjects. The initial quality index of health goods (in 1870), Q_0 , is one percent of the steady state value of Q that results for $\varphi = 0.05$.²⁴ However, future rationing measures would mitigate the improvements in access to health care over time possibly to a point that raises φ_t . (We will consider that case as our alternative policy scenario.)

The calibrated model fits the survival functions quite well, as shown in Figure 1. Importantly, we use the cross section of mortality rates for a given year (“period mortality rates”) rather than those for a given cohort over time. Doing so is consistent with the standard way of computing “period life expectancy”.²⁵ In contrast to the alternative and theoretically correct concept of “cohort life expectancy”, it does not account for changes in access or quality to health care over time, that would alter future mortality rates.

In Figure 1, the most important deviation from the data (solid lines) is for middle-aged individuals in 1950 and to a lesser degree in 1970. Second, the implied health expenditure share in GDP (\mathfrak{s}_t) is 5.0 percent in 1980, 5.1 percent in 1990, 6.2 percent in 2000 and 8.3 percent in 2010, compared to the observed UK levels of 5.1, 5.1, 6.3 and 8.5 percent, respectively (OECD, 2016). Third, the rate of change of the health deficit index across cohorts implied by the calibration is 3.8 percent. According to Mitnitski et al. (2002a), the estimated rate of change of the health deficit index at a given year in the cross-section of Canadian cohorts is equal to 4.3 percent for men and 3.1 percent for women. Finally, we may approximate ℓ_t^H with the employment share in human health activities as published by the OECD. For the UK, in 2010, it was 7.3 percent.²⁶ Including

²⁴Our calibrated model leads to the case where steady state quality of health goods $\hat{Q} \equiv \lim_{t \rightarrow \infty} Q_t < \bar{Q}_t$. We can verify that the steady state equilibrium of the calibrated model is saddle-point stable.

²⁵Table A.1 in the Online-Appendix compares in detail the remaining “period life expectancy” at a given age implied by the calibrated model with the empirical ones in the UK. Appendix A shows in detail how remaining life expectancy is computed.

²⁶See http://stats.oecd.org/Index.aspx?DataSetCode=SNA_TABLE3, retrieved on January 31, 2016.

additionally residential care and social work activities (that may include other activities than health care provision) would suggest that ℓ^H was 12.7 percent. Our calibrated model gives us a value in-between, equal to 10 percent in 2010.

Unfortunately, we do not have data for the UK employment share of medical R&D workers (ℓ_t^Q) and the effective patent length (EPL_t) in the medical sector. ℓ_t^Q is critically determined by the price mark up for medical goods (Γ).²⁷ For $\Gamma = 1.25$, we obtain $\ell_t^Q = 0.012$ for the year 2010.²⁸ Moreover, the calibrated model implies a non-profit driven and total innovation probability of 4.1 and 9 percent, respectively, ($\bar{\mu}_{t+1} = 0.034$, $\mu_{t+1} = 0.08$). The implied effective patent length is given by $EPL_t = 1/\mu_{t+1} = 12.5$, close to the 10 years assumed in Jones and Williams (2000). Finally, the ratio of population size aged 63+ (retirement age) to the population size aged 20-62 (working age), DPR_t , implied by the calibrated model is 40 percent for 2010.²⁹

3.3 Results

We now examine for alternative policy scenarios the future evolution (for periods $t \geq t_0$) of age-specific survival rates (based on the “period mortality rates” across cohorts for a given year), age-specific morbidity ($d_{v,t}$), age-specific health care demand ($h_{v,t}$), the total health expenditure share (\mathfrak{s}_t), the employment structure (ℓ_t^H, ℓ_t^Q), the old-age dependency ratio (DPR_t), and age-specific life expectancies.

²⁷See Appendix A for the long run relationship of endogenous observables and the role of the mark up.

²⁸The implied share of workers in medical R&D occupations of about one percent seems high at the first glance, if a strict definition of this occupation is applied, like medical scientists and engineers. For instance, we may consider US data from the Bureau of Labor Statistics (2016) for data availability reasons. Adding up for the year 2015 the number of biological scientists (102,000 employees), medical scientists (110,000 employees) and biomedical engineers (21,000 employees) suggests a combined employment share of only 1.7 per mill. However, a more appropriate interpretation of employment related endogenous technical progress in our model requires to add managers (for strategic decisions and marketing) and other professionals (like patent lawyers) who organize and commercialize medical R&D.

²⁹This is considerably higher than the level in the data (33.1 percent); see Office for National Statistics (2016). The deviation mainly and reflects our neglect of recent immigration into the UK labor market that was primarily enabled by the free movement of labor within the European Union. In the next section, we will thus interpret the change of DPR_t over time rather than its level.

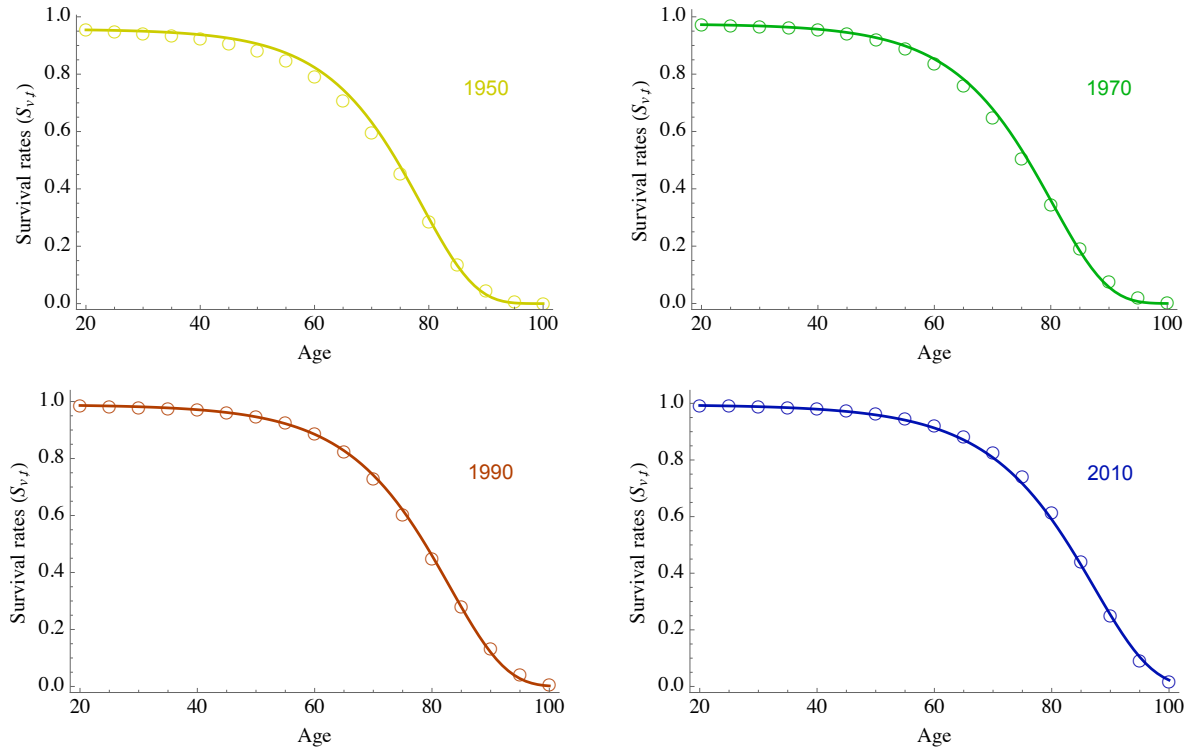


Figure 1: Survival curves for 1950, 1970, 1990 and 2010: Calibrated model vs. UK data.

Notes. (1) Empirical series: solid lines, calibrated model: circles (2) Data source: www.mortality.org. (3) Time paths $\{\varphi_t\}$ and $\{S_{v,v}\}$ are displayed in Figure A.1 (Online-Appendix). (4) Initial quality index (in 1870) $Q_0 = 0.01 \cdot \lim_{t \rightarrow \infty} Q_t$ for $\lim_{t \rightarrow \infty} \varphi_t = 0.05$. (5) Other parameters: $\alpha = 0.38$, $\delta^K = 0.07$, $\sigma = 1.5$, $\phi = 2.65$, $\chi = 0.9$, $\varrho = 0.04$, $\kappa = 0.06$, $\xi = 0.065$, $\eta = 0.12$, $\delta^Q = 0.02$, $\vartheta = 0.6$, $g = 0.02$, $\bar{r} = 0.05$, $d_{\min} = 0.03$, $d_{\max} = 0.67$, $\gamma = 0.1$, $\Gamma = 1.25$, $T = 101$, $R = 43$.

3.3.1 Baseline Scenario

We start with the implications of the baseline scenario for the future. Panel (a) of Figure 2 displays implied survival curves for 2020 (solid black line), 2050 (dashed blue line) and 2080 (dotted green line), suggesting that they are considerably shifting upwards over time. Rising survival rates are driven by declining morbidity, displayed in panel (b). This is because age-specific mortality rates ($m_{v,t}$) decrease when health deficits ($d_{v,t}$) at a given age decline over time, according to (1). According to (15), the improving health status is jointly driven by the assumed (slight) improvements the future access to health care and the endogenously increasing stock of medical knowledge (Q_t). For instance, the

health deficit index (the fraction of actual health deficits out of a set of possible deficits) for someone having reached age 80 declines from 18.5 percent in 2020 to 12.9 percent in 2050 and 9.7 percent in 2080.

