# Medical Progress and Life Cycle Choices-

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Abstract. In this paper, I show how medical progress, conceptualized as increasing effectiveness of health spending in reducing health deficits, affects optimal lifetime health behavior and health outcomes. To that end, I set up a stochastic life cycle model with endogenous health and longevity, calibrate it for an average American in the year 2010, and use counterfactual computational experiments to examine behavior and outcomes at lower and higher levels of medical efficacy. I begin with the standard health deficit model and the consideration of optimal health expenditure and savings. I then extend the model towards choices of occupation, unhealthy consumption, and retirement. When medical effectiveness increases by 50 percent, the benchmark American is predicted to display 23 percent fewer health deficits at age 65, retire more than 10 years later, live more than 7 years longer, and experience a 10 percent increase in the value of life at age 65. Richer and better educated individuals are predicted to benefit more from medical progress in terms of reduced morbidity and increased longevity.

*Keywords:* medical progress, health behavior, health deficits, longevity, life cycle model.

JEL: D15, I10, I12, J24, J26.

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## 1. INTRODUCTION

Since the mid 19th century, humans experienced a remarkable increase of longevity. Best practice life expectancy (i.e. worldwide highest life expectancy in cross country comparison) increased at a basically constant trend of 1/4 year per year and almost doubled from 45 years in 1840 to 87 years in 2017 (Vaupel et al., 2021). Whether and at which speed the trend will continue in the future is a highly debated issue. In this debate, the projections of the United Nations take a middle ground by assuming that life expectancy will continue to increase albeit at a slower pace and that all countries, at their individual adjustment speeds, converge to a rate of longevity improvement of 0.125 years per year (UN, 2019).

An interesting question for health economics to address is how improving longevity affects (optimal) life cycle choices such as savings and retirement. Longevity, however, is itself endogenous and partly determined by life cycle behavior. In this paper, I resolve the endogeneity problem by focussing on medical progress. While medical technology is potentially endogenous at the macro level (see e.g. Böhm et al., 2021), it can safely be viewed as exogenous from an individual perspective. Specifically, I set up a health deficit model (Dalgaard and Strulik, 2014), calibrate it for an average U.S. American in the year 2010, and investigate how medical progress, conceptualized as increasing effectiveness of health spending in reducing health deficits, affects optimal lifetime health behavior and health outcomes.

The health deficit model is particularly useful to address this research question because its measure for health can be observed as the frailty index (in contrast to latent health capital, Grossman, 1972). The frailty index simply records the fraction of a large list of aging-related health conditions (deficits) that is present in an individual (Mitnitski et al., 2001; Searle et al., 2008). Biological aging defined as the intrinsic, cumulative, progressive, and deleterious loss of function (Arking, 2008) is expressed as gradual increase of the frailty index. The index is a measure of morbidity with very high predictive power for mortality (Mitnitski et al., 2002; Dalgaard et al., 2022). It has been validated and used by countless studies in gerontology and, more recently, also in economics (see Strulik, 2022a, for a survey). Studies of different populations around the world have documented that, on average, individuals accumulate health deficits exponentially with age at a rate of 2 to 5 percent per year (Mitnitski et al., 2002a.b; Mitnitski and Rockwood, 2016, Harttgen et al., 2013; Abeliansky and Strulik, 2018; Abeliansky et al., 2020). The health deficit model predicts this outcome as a self-productive process of aging, in which the presence of health deficits leads to the development of new deficits. In contrast to chronological aging, biological aging is malleable. It can be accelerated or slowed down by health behavior. The efficacy of health investments in reducing health deficits is conceptualized as medical technology and improvements in efficacy as medical progress.