The evolution of health deficits ($d_{v,t}$) determines, in interaction with survival rates ($S_{v,t}$), the evolution of age-specific health care demand ($h_{v,t}$), according to (16). As displayed in panel (c), total age-specific health care demand is inverted U-shaped as a function of age.³⁰ Over time it shifts to the right. That is, health care demand decreases for younger individuals and increases for older ones. The shift reflects that, for younger individuals, improvements in the quality of health goods have little effect on survival rates, whereas the opposite holds for older individuals. In fact, survival rates of younger individuals are high and their deficit index is low to begin with. By contrast, total health care demand for older age-groups is rising over time since improvements in both access to health care and better quality help reducing age-specific mortality rates considerably.

Despite declining morbidity and declining mortality at any age, health costs may increase as response to higher survival rates. In other words, population ageing may result in increasing health expenditure shares (\mathfrak{s}_t). Panel (d) indeed shows that \mathfrak{s} increases over time from 8.4 percent in 2020 to 9.2 percent in 2050 and 10.3 percent in 2080.

Panel (e) shows that rising health care demand is, quite intuitively, associated with a rising employment share in the production of health goods (ℓ_t^H). Importantly, it also raises incentives for health innovations through increased market size. This implies that the medical R&D labor share (ℓ_t^Q) is rising over time as well, according to panel (f).

As is well known, demographic change induced by human ageing leads to a rising old-age dependency ratio (DPR_t) over time. The interesting question is by how much rising survival rates ($S_{v,t}$) raise DPR_t , according to (22). Projections in the literature that do not account for the endogeneity of health care quality and possible changes to health care access are not very informative in this respect. Panel (i) shows the evolution of the ratio of population size aged 63+ (retirement age) to the population size aged

³⁰We use the true “cohort mortality rates” ($m_{v,t}$) for computing survival rates rather than “period mortality rates”, unlike in panel (a) of Figure 1.

20-62 (working age). It suggests that DPR rises from 45 percent in 2020 to 65.2 percent in 2050 and 88.9 percent in 2080. Thus, our model implies that the ratio of retirees to workers will be doubling in only 60 years.

In sum, our model gives rise to an important insight that has yet not been clearly worked out in the literature: population ageing that is associated with health improvements at any age may inevitably be associated with rising health expenditure shares even though prices of health goods grow at the same rate than income.³¹ In this sense, rising health costs are good news. As we will argue in the next section (welfare analysis), therefore, measures to raise health care rationing may not be desirable.

3.3.2 Reform Scenario: Stable Health Expenditure Share

Before doing so, we analyze the consequences of a health care rationing scheme that stabilizes the health expenditure share (\mathfrak{s}_t) for $t \geq t_0$, starting in 2020. It requires to substantially increase in the health care provision wedge (φ_t) over time, from 11 percent in 2020 to 17 percent in year 2050 and 27.2 percent in year 2080.³² The thick lines in Figure 3 repeat the results for the baseline scenario shown in Figure 2, whereas the thin lines correspond to the reform scenario with extended health care rationing. Panels (a) and (b) suggest that survival rates and morbidity ($d_{v,t}$) do not improve much over time, respectively, in contrast to the baseline scenario. The differences across policy regimes are particularly visible for 2080, whereas differences are small for 2050. Panel (c) shows that age-specific health care demand ($h_{v,t}$) is reduced compared to the baseline scenario, particularly for older age-groups. It reflects that survival rates of older cohorts do not improve much anymore over time. Panel (d) displays the, by design, time-invariant health expenditure share (\mathfrak{s}_t) in the reform scenario. Related, panel (e) shows that the employment share in the production of health goods (ℓ_t^H) is basically time-invariant, reflecting policy-driven stabilization of market size. In turn, according to panel (f), the

³¹Recall that labor income is the exclusive source of health care finance in our model and health good prices grow at the same rate than wage rates by construction.

³²The scheme is displayed in Figure A.2 of the Online-Appendix.

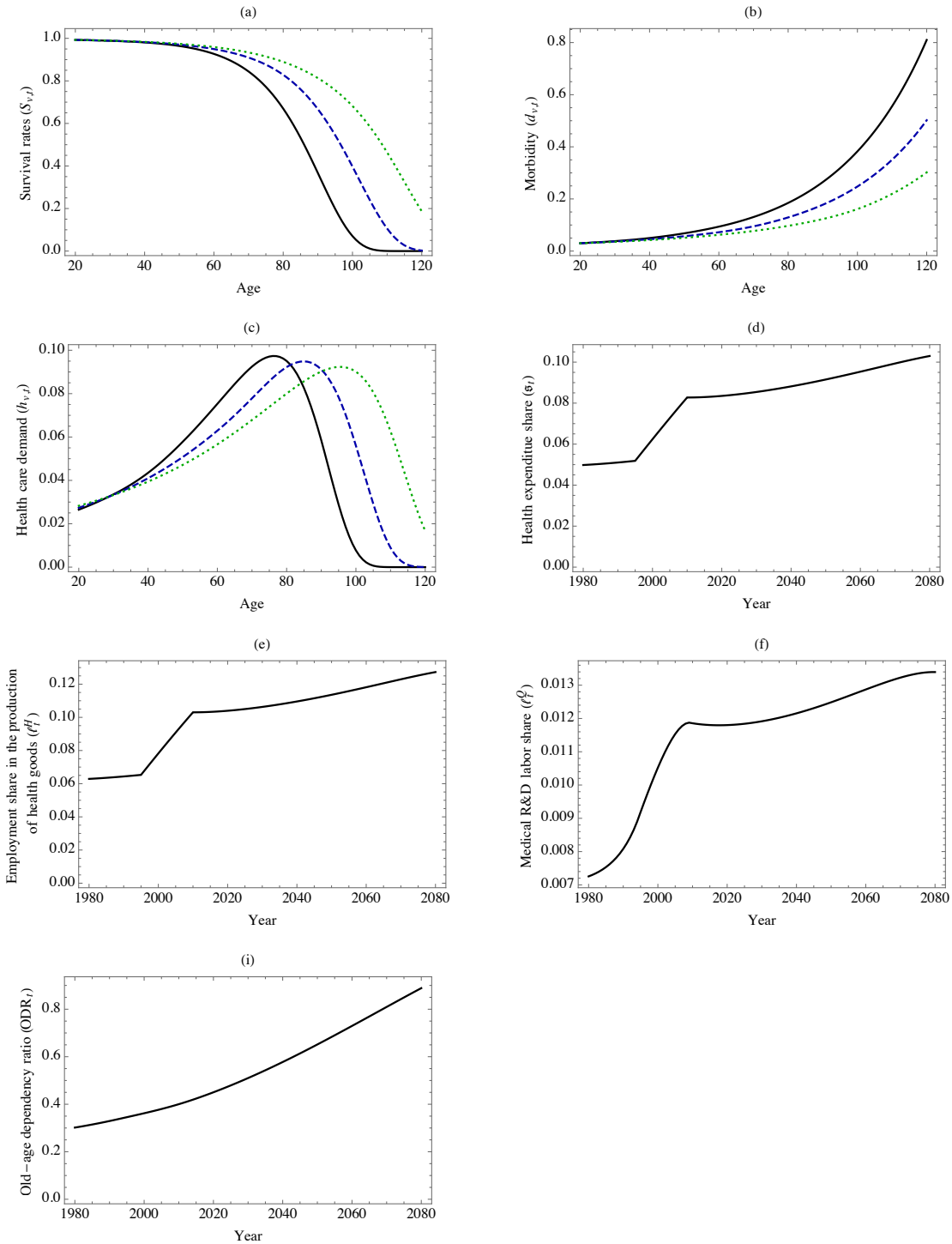


Figure 2: The future of human health, longevity, and health costs for the baseline policy scenario.

Notes: Panels (a)-(c): Solid black line for 2020, dashed (blue) line for 2050, dotted (green) line for 2080. Parameters as for Figure 1.

medical R&D labor share (ℓ_t^Q) is quite stable for time as well. That is, compared to the baseline scenario, medical R&D effort is considerably reduced. Such dynamic incentive effect of health care rationing adds to the static reduction in health care usage to jointly slow down both the process of population ageing and health improvements in society. According to panel (i), it also materializes in a slowdown of the increase over time in the old-age dependency ratio (DPR_t), now rising more moderately than in the baseline scenario, from 45 percent in 2020 to 64.6 percent in 2050 and 83.6 percent in 2080.

3.3.3 Comparing Life Expectancy Effects

We can compare age-specific (remaining) life expectancies from the age-specific mortality rates for the two scenarios. We can do that in two ways. First, we can calculate for both scenarios the “period life expectancy”, as it is usually done in the literature (e.g. Kontis et al., 2017). For this, like for the displayed survival rates, we use the “period mortality rates” from the cross-section of cohorts and pretend they stay constant over time. As will become apparent shortly, this dramatically underestimates life expectancy when access or quality to health care significantly improves over time. Second, therefore, what we shall really be interested in is “cohort life expectancy”, that uses the correct age-specific mortality rates ($m_{v,t}$) in the future to compute remaining life expectancy of a member of a cohort born in v from t onwards.

Period Life Expectancy Figure 4 displays the life expectancy differences across scenarios (solid vs. dashed line) over time for someone having reached age 20 and someone aged 65 in a given year. The circles show the evolution of the respective empirical period life expectancies in the UK, underlying how well the calibrated model fits the data.

For the baseline scenario, we find that an individual that has reached age 20 in year 2020 (i.e. was born in 2000) can expect to live until age 83.6 under the (invalid) assumption that the stock of medical knowledge (Q) and the health care wedge (φ) remains constant over time. Analogous figures are 93.5 and 103.7 years when reaching

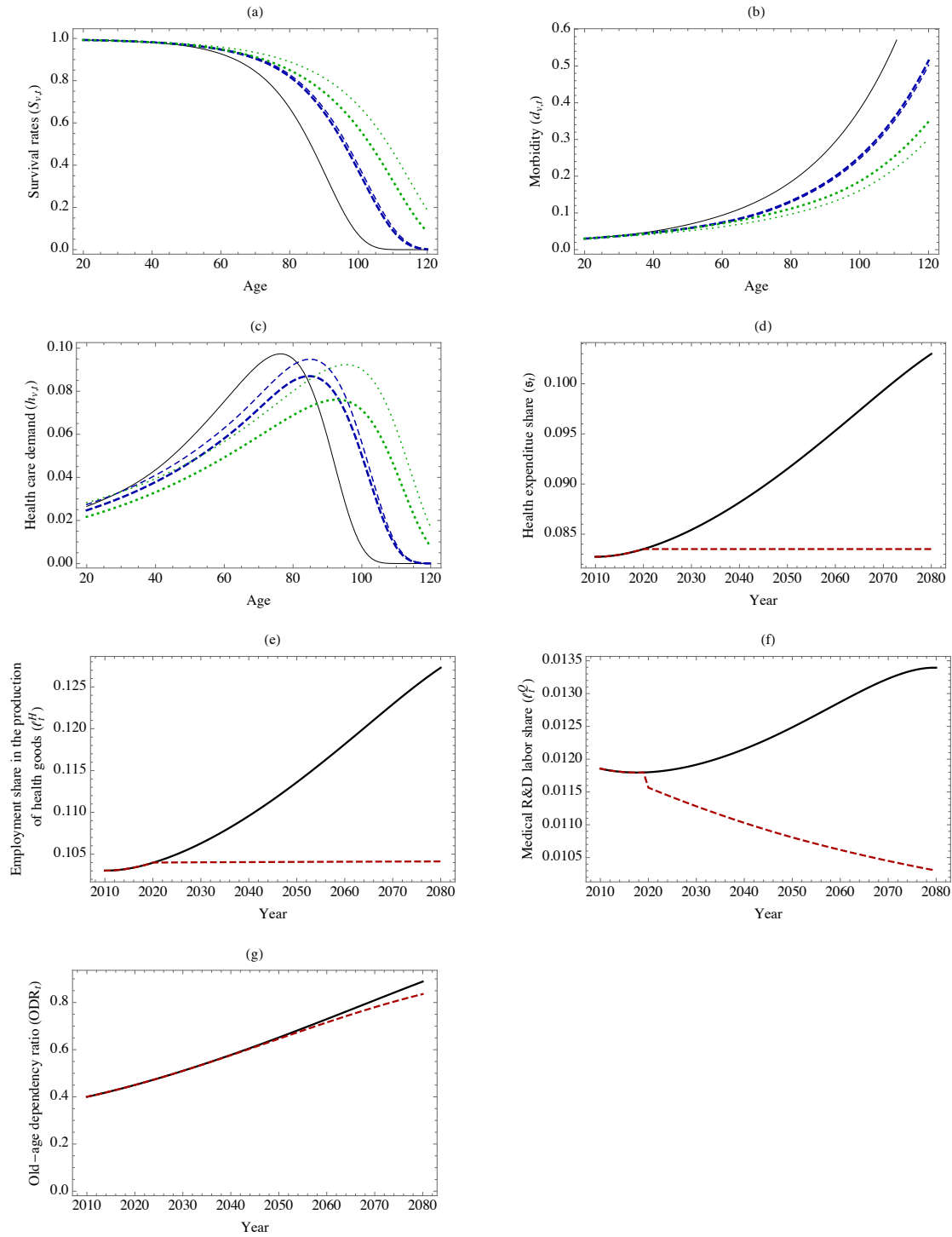


Figure 3: Effects of extending health care rationing from year 2020 onwards for stabilizing the health expenditure share (reform scenario).

Notes: (1) Panels (a)-(c): Solid black line for 2020, dashed (blue) line for 2050, dotted (green) line for 2080. (2) Thin lines repeat the baseline scenario, thick lines show the new scenario.

(3) Time path $\{\varphi_t\}$ that is displayed in Figure A.2 (Online-Appendix). Parameters as for Figure 1.

age 20 in 2050 and 2080, respectively.³³ Moreover, someone having reached age 65 in 2020, 2050 and 2080 can expect to live until age 86.9, 96.2 and 106.2, respectively.

With the considered health care reform that stabilizes the health expenditure share, period life expectancy increases less than in the baseline scenario. The difference across scenarios is 0.8 years and 4.6 years for someone reaching age 20 in year 2050 and 2080, respectively, and 0.7 and 4.0 years for someone having reached age 65 in 2050 and 2080, respectively.³⁴

In sum, the model suggests for both scenarios considerable gains in period life expectancy gains over time. Shorter run effects from implementing the cost-saving health care reform are smaller than longer run effects. Over time, by raising morbidity, the reform induces sizable reductions in life expectancy gains.

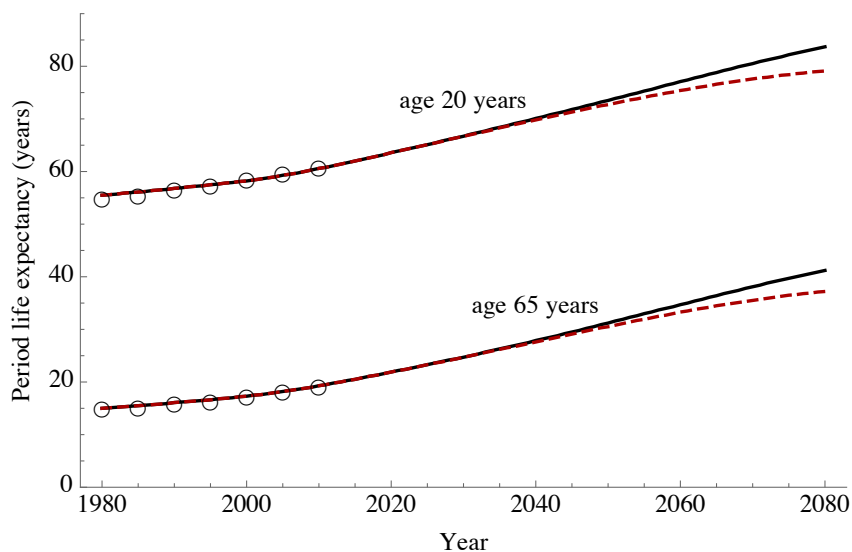


Figure 4: Implied remaining period life expectancies at age 20 and age 65: baseline vs. reform scenario.

Notes: (1) Solid line for baseline, dashed line for reform, circles according to UK data. (2) Parameters as for Figure 2 (baseline) and Figure 3 (reform).

³³See Table A.2 in Online-Appendix (left columns) for the *remaining* age-specific “period life expectancies”.

³⁴Again, see Table A.2 in Online-Appendix (right columns).

Cohort Life Expectancy Figure 5 again compares the two scenarios, but now examines the cohort life expectancies at age 20 and 65, fully taking into account that mortality rates may (endogenously) change over time. In the baseline scenario, they will unambiguously decrease because of an endogenously increasing Q and our assumption that the health care wedge (φ_t) is non-increasing over time. Also recall that, in the reform scenario, φ_t is increasing from 2020 onwards in order to stabilize the health expenditure share, in turn reducing innovation incentives.

First, we see from Figure 5 that in both scenarios the (conceptually correct) life expectancy for those cohorts born already are considerably higher than period life expectancy. Someone with age 20 in year 1980 (i.e. born in 1960) can expect to live until age 91.1 years in the baseline scenario and 90.3 years in the reform scenario when taking into account favorable future reductions in mortality rates. The static view displayed in Figure 4 would underestimate the remaining life expectancy in both scenarios by more than 14 years. In the baseline scenario, someone who is 20 year old in 2020 can expect to die at age 106.2 whereas period life expectancy is 22.6 years shorter. Someone with age 65 in 1980 could have expected to live 16.4 additional years in both scenarios, whereas according to period life expectancy it was 15 years. Clearly, the error by taking period life expectancy rather than cohort life expectancy is much smaller for higher ages. It reflects that the time frame to profit from improvements in health care quality and access is smaller, given that an individual accumulates health deficits grow exponentially when holding Q and φ constant.

Second, the difference in the evolution of life expectancy across scenarios is considerably higher in Figure 5 compared to Figure 4. An individual that has reached age 20 in year 2050 can expect to live until age 111 in the baseline scenario and until age 100.6 in the reform scenario, i.e. one decade less.³⁵ Thus, the concept of period life expectancy

³⁵See Table A.3 in Online-Appendix. Our predictions may be compared to the estimates of cohort life expectancy by the Office for National Statistics (2015) for the UK. It suggests that a female who has reached age 20 in year 2050 can expect to live until age 109.1 in the most optimistic of three scenarios (2.1 years longer than a comparable male), but only until age 85.5 years in the most pessimistic scenario (2.9 years longer than a comparable male).

severely underestimates the potential life expectancy effects of health care rationing (recall that the difference in period life expectancy across scenarios in the same case is only 0.8 years). Someone who is 65 in 2050 can expect to live until age 106.1 in the baseline scenario and 3.7 less in the reform scenario. Hence, like for period life expectancy, the loss in remaining life expectancy from stabilizing the health expenditure share is lower for older persons.