Longitudinal analyses of the frailty index have shown that, on average, later born individuals display fewer health deficits at given age. For cohorts from 14 European countries and Caucasian U.S. Americans born between 1908 and 1964 it has been estimated that the frailty index at any given age declined by 1.3-1.4 percent per year of later birth (Abeliansky an Strulik, 2019;

Abeliansky et al., 2020). The long-run trend in longevity, cited at the beginning, can thus be conceptualized as an expression of the long-run trend of improving health.<sup>1</sup>

Acknowledging that health improvements could have multiple causes, including rising incomes and an expanding public health sector, the estimated trend of the frailty index can be regarded as an upper bound on the *effective* rate of medical progress. Here, we explore with counterfactual analyses how health behavior and health outcomes of the calibrated American change when medical technology changes. The model predicts that, taking behavioral responses into account, a 50 percent increase of medical technology leads to an about 20 percent decline of the frailty index (at age 65). Considering, for example, that the increase of technology was accomplished over a period of 20 years, the model's prediction implies that a gross rate of progress of about 2 percent per year causes an effective rate of medical progress (decline in frailty) of about 1 percent per year.

## 2. Basic Life Cycle Model

2.1. Setup. Consider an individual who experiences utility U(c) from consumption c such that expected lifetime utility V is given by

$$V = \int_0^T S(D)U(c) \mathrm{e}^{-\rho t} \mathrm{d}t,\tag{1}$$

in which t is age and  $\rho$  denotes the time preference rate. The time of death is uncertain and the survival probability S is a negative function of the individual's health deficits D, S(D) with S'(D) < 0. The function S(D) captures also, in reduced form, the feature that experienced utility declines with deteriorating health. We consider a utility function with constant relative risk aversion,  $U(c) = c^{1-\sigma}/(1-\sigma)$ , and normalize utility such that being dead provides zero utility. There exists a level of health deficits  $\overline{D}$  beyond which survival is impossible such that  $S(\overline{D}) = 0$ , implying that maximum lifespan T is endogenously determined as the solution of a free terminal time problem with  $S(D(T)) = S(\overline{D})$ .

Health deficits are measured by the frailty index and evolve according to

$$\dot{D} \equiv \frac{\mathrm{d}D}{\mathrm{d}t} = \mu (D - Ah_I + a). \tag{2}$$

A greater prevalence of health deficits D leads to faster development of new health deficits such that health deficits increase with age in quasi-exponential fashion, in line with the empirical evidence cited in the Introduction. For A = a = 0, health deficits accumulate at an exactly constant rate  $\mu$  (the natural force of aging). For A > 0, the accumulation of health deficits can be slowed down by health investments  $h_I$ . The parameter  $\gamma$ ,  $0 < \gamma < 1$ , reflects decreasing returns of preventive and curative health spending and the parameter A captures the general effectiveness of health investments, i.e. the state of medical technology. Increasing A is conceptualized as medical progress. The main application of the model will be the comparative dynamics of health behavior and health outcomes that are elicited by a change of A. The parameter a is a

<sup>&</sup>lt;sup>1</sup>Another expression of this feature is the strong correlation between life expectancy and healthy life expectancy, see e.g. Strulik and Werner (2016).

residual that captures all other potential influences on health deficit accumulation that are not explicitly modeled.

Individuals face the budget constraint

$$\dot{k} = w + (r+m)k - c - \pi \left(h_I + h_N\right), \tag{3}$$

in which w is wage income until retirement and pension income thereafter. The age at retirement is exogenous for the basic model. Financial capital k is hold in form of annuities and we consider a fair annuity market such that the return on financial wealth is r + m, in which r is the real interest rate and  $m \equiv \dot{S}/S$  is the conditional survival probability. Income is used to finance consumption, savings  $\dot{k}$ , and health expenditure. The relative price of health care is denoted by  $\pi$ . Total health care h consists of health investments  $h_I$  (a choice variable) and necessary health expenditures  $h_N$  that increase with accumulated deficits but are ineffective in preventing or curing health deficits,  $h \equiv h_I + h_N$ . These aging-related expenditures capture, for example, expenditures for (chronic) pain treatment, long-term care, and palliative care and evolve with deficits as  $h_N = \eta D^{\beta}$ , with  $\eta > 0, \beta > 0.^2$ 

Individuals maximize (??) subject to (??) and (??), the initial conditions k(0), D(0) and the final conditions  $k(T) = \bar{k}$  and  $D(T) = \bar{D}$ . For brevity, we ignore inheritances and bequests such that  $k(0) = \bar{k} = 0$ . Optimal life cycle choices lead the individual from the initial conditions to the final conditions. In their life cycle choices, individuals consider two fundamental tradeoffs. Income can be used for consumption, savings, or health investments. Forgoing consumption, which is used for health investments, reduces morbidity and mortality and thus ensures higher expected consumption later in life. Likewise, savings, i.e. forgone current consumption or health expenditure, enables higher consumption or health expenditure later in life. These tradeoffs are formally expressed in terms of Euler equations and they are extensively discussed in Dalgaard and Strulik (2014) and Strulik (2015). Here we focus on the explicit numerical solution of a calibrated model.

2.2. Calibration. We consider the calibration of the model for an average U.S. American man who starts life in the year 2010 at model-age 0 when he is 20 years old. The force of aging  $\mu$  is set to 0.043, as estimated by Mitnitski et al. (2002a) and Abeliansky et al (2020). We set r = 0.07, as estimated by Jorda et al. (2017) for the long-run rate of return on equity and real estate, and we set  $\rho = 0.07$  such that consumption is constant over the life cycle (as observed for childless households; Browning and Ejrnæs, 2009). The relative price of health  $\pi$  is normalized to one. Labor income w is set to \$ 27,928, according to the earnings of single men in 2010 (BLS, 2012). The retirement age is set to 65.5 (CRR, 2018), and the replacement rate of pension income is set to 0.47 (OECD, 2013). I set  $\overline{D} = 0.5$ , parameterize the survival function as  $S(D) = e^{-m(D)}$ , and exploit the feature of a strong empirical association between the logged frailty index and the logged mortality rate (Mitnitski et al., 2002b; Dalgaard et al., 2022) such that  $\log(m) = \log(\xi) + \psi \log(D)$ . A nice implication is that the model is consistent with the Gompertz-Makeham law of mortality.

<sup>&</sup>lt;sup>2</sup>Extensions of the basic model have been used to explore more thoroughly the role of pain treatment and long-term care for health behavior and health outcomes (Strulik, 2021; Schünemann et al., 2022a).

The parameters A, a,  $\beta$ ,  $\gamma$ ,  $\eta$ ,  $\sigma$ ,  $\psi$ ,  $\xi$ , and the initial value D(0) are jointly calibrated to fit the following stylized facts: (a) The model predicts the actual accumulation of health deficits of American men as estimated by Abeliansky et al. (2020). (b) The predicted survival curve fits the actual survival curve for American men (obtained from estimates in Strulik and Vollmer, 2013) and implies a life expectancy at 20 of 57.1 years (expected death at 77.1 years), which was the life expectancy of 20-year-old American men in 2010 (NVSS, 2014). (c) Predicted total health expenditure  $\pi(h_I + h_N)$  approximates health care expenditure of American men in 2010 at the age of 30, 50, 70, 80, 90, and 95 (MEPS, 2010 and de Nardi et al., 2016). (d) Health care expenditure consists almost exclusively on health investments up to age 50 and then increasingly consists of necessary expenditure (long-term care etc). (e) Aggregated over the lifetime, expected health investments account for half of expected total health expenditure. Unfortunately, there exists no well-defined statistics of health investment. Here, we consider health expenditure for preventive and curative care as health investments since these expenditures are clearly motivated by the desire to slow down health deficit accumulation. The calibration target takes into account that, according to the OECD (2022), expenditure on preventive and curative care accounts for around half of U.S. total health expenditure.

The calibration provides the estimates: A = 0.0010, a = -0.0017,  $\beta = 1.58$ ,  $\gamma = 0.27$ ,  $\eta = 200$ ,  $\sigma = 1.07$ ,  $\psi = 2.2$ ,  $\xi = 16$ , D(0) = 0.027. The estimated value of  $\sigma$  agrees well with studies suggesting that the intertemporal elasticity of substitution is close to unity (Chetty, 2006). The estimated value of  $\gamma$  indicates strongly decreasing returns of health investments. The estimate of 0.27 is slightly larger than the corresponding estimate in Dalgaard and Strulik's (2014) deterministic health capital model and it is in the middle range of Hall and Jones' (2007) age-depending estimates of the elasticity of health status with respect to health investment.<sup>3,4</sup> As a non-targeted result, the model predicts a value of life of \$ 5.2 million, which is in order of magnitude comparable to the statistical value of life of \$ 6.3 million, assumed by Murphy and Topel (2006).<sup>5</sup>