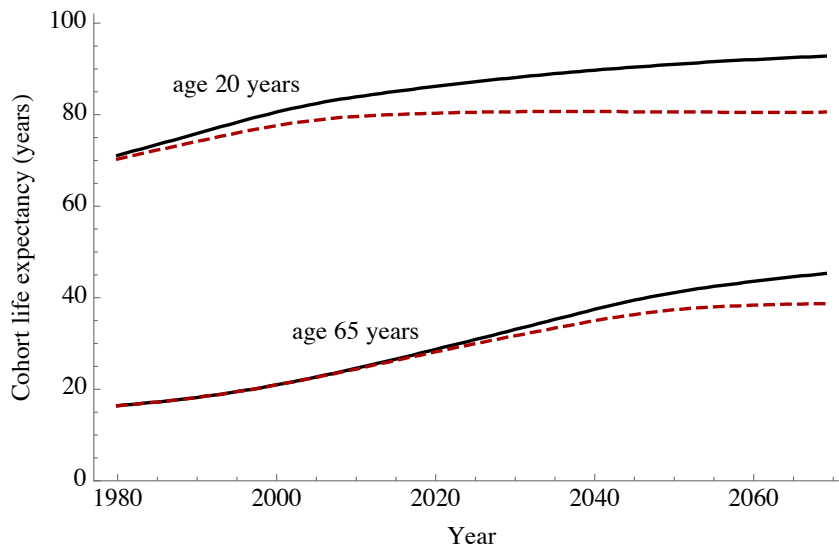


Figure 5: Implied remaining cohort life expectancies at age 20 and age 65: baseline vs. reform scenario.

Notes: (1) Solid line for baseline, dashed line for reform. (2) Parameters as for Figure 2 (baseline) and Figure 3 (reform).

4 Normative Analysis

In this section, we examine the welfare implications of the switch in health policy from the baseline scenario (Figure 2) to the one of extended rationing from year 2020 onwards (Figure 3). For concreteness, we assume that the policy regime switch is not anticipated by living members of generations born before the shock.

4.1 Welfare Behind the Veil of Ignorance

We first need to define an appropriate welfare criterion. Facing uncertain death, rational individuals calculate (under rational expectations) the expected utility from life-time consumption by multiplying the instantaneous utility u experienced in a given period with the probability to survive beyond that period ($S_{v,t}$). In this section we consider welfare behind the veil of ignorance. We assume that instantaneous utility depends on current consumption levels of the numeraire and health status as measured by the health deficit index.

Formally, with maximum life span T , a member of cohort v has preferences that are represented by the intertemporal utility function

$$U_v = \sum_{t=v}^{v+T-1} \beta^{t-v} S_{v,t} u(c_{v,t}, d_{v,t}), \quad (23)$$

where instantaneous utility depends on consumption level, $c_{v,t}$, and morbidity (i.e. health deficit index, $d_{v,t}$):

$$u(c_{v,t}, d_{v,t}) \equiv \frac{\log c_{v,t}}{(1 + d_{v,t})^\zeta}. \quad (24)$$

$\beta \geq 0$ is the discount factor. $\zeta > 0$ measures to which extent a higher deficit state reduces the marginal utility of consumption. For an individual without health deficits ($d_{v,t} = 0$) or in the case where $\zeta = 0$, we are back to a standard instantaneous utility function. With log-utility, the intertemporal elasticity of substitution is unity, as supported by Chetty (2006), among others.

We assume that the health care system is financed by a constant contribution rate out of wage income, denoted by τ_t in period t .³⁶ The health care budget is balanced in each point in time; that is, revenue, $\tau_t w_t L_t$, equals expenses, $p_t H_t$. Recalling (12), the health contribution rate is proportional to the share of labor (ℓ^H) allocated for producing

³⁶Assuming that health insurance is paid by workers and enjoyed by retirees greatly simplifies the analysis. If health insurance were also be financed by capital income, we would have to keep track of aggregate asset holdings in the economy. Recall that these are unrelated to investments in our model. In our model, tax-financing health care no distortions because we abstract from a labor supply choice.

health goods and services:

$$\tau_t = \Gamma \ell_t^H. \quad (25)$$

Denote asset holding (“wealth”) of a member of cohort v in t by $a_{v,t}$. Initial asset holding is $a_{v,v} = 0$ since there is no bequest motive and the annuity market is perfect. We assume fair insurance within a cohort in the annuity market, where zero-profit insurance companies keep the individuals’ wealth after death. The law of motion for an individual of cohort v , wealth at $t \geq v$ can be written as

$$a_{v,t+1} = (1 - \tau_t)w_t + (1 + r_{v,t})a_{v,t} - c_{v,t}, \quad (26)$$

where the cohort-specific interest factor between date t and $t + 1$ is given by³⁷

$$1 + r_{v,t} = \frac{1 + \bar{r}}{1 - m_{v,t-1}}. \quad (27)$$

Individuals of each generation v choose their consumption paths $\{c_{v,t}\}_{t \geq v}$ to maximize utility U_v s.t. (26) and non-negativity constraint $a_{v,v+T} \geq 0$. They have perfect foresight about the health contribution rate and health deficit states (including their implications on mortality risks as given by 1)) that would result in the baseline policy regime and take these as given when optimizing.

The policy reform of extended rationing, assumed to apply in period t_0 (again, in year 2020) is assumed to be unanticipated. That is, living members of generations $v < t_0$ (i.e. those already born) re-optimize. All agents have perfect foresight of the new policy regime from t_0 onwards. The optimization problems of both generations $v < t_0$ and $v \geq t_0$ are solved in Appendix B. Welfare behind the veil of ignorance equals expected life-time utility from the resulting consumption paths.

Welfare effects of policy reforms are evaluated as follows. Let superscript 0 on consumption levels, deficit states and survival rates denote the values of these variables in the

³⁷See e.g. Heijdra, Mierau and Trimborn (2016).

baseline policy regime and superscript 1 the values in the policy reform regime. Moreover, let

$$U_v^i(\psi) \equiv \sum_{t=v}^{v+T-1} \beta^{t-v} S_{v,t}^i \frac{\log(\psi c_{v,t}^i)}{(1 + d_{v,t}^i)^\zeta} \quad (28)$$

denote the life-time utility of cohort v when consumption levels in scenario $i \in \{0, 1\}$ are multiplied with factor $\psi > 0$. By definition (28), life-time utility in the reform scenario is $U_v^1(1)$. We report cohort-specific factors ψ_v that solve

$$U_v^0(\psi_v) = U_v^1(1). \quad (29)$$

Thus, ψ_v is the equivalent variation (EV) welfare measure in the baseline scenario such that cohort v gets the same utility than in the reform scenario.³⁸

4.2 Calibration

We choose a typical value for the subjective discount rate, β , such that $\beta(1 + \bar{r}) > 1$,³⁹ setting $\beta = 0.98$ (recall $\bar{r} = 0.05$). Next, we calibrate ζ , which determines the loss in marginal utility from consumption caused by health deficits. Finkelstein et al. (2013) find that, starting at the mean, a one-standard deviation increase of chronic diseases is associated with a decline in the marginal utility of consumption, denoted by *LOSS*, of 11.2 percent. The 95% confidence interval ranges from 2.7% to 16.8%. Marginal consumption utility reads as $(1 + d_{v,t})^{-\zeta}/c_{v,t}$. Evaluated at the mean deficit index, $\mathbb{E}(d)$, and denoting the standard deviation by $\mathcal{STD}(d)$, the estimate of Finkelstein et al. (2013) then suggests that ζ is given by

$$\frac{[1 + \mathbb{E}(d) + \mathcal{STD}(d)]^{-\zeta}}{[1 + \mathbb{E}(d)]^{-\zeta}} = 1 - \text{LOSS}. \quad (30)$$

³⁸See Jones and Klenow (2016) for a similar way to measure welfare differences of randomly chosen individuals in a cross-country context rather than across policy regimes.

³⁹If we assumed $\beta(1 + \bar{r}) = 1$, then individual consumption would monotonically decrease with age, which is inconsistent with the evidence.

According to Mitnitski et al. (2002), the mean deficit index in the population is $\mathbb{E}(d) = 0.054$ and the standard deviation is $\mathcal{STD}(d) = 0.024$. Hence, $\zeta = -44.42 \cdot \log(1 - LOSS)$. The point estimate of $LOSS = 0.112$ thus suggests $\zeta = 5.1$; the bounds of the 95% confidence interval imply $\zeta \in [1.22, 8.17]$.

Finally, we have to calibrate the initial general state of technology, A_0 . This is because the time path of productivity and wage income potentially affects welfare changes. We do this by targeting a certain ratio of the value of life to GDP per worker. Denote the value of life of an individual born in v by W_v and assume it is given by expected (indirect) life-time utility in the baseline scenario for a cohort with age 20 in 2010 normalized by the marginal instantaneous (indirect) utility in the initial period of life:

$$W_v \equiv \frac{U_v^0(1)}{\frac{\partial u(c_{v,v}, d_{\min})}{\partial c}} = U_v^0(1) (1 + d_{\min})^\zeta c_{v,v}. \quad (31)$$

We set A_0 (still assuming that A_t grows annually at rate $g = 0.02$) such that for the year 2010 W_v/y_v equals 80 or, alternatively 60 and 100.⁴⁰ Given that GDP per person employed in the UK was about 75,000 US\$ (PPP) in 2010, $W_v/y_v = 80$ corresponds to a value of life of 6 million US\$, whereas $W_v/y_v = 60$ and $W_v/y_v = 100$ corresponds to a value of life of 4.5 and 7.5 million US\$, respectively.

4.3 Results

Figure 6 displays the cohort-specific welfare effects (EV) of extending health care rationing from year 2020 onwards for stabilizing the health expenditure share, compared to the baseline scenario without policy change. For older cohorts (born in the 1960s), the policy reform is almost neutral for welfare. On the one hand, those close to retirement age do not save much health care contributions (that we assumed to be entirely paid by

⁴⁰This is an explicit normative judgement. In fact, the value of life is an inherently normative concept. Any attempt to compute it in the literature has necessarily been based on strong assumptions. For instance, Hall and Jones (2007) assume that the value of an additional year lived equals the health costs to increase life expectancy by an additional year. This implicitly assumes that the US health system is optimal in the sense of equating marginal benefits and marginal costs of saving lives.

workers) from the reform. On the other hand, the detrimental effects from the reform on longevity and morbidity are small for individuals who are old already at the time of the reform.

For later cohorts, however, the welfare change becomes substantially and more highly negative, the later the year of birth. This is remarkable since younger cohorts save health contributions over a long working period. Those who start working life after the reform year 2020 benefit from reduced contributions even for the entire working life, whereas reductions in survival rates in response to the reform are minor for working-aged individuals. However, reduced survival rates during retirement and reduced instantaneous utility from higher health deficits by far outweigh the utility increases from higher disposable income for younger generations, especially future ones. We estimate that someone who is 20 years old in 2020 would experience a reform-induced welfare loss of 20.4 percent when assuming the medium ratio of the value of life to GDP per worker. Assuming alternatively a lower or higher ratio, the losses are 16.1 and 24.4 percent, respectively. Someone who is 20 years old in 2050 would experience a corresponding welfare loss of in the range of 34.4-47.8 percent, where the loss is 41.5 percent in the medium case. Thus, our welfare analysis suggests potentially dramatic welfare losses from extending health care rationing, reflecting the sizable losses in cohort life expectancy from the reform displayed in Figure 5.

5 Conclusion

We studied the interdependence of medical R&D, health expenditure, longevity and morbidity of an age-structured population in a novel, multi-period overlapping generations model. Our analysis sheds light on the important debate on the sustainability of health care finance that results from medical advances and associated gains on longevity. A salient feature that enables us to perform such analysis is to capture biologically founded ageing, based on gerontology research, in order to calibrate the model.

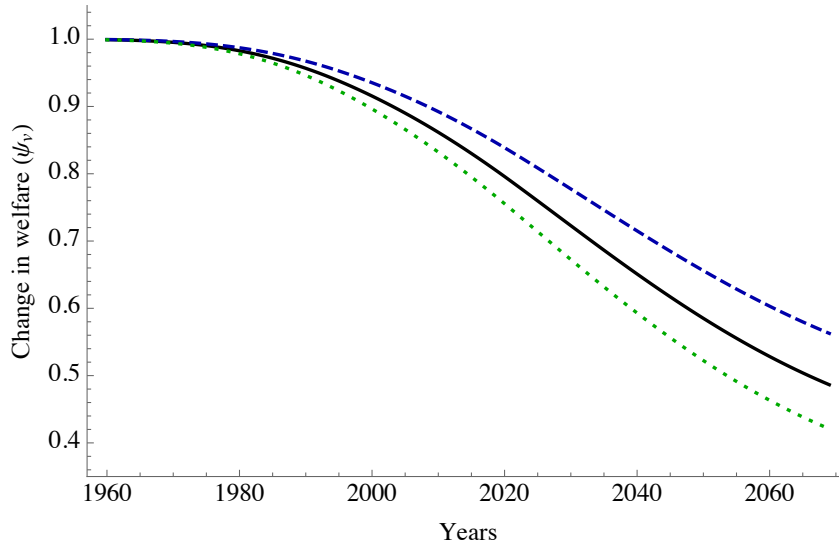


Figure 6: Cohort-specific welfare effects (EV) of extending health care rationing for stabilizing the health expenditure share in three alternative cases.

Notes: (1) For instance, the displayed change in welfare evaluated at year 2020 corresponds to the EV of the cost-saving reform for someone who is 20 years old in 2020. (2) Solid (black) line: medium ratio of value of life to GDP per worker, dashed (blue) line: low ratio, dotted (green) line: high ratio, (2) $\beta = 0.98$, $\zeta = 5.1$. $A_0 \in \{1.55, 6, 23\}$ for small, medium, high ratio of value of life to GDP per worker. Time path $\{\varphi_t\}$ in baseline scenario 0 and reform scenario 1 are displayed in Figure A.1 and Figure A.2, respectively (Online-Appendix). Other parameters as for Figure 1.

Our calibrated model implies substantial future increases in human longevity that are associated with both reductions in morbidity and a rising health expenditure share in GDP. Moreover, the results suggest that stabilizing the health expenditure share by extending health care rationing has potentially sizable effects on morbidity and longevity in the longer run, associated with reduced medical R&D incentives. The implied welfare effects of extending health care rationing may be substantially negative particularly for future generations.

Our results may be understood as warning for policy makers to overlook the detrimental welfare costs from reduced longevity and increased morbidity of health care rationing for the purpose of addressing budgetary problems in health care finance. Our analysis suggests, in fact, that population ageing and rising health costs interact with each

other through the market size effect of increased life expectancy on medical technological progress. In this sense, rising health expenditure shares are not a problem but a blessing for human health and longevity that is fueled by medical R&D.

In future research we aim to allow for the possibility of private purchases of health goods and services in a health care system with rationing. Its consideration would naturally refocus the debate on health inequality issues, for instance, when purchases of life-saving drugs may be available only for richer individuals. Such policy regime could give rise to major distributional conflicts that are different to those in societies without significant health care rationing. The associated challenges for modern societies appear profound and discomfoting.

Appendix

A. Positive Analysis

- **Dynamical System:** Recall that $V_{t+1}(j)$ is the value of an innovation in health sector j resulting from R&D effort in t . A representative R&D firm searching for a vertical innovation to treat illness j solves

$$\max_{l_t(j)} \{\mu_{t+1}(j)V_{t+1}(j) - w_t l_t(j)\} = \left(\tilde{\xi}_t V_{t+1}(j) - w_t \right) l_t(j), \quad (32)$$

according to (7). Thus, $\tilde{\xi}_t V_{t+1}(j) = w_t$ for all j . Thus, in equilibrium, R&D firms do not earn profits. Moreover, $l_t(j) = L_t^Q$ and $V_{t+1}(j) = V_{t+1}$ are the same for all $j \in [0, 1]$. Using $\tilde{\xi}_t = \xi \cdot (L_t^Q)^{-\vartheta}$, the zero-profit condition for R&D firms reads as

$$V_{t+1} \xi (L_t^Q)^{-\vartheta} = w_t. \quad (33)$$

Given that there is a unit mass of health sectors, the total and per firm amount of labor allocated to the production of health goods is given by $L_t^H = \chi H_t$. Thus,

with mark up Γ , the profit per health good producer is

$$\pi_t = (p_t - \chi w_t) H_t = (\Gamma - 1)\chi w_t H_t = (\Gamma - 1)w_t L_t^H, \quad (34)$$

according to (12). According to (18),

$$\begin{aligned} V_t = & \pi_t + \frac{1 - \mu_{t+1}}{1 + \bar{r}} \pi_{t+1} + \frac{(1 - \mu_{t+1})(1 - \mu_{t+2})}{(1 + \bar{r})^2} \pi_{t+2} + \\ & \frac{(1 - \mu_{t+1})(1 - \mu_{t+2})(1 - \mu_{t+3})}{(1 + \bar{r})^3} \pi_{t+3} + \dots, \end{aligned} \quad (35)$$

$$V_{t+1} = \pi_{t+1} + \frac{1 - \mu_{t+2}}{1 + \bar{r}} \pi_{t+2} + \frac{(1 - \mu_{t+2})(1 - \mu_{t+3})}{(1 + \bar{r})^2} \pi_{t+3} + \dots = \frac{1 + \bar{r}}{1 - \mu_{t+1}} (V_t - \pi_t). \quad (36)$$

Using (34) in (36), we get the following no-arbitrage condition in the market that finances health R&D:

$$\frac{1 - \mu_{t+1}}{1 + \bar{r}} \frac{V_{t+1}}{V_t} + \frac{(\Gamma - 1)w_t L_t^H}{V_t} = 1. \quad (37)$$

Now let us define $\mathcal{V}_t \equiv V_t/A_t$. Denote by $\mathfrak{d}_{\mathbf{a},t}$ the health deficit index of a surviving individual of age \mathbf{a} in period t and $\tilde{\mathfrak{a}}_t$ as the highest age in period t such that $\mathfrak{d}_{\mathbf{a},t} \leq d_{\max}$. Thus, $\bar{\mathfrak{a}}_t \equiv \min(\tilde{\mathfrak{a}}_t, T)$ is the age at which an individual dies for sure. Neglecting the household side (which is relevant for the welfare analysis only), the dynamical system can be summarized as follows:

$$\mathfrak{d}_{1,t+1} = [1 + \varrho - (1 - \varphi)\kappa Q_t] d_{\min}, \quad (38)$$

$$\mathfrak{d}_{2,t+1} = [1 + \varrho - (1 - \varphi)\kappa Q_t] \mathfrak{d}_{1,t}, \quad (39)$$

$$\mathfrak{d}_{3,t+1} = [1 + \varrho - (1 - \varphi)\kappa Q_t] \mathfrak{d}_{2,t}, \quad (40)$$

⋮

$$\mu_{t+1} = \eta Q_t + (1 - \eta Q_t) \cdot \xi \cdot (L_t^Q)^{1-\vartheta}, \quad (41)$$

$$Q_{t+1} - Q_t = \gamma (1 - \eta Q_t) \xi (L_t^Q)^{1-\vartheta} - (\delta^Q - \gamma \eta) Q_t, \quad (42)$$

$$\frac{1 - \mu_{t+1}}{1 + \bar{r}} \mathcal{V}_{t+1} (1 + g) + (\Gamma - 1) w_t L_t^H = \mathcal{V}_t, \quad (43)$$

$$\mathcal{V}_{t+1} (1 + g) \xi \cdot (L_t^Q)^{-\vartheta} = \omega, \quad (44)$$

$$\begin{aligned} H_t = & (1 - \varphi_t) S_{t,t} d_{\min} + (1 - \varphi_t) (1 - \tilde{m}(d_{\min})) \times \\ & \{S_{t-1,t-1} \mathfrak{d}_{1,t} + \mathfrak{d}_{2,t} S_{t-2,t-2} (1 - \tilde{m}(\mathfrak{d}_{1,t-1})) + \\ & \mathfrak{d}_{3,t} S_{t-3,t-3} (1 - \tilde{m}(\mathfrak{d}_{2,t-1})) (1 - \tilde{m}(\mathfrak{d}_{1,t-2})) + \dots + \\ & \mathfrak{d}_{\bar{a}_t,t} S_{t-\bar{a}_t,t-\bar{a}_t} (1 - \tilde{m}(\mathfrak{d}_{\bar{a}_t-1,t-1})) (1 - \tilde{m}(\mathfrak{d}_{\bar{a}_t-2,t-2})) \times \dots \times (1 - \tilde{m}(\mathfrak{d}_{1,t-\bar{a}_t+1}))\} \end{aligned} \quad (45)$$

$$L_t^Y + L_t^H + L_t^Q = L_t, \quad (46)$$

according to (15), (9), (11), (37), (33), (17) and (19), respectively, for a given $Q_0 > 0$ and a given vector of current deficit states of the cohorts living in period 0, $\mathbf{d}_0 \equiv (\mathfrak{d}_{1,0}, \mathfrak{d}_{2,0}, \mathfrak{d}_{3,0}, \dots, \mathfrak{d}_{\bar{a}_0,0})$.

- **Long Run Equilibrium:** We next derive the long run equilibrium (focussing on the case where $Q_{t+1} = Q_t$ holds for $t \rightarrow \infty$ only). Setting $Q_{t+1} = Q_t = Q$ in (10) and omitting the time index, we obtain

$$L^Q = \left(\frac{\delta^Q Q - \bar{\mu}}{(1 - \bar{\mu}) \xi} \right)^{\frac{1}{1-\vartheta}}. \quad (47)$$

Using $\mathcal{V}_{t+1} = \mathcal{V}_t = \mathcal{V}$ in (43) implies

$$\mathcal{V} = \frac{(\Gamma - 1)(1 + \bar{r}) \omega L_t^H}{\bar{r} - g + \mu(1 + g)}. \quad (48)$$

Moreover, according to (44) and (47),

$$\mathcal{V} = \frac{\omega(L^Q)^\vartheta}{(1+g)\xi}. \quad (49)$$

Combining (48) and (49) implies

$$\frac{(L^Q)^\vartheta}{\xi} = \frac{(\Gamma-1)(1+\bar{r})L^H}{\frac{\bar{r}-g}{1+g} + \mu} \quad (50)$$

Let $\hat{\mathbf{d}}_{\mathbf{a}}$ denote the long run health deficit index of someone of age $\mathbf{a} \geq 0$, associated with the steady state quality index $\hat{Q} < \bar{Q}$. Moreover, let $\hat{\varphi} \equiv \lim_{t \rightarrow \infty} \varphi_t$ and suppose that $\hat{S} \equiv \lim_{v \rightarrow \infty} S_{v,v} = 1$. According to (15),

$$\hat{\mathbf{d}}_{\mathbf{a}+1} = \left[1 + \varrho - (1 - \hat{\varphi})\hat{Q} \right] \hat{\mathbf{d}}_{\mathbf{a}}, \quad (51)$$

with initial condition $\hat{\mathbf{d}}_0 = d_{\min} > 0$. The solution of difference equation (51) gives us the steady state age-path of the health deficit index conditional on φ and \hat{Q} , denoted by $\mathfrak{D}(\mathbf{a}, \varphi, \hat{Q})$, $\mathbf{a} \geq 0$. Function $\mathfrak{D}(\mathbf{a}, \varphi, Q)$ is increasing in age, \mathbf{a} , increasing in φ , and decreasing in quality index, Q . Let $\bar{\mathbf{a}}_\infty$ denote the largest age \mathbf{a} such that $\mathfrak{D}(\mathbf{a}, \varphi, Q) \leq d_{\max}$ and define function

$$\tilde{H}(\varphi, Q) \equiv (1 - \varphi) \left[\sum_{\mathbf{a}=0}^{\bar{\mathbf{a}}_\infty} \mathfrak{D}(\mathbf{a}, \varphi, Q) \prod_{u=0}^{\mathbf{a}} [1 - \tilde{m}(\mathfrak{D}(u, \varphi, Q))] \right], \quad (52)$$

where $\bar{\mathbf{a}}_\infty \equiv \min(\bar{\mathbf{a}}_\infty, T)$. Substituting (47) into (41), we have

$$\mu = \frac{\delta^Q}{\gamma} Q. \quad (53)$$

Substituting (53) into (50) and using $\bar{\mu} = \eta Q$, $L^H = \chi \tilde{H}(\varphi, Q)$ and (47) we obtain

$$\frac{\delta^Q}{\gamma} Q = \left(\frac{\frac{1}{Q} - \eta}{\frac{\delta^Q}{\gamma} - \eta} \right)^{\frac{\vartheta}{1-\vartheta}} \xi^{\frac{1}{1-\vartheta}} (\Gamma-1)(1+\bar{r}) \chi \tilde{H}(\varphi, Q) - \frac{\bar{r}-g}{1+g}, \quad (54)$$

which implicitly defines \hat{Q} . We see that \hat{Q} is unique when $\tilde{H}(\varphi, Q)$ is non-increasing in Q . The other long run values follow.

- **Calibration:** A steady state analysis is instructive to understand the relationship between endogenous observables and helps us to calibrate the model.

1. First, setting $Q_{t+1} = Q_t = Q$ in (42) and using both $\bar{\mu} = \eta Q$ and $\tilde{\mu} = \xi(L^Q)^{1-\vartheta}$, we obtain

$$[\bar{\mu} + (1 - \bar{\mu})\tilde{\mu}] \mu = \frac{\delta^Q}{\gamma\eta} \bar{\mu} = \frac{\delta^Q}{\gamma} Q. \quad (55)$$

Thus, in the long run, the total innovation probability μ is proportional to $\bar{\mu}$ and thus proportional to the medical knowledge stock, Q .

2. Second, according to (41),

$$\frac{(L^Q)^\vartheta}{\xi} = \frac{(1 - \bar{\mu})L^Q}{\mu - \bar{\mu}}. \quad (56)$$

Combining (56) with (50) and using both $L^H = \chi H$ and (55) implies that

$$\ell^Q = \frac{\frac{\delta^Q}{\gamma\eta} - 1}{\frac{1}{\bar{\mu}} - 1} \frac{(\Gamma - 1)(1 + \bar{r})\ell^H}{\frac{\bar{r}-g}{1+g} + \frac{\delta^Q}{\gamma\eta}} \quad (57)$$

holds in the long run (recall that $\delta^Q > \gamma\eta$).

3. Third, according to (20), the health expenditure share can be written as

$$\mathfrak{s} = \frac{pH}{Y + pH} = \frac{1}{\frac{Y}{pH} + 1} = \frac{1}{\frac{L^Y}{\Gamma\omega L^H} \left(\frac{K^Y}{AL^Y}\right)^\alpha + 1} = \frac{1}{\frac{\ell^Y}{(1-\alpha)\Gamma\ell^H} + 1}, \quad (58)$$

where we used (3), $\omega = (1 - \alpha)(AL^Y/K^Y)^{-\alpha}$ and (12).

4. Fourth, according to (1), (2) and (15), the time paths of the health care wedge, $\{\varphi_t\}_{t=0}^\infty$, and initial cohort sizes, $\{S_{v,v}\}_{v=0}^\infty$, drive (along with the endogenous time path of the quality of health goods, $\{Q_t\}_{v=0}^\infty$) the evolution of survival functions over time.

- **Remaining life expectancy:** Remaining life expectancy is computed as follows. Recall that the number of persons surviving to age $t-v$ is given by (2). We calculate the "person-years lived" between ages $t-v$ and $t-v+1$ when born in v as

$$\mathcal{P}_{v,t} = S_{v,t+1} + 0.5 \cdot S_{v,t} m_{v,t}, \quad (59)$$

where $S_{v,t} m_{v,t}$ is the number of persons dying between age $t-v$ and $t-v+1$ from the cohort born in v . Now define

$$\mathcal{L}_{v,t} \equiv \frac{\sum_{u=t-120}^v \mathcal{P}_{u,t}}{S_{v,t}} \quad (60)$$

as the total number of years lived after attaining age $t-v$ divided by the $S_{v,t}$ individuals reaching that age, where the maximum age is restricted to 120. Strictly speaking, (60) gives us remaining life expectancy at a given age under the assumption that there is no medical technological progress. Therefore, although typically used, it is likely to understate the average remaining years at age $t-v$ that surviving members born in v will live.

B. Normative Analysis: Consumption Paths

- **Anticipated Health Policy:** Let us start with the case without unanticipated policy shocks. Using $S_{v,t} = S_{v,v} \prod_{u=v}^{t-1} (1 - m_{v,u})$ in (23), the Lagrangian \mathcal{L}_v associated with maximizing U_v subject to (26) and $a_{v,v+T} \geq 0$ is

$$\begin{aligned} \mathcal{L}_v = & \dots + \beta^{t-v} S_{v,v} \prod_{u=v}^{t-1} (1 - m_{v,u}) \frac{\log c_{v,t}}{(1 + d_{v,t})^\zeta} + \\ & \beta^{t+1-v} S_{v,v} \prod_{u=v}^t (1 - m_{v,u}) \frac{\log c_{v,t+1}}{(1 + d_{v,t+1})^\zeta} + \dots + \\ & \lambda_{v,t} [(1 - \tau_t) w_t + (1 + r_{v,t}) a_{v,t} - c_{v,t} - a_{v,t+1}] + \\ & \lambda_{v,t+1} [(1 - \tau_{t+1}) w_{t+1} + (1 + r_{v,t+1}) a_{v,t+1} - c_{v,t+1} - a_{v,t+2}] + \dots \quad (61) \end{aligned}$$

where $\lambda_{v,t}$, $\lambda_{v,t+1}$, etc. denote the multipliers for period t , $t+1$, etc. The first-order conditions $\partial \mathcal{L}_v / \partial c_{v,t} = \partial \mathcal{L}_v / \partial c_{v,t+1} = \partial \mathcal{L}_v / \partial a_{v,t+1} = 0$ can be written as

$$\frac{\beta^{t-v} S_{v,v} \prod_{u=v}^{t-1} (1 - m_{v,u})}{(1 + d_{v,t})^\zeta c_{v,t}} = \lambda_{v,t}, \quad (62)$$

$$\frac{\beta^{t+1-v} S_{v,v} \prod_{u=v}^t (1 - m_{v,u})}{(1 + d_{v,t+1})^\zeta c_{v,t+1}} = \lambda_{v,t+1}, \quad (63)$$

$$\lambda_{v,t} = \lambda_{v,t+1} (1 + r_{v,t+1}). \quad (64)$$

Combining (62)-(64) leads to

$$\frac{(1 + d_{v,t+1})^\zeta c_{v,t+1}}{(1 + d_{v,t})^\zeta c_{v,t}} = \beta (1 - m_{v,t}) (1 + r_{v,t+1}). \quad (65)$$

Using (27) in (65) implies

$$c_{v,t+1} = \left(\frac{1 + d_{v,t}}{1 + d_{v,t+1}} \right)^\zeta \beta (1 + \bar{r}) c_{v,t}. \quad (66)$$

Iterating and using $d_{v,v} = d_{\min}$, we obtain

$$c_{v,t} = \left(\frac{1 + d_{\min}}{1 + d_{v,t}} \right)^\zeta \beta^{t-v} (1 + \bar{r})^{t-v} c_{v,v}. \quad (67)$$

From (26), (27), $a_{v,v} = 0$ and $a_{v,v+T} = 0$ (reflecting that it is optimal not to hold wealth after certain death), we find that the intertemporal budget constraint of a member of cohort v is given by

$$c_{v,v} + \sum_{t=v+1}^{v+T-1} \left(\frac{c_{v,t}}{\prod_{u=v+1}^t (1 + r_{v,u})} \right) = (1 - \tau_v) w_v + \sum_{t=v+1}^{v+R-1} \left(\frac{(1 - \tau_t) w_t}{\prod_{u=v+1}^t (1 + r_{v,u})} \right). \quad (68)$$

Using (27) and (67), we obtain for the left-hand side of (68) that

$$c_{v,v} + \sum_{t=v+1}^{v+T-1} \left(\frac{c_{v,t}}{\prod_{u=v+1}^t (1+r_{v,u})} \right) = c_{v,v} \left(1 + \sum_{t=v+1}^{v+T-1} \beta^{t-v} \left(\frac{1+d_{\min}}{1+d_{v,t}} \right)^\zeta \prod_{u=v}^{t-1} (1-m_{v,u}) \right). \quad (69)$$

Equating the right-hand sides of (68) and (69), and using (27), $w_t = \omega A_t$ with ω given by (4), (2) with $S_{v,v} = 1$ and $A_t = A_v(1+g)^{t-v}$, implies that the initial consumption level, $c_{v,v}$, is given by

$$c_{v,v} = \omega A_v \frac{1 - \tau_v + \sum_{t=v+1}^{v+R-1} (1 - \tau_t) \left(\frac{1+g}{1+\bar{r}} \right)^{t-v} \frac{S_{v,t}}{S_{v,v}}}{1 + \sum_{t=v+1}^{v+T-1} \beta^{t-v} \left(\frac{1+d_{\min}}{1+d_{v,t}} \right)^\zeta \frac{S_{v,t}}{S_{v,v}}}. \quad (70)$$

- **Unanticipated Health Policy Shock:** We now turn to the case where some individuals experience an unanticipated policy shock in period t_0 . That is, for $t < t_0$ they follow the same consumption path as computed in the previous case and then they re-optimize in t_0 . According to (66), knowing c_{v,t_0} , the path of consumption of any living member of generation v for future dates for $t \geq t_0$ evolves as

$$c_{v,t} = \left(\frac{1+d_{v,t_0}}{1+d_{v,t}} \right)^\zeta \beta^{t-t_0} (1+\bar{r})^{t-t_0} c_{v,t_0}. \quad (71)$$

Using (26) and $a_{v,v} = 0$, for $t_0 < v + R$ we have

$$\frac{a_{v,t_0}}{\prod_{u=v+1}^{t_0-1} (1+r_{v,u})} = (1 - \tau_v) w_v - c_{v,v} + \sum_{t=v+1}^{t_0-1} \frac{(1 - \tau_t) w_t - c_{v,t}}{\prod_{u=v+1}^t (1+r_{v,u})} \quad (72)$$

Using (27), (67) and (2), we obtain

$$c_{v,v} + \sum_{t=v+1}^{t_0-1} \left(\frac{c_{v,t}}{\prod_{u=v+1}^t (1+r_{v,u})} \right) = c_{v,v} \left(1 + \sum_{t=v+1}^{t_0-1} \beta^{t-v} \left(\frac{1+d_{\min}}{1+d_{v,t}} \right)^\zeta \frac{S_{v,t}}{S_{v,v}} \right). \quad (73)$$

Using (27) and (2), we also get

$$\frac{1}{\prod_{u=v+1}^{t_0-1} (1+r_{v,u})} = \frac{S_{v,t_0-1}}{S_{v,v}(1+\bar{r})^{t_0-1-v}}. \quad (74)$$

Substituting (73), (74), $w_t = \omega A_t$ and $A_t = A_v(1+g)^{t-v}$ into (72), the wealth holding of a member of generation v in $t_0 < v+R$ is given by

$$\begin{aligned} a_{v,t_0} &= (1+\bar{r})^{t_0-v-1} \frac{S_{v,v}}{S_{v,t_0-1}} \left[A_v \omega \left(1 - \tau_v + \sum_{t=v+1}^{t_0-1} (1-\tau_t) \left(\frac{1+g}{1+\bar{r}} \right)^{t-v} \frac{S_{v,t}}{S_{v,v}} \right) - \right. \\ &\quad \left. c_{v,v} \sum_{t=v+1}^{t_0-1} \left(\frac{1+d_{\min}}{1+d_{v,t}} \right)^\zeta \beta^{t-v} \frac{S_{v,t}}{S_{v,v}} - c_{v,v} \right]. \end{aligned} \quad (75)$$

Analogously, for $t_0 \geq v+R$, we have

$$\begin{aligned} a_{v,t_0} &= (1+\bar{r})^{t_0-v-1} \frac{S_{v,v}}{S_{v,t_0-1}} \left[A_v \omega \left(1 - \tau_v + \sum_{t=v+1}^{v+R-1} (1-\tau_t) \left(\frac{1+g}{1+\bar{r}} \right)^{t-v} \frac{S_{v,t}}{S_{v,v}} \right) - \right. \\ &\quad \left. c_{v,v} \sum_{t=v+1}^{t_0-1} \left(\frac{1+d_{\min}}{1+d_{v,t}} \right)^\zeta \beta^{t-v} \frac{S_{v,t}}{S_{v,v}} - c_{v,v} \right]. \end{aligned} \quad (76)$$

Recall that $c_{v,v}$ is the initial consumption level chosen before the unanticipated shock occurs. Next, use (26) and $a_{v,v+T} = 0$ to obtain

$$c_{v,t_0} + \sum_{t=t_0+1}^{v+T-1} \frac{c_{v,t}}{\prod_{u=t_0+1}^t (1+r_{v,u})} = (1+r_{v,t_0})a_{v,t_0} + (1-\tau_{t_0})w_{t_0} + \sum_{t=t_0+1}^{v+R-1} \frac{(1-\tau_t)w_t}{\prod_{u=t_0+1}^t (1+r_{v,u})}. \quad (77)$$

Using (71) implies

$$c_{v,t_0} + \sum_{t=t_0+1}^{v+T-1} \frac{c_{v,t}}{\prod_{u=t_0+1}^t (1+r_{v,u})} = c_{v,t_0} \left(1 + \sum_{t=t_0+1}^{v+T-1} \left(\frac{1+d_{v,t_0}}{1+d_{v,t}} \right)^\zeta \beta^{t-t_0} \prod_{u=t_0}^{t-1} (1-m_{v,u}) \right). \quad (78)$$

Equating the right-hand sides of (77) and (78) and using (27), $w_t = \omega A_t$ and

$A_t = A_{t_0}(1 + g)^{t-t_0}$ implies, for $t_0 < v + R$, the consumption level:

$$c_{v,t_0} = \frac{\frac{1+\bar{r}}{1-m_{v,t_0-1}}a_{v,t_0} + \omega A_{t_0} \left(1 - \tau_{t_0} + \sum_{t=t_0+1}^{v+R-1} (1 - \tau_t) \left(\frac{1+g}{1+\bar{r}}\right)^{t-t_0} \prod_{u=t_0}^{t-1} (1 - m_{v,u})\right)}{1 + \sum_{t=t_0+1}^{v+T-1} \left(\frac{1+d_{v,t_0}}{1+d_{v,t}}\right)^\zeta \beta^{t-t_0} \prod_{u=t_0}^{t-1} (1 - m_{v,u})} \quad (79)$$

with a_{v,t_0} given by (75) and $A_{t_0} = A_v(1 + g)^{t_0-v}$. Analogously, for $t_0 \geq v + R$ (i.e. the individual is retired when the shock hits), we have

$$c_{v,t_0} = \frac{\frac{1+\bar{r}}{1-m_{v,t_0-1}}a_{v,t_0}}{1 + \sum_{t=t_0+1}^{v+T-1} \left(\frac{1+d_{v,t_0}}{1+d_{v,t}}\right)^\zeta \beta^{t-t_0} \prod_{u=t_0}^{t-1} (1 - m_{v,u})} \quad (80)$$

with a_{v,t_0} given by (76).

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Online-Appendix:

Additional Figures and Tables

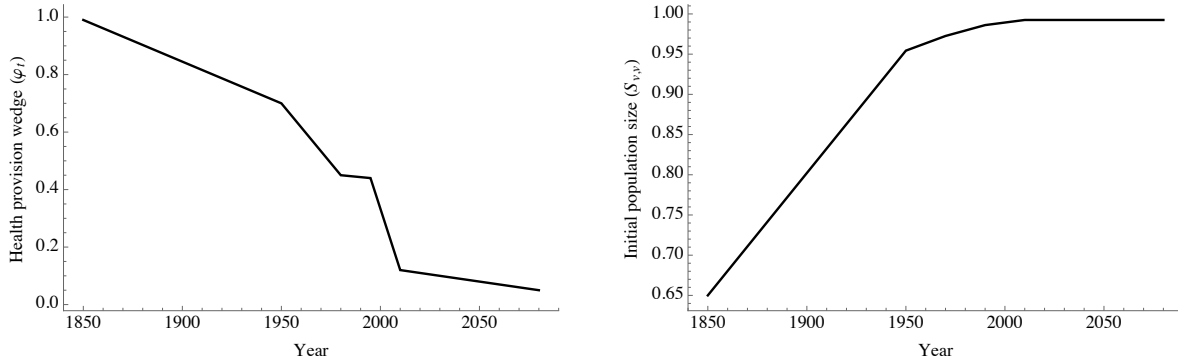


Figure A.1: Calibration of the time paths of the health care wedge and initial cohort sizes in the baseline scenario.

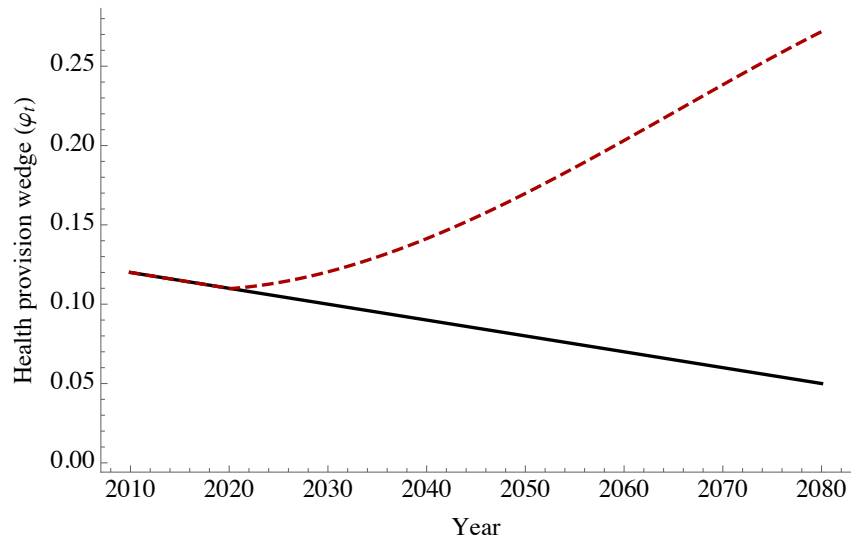


Figure A.2: Calibration of the time paths of the health care wedge from year 2010 onwards in the reform scenario (dashed line) and baseline scenario (solid line).

Age	1950		1970		1990		2010	
	Data	Model	Data	Model	Data	Model	Data	Model
20	51.8	53.0	53.8	54.4	56.7	56.8	61.0	60.6
25	47.0	48.1	49.0	49.4	51.9	51.9	56.1	55.7
30	42.4	43.2	44.2	44.6	47.1	47.0	51.2	50.8
35	37.8	38.4	39.4	39.8	42.3	42.2	46.4	46.0
40	33.2	33.7	34.7	35.0	37.5	37.5	41.6	41.2
45	28.7	29.1	30.1	30.4	32.8	32.8	36.9	36.5
50	24.4	24.7	25.7	26.0	28.2	28.3	32.3	31.9
55	20.3	20.5	21.6	21.7	23.9	24.0	27.8	27.5
60	16.6	16.6	17.7	17.7	19.8	19.9	23.5	23.3
65	13.2	13.0	14.3	14.1	16.1	16.1	19.4	19.3
70	10.2	9.9	11.3	10.8	12.9	12.6	15.5	15.6
75	7.6	7.2	8.7	8.0	10.0	9.6	12.0	12.2
80	5.6	5.0	6.5	5.7	7.5	7.0	8.9	9.3
85	4.1	3.4	4.8	3.9	5.5	4.9	6.4	6.8
90	3.0	2.1	3.5	2.5	4.0	3.3	4.4	4.8
95	2.2	1.2	2.6	1.5	2.9	2.1	3.1	3.2
100	1.8	0.6	2.0	0.8	2.1	1.2	2.2	2.0

Table A.1: Comparison of remaining period life expectancy according to age: UK data vs calibrated model, for years 1950, 1970, 1990, 2010.

Age	2020	2050		2080	
	Baseline	Baseline	Reform	Baseline	Reform
20	63.6	73.5	72.7	83.7	79.1
25	58.7	68.6	67.9	78.8	74.3
30	53.8	63.8	63.0	74.0	69.4
35	49.0	59.0	58.2	69.2	64.6
40	44.2	54.2	53.4	64.4	59.9
45	39.5	49.4	48.7	59.6	55.2
50	34.8	44.8	44.0	54.9	50.5
55	30.3	40.1	39.4	50.3	46.0
60	26.0	35.6	34.9	45.7	41.5
65	21.9	31.2	30.5	41.2	37.2
70	18.0	26.9	26.3	36.8	33.0
75	14.4	22.9	22.3	32.5	28.9
80	11.2	19.0	18.5	28.4	25.0
85	8.5	15.5	15.0	24.4	21.3
90	6.1	12.3	11.9	20.5	17.8
95	4.3	9.5	9.1	16.9	14.5
100	2.8	7.1	6.8	13.4	11.4

Table A.2: Implied remaining period life expectancies according to age: baseline vs. reform scenario for years 2020, 2050, 2080.

Age	2020	2050		2080	
	Baseline	Baseline	Reform	Baseline	Reform
20	86.2	91.0	80.6	92.8	80.6
25	80.2	85.5	75.8	87.5	75.7
30	74.2	80.0	71.0	82.3	70.8
35	68.0	74.5	66.2	77.0	66.1
40	61.4	68.9	61.4	71.7	61.4
45	54.6	63.4	56.6	66.4	56.7
50	47.8	57.8	51.8	61.1	52.1
55	41.1	52.2	47.0	55.8	47.6
60	34.7	46.7	42.3	50.5	43.1
65	28.7	41.1	37.4	45.3	38.7
70	23.1	35.5	32.3	40.2	34.4
75	18.1	29.8	27.3	35.2	30.2
80	13.7	24.4	22.4	30.3	26.1
85	10.0	19.5	18.0	25.5	22.0
90	7.0	15.2	14.0	20.9	18.0
95	4.7	11.4	10.5	16.5	14.2
100	3.0	8.2	7.6	12.6	10.8

Table A.3: Implied remaining cohort life expectancies according to age: baseline vs. reform scenario for years 2020, 2050, 2080.