The predicted life cycle trajectories are shown in Figure 1 by blue (solid) lines. The targeted data are shown by circles. As the individual grows older, he accumulates health deficits in quasi-exponential fashion (upper left panel) and his survival probability declines (upper right panel). With advancing age, optimal health expenditure increases and after age 70 an increasing part of health care consists of long-term care (lower left panel). The individual accumulates wealth until he retires and uses the accumulated funds to finance consumption and increasing health expenditure in old age.

 $<sup>^{3}</sup>$ Hall and Jones (2007) conceptualize health status as the inverse of the mortality rate and do not consider the accumulation of health deficits.

<sup>&</sup>lt;sup>4</sup>The health deficit model supports a steady state of constant health if  $\gamma$  becomes sufficiently high. The calibrated value of  $\gamma$ , however, is by far too low to support such a steady state of non-aging humans. Dragone and Strulik (2020) discuss a variant of the health deficit model, which formalizes the ideas of De Grey (2013) and Kurzweil and Grossman (2010), who envision a future in which health deficits are resolved at a sufficiently rapid rate such that physiological aging is abolished.

<sup>&</sup>lt;sup>5</sup>The value of life is computed as expected life time utility evaluated at the initial marginal utility from consumption,  $\int_0^T e^{-\rho\tau} u[c(\tau), D(\tau), R(\tau)] d\tau / u_c(c, D, R)$ .



Figure 1: Life Cycle Health Choices and Health Outcomes

Solid blue lines: benchmark model prediction; circles: targeted data (from Abeliansky et al., 2020, for health deficits; MEPS, 2010, for health expenditure at age 30, 50 and 70; De Nardi et al., 2016, for health expenditure (incl. long-term care) at age 80, 90, and 95; and Strulik and Vollmer, 2013, for survival probability). Dashed red lines: 50% lower medical efficacy; Green dashed lines: 50% higher medical efficacy.

2.3. Medical Progress: Comparative Dynamic Analysis. The model is used to asses how medical progress will change health behavior and health outcomes. The predicted comparative dynamics for a 50% increase of medical efficacy (parameter A) are shown by green (dash-dotted) lines in Figure 1. Given the back-of-the-envelope calculations from the Introduction, the results can be interpreted as the life cycle trajectories of the benchmark individual born 20 years later. Greater medical efficacy has a direct effect on slower physiological ageing (see eq. 2). Additionally, the individual responds to improved technology by spending more on health in young and middle age, which further reduces the speed of aging. The gain in health is visible as an outward shift of the deficit curve (upper left panel). We see, for example, that the level of the frailty that the benchmark individual showed at age 70 is now only reached at age 77. In physiological terms, the individual is 7 years younger. The associated gain in longevity is visible as the outward shift of the survival curve (upper right panel). As shown in the bottom right panel, an expected longer life leads to more accumulation of wealth in young and middle age and a slower depletion of wealth in old age.

Interestingly, the model predicts that, in old age, health expenditure by age is *lower* than in the benchmark case. The reason is that in old age an increasing share of health expenditure consists of deficit-dependent health care (long-term care) and that with improved medical technology a certain level of health deficits is reached at a later age.

Life cycle trajectories predicted for a 50 percent lower level of medical efficacy are shown by red (dashed) lines in Figure 1. They are a mirror-image of the advanced technology case: health deficits accumulate faster (benchmark deficits at age 70 are already reached at age 66), survival

case	par. change	remark	$\Delta D(65)$	$\Delta LE$	$\Delta h_I$	$\Delta h$	$\Delta k^*$	$\Delta V(65)$
1)	$\Delta A = +50\%$	higher med. tech	-22.1	7.3	84.5	45.7	13.4	17.8
2)	$\Delta A = -50\%$	lower med. tech	19.8	-4.7	-62.4	-33.6	-9.2	-16.2
3)	$\Delta w = -50\%$	poorer person	9.2	-2.1	-67.5	-35.2	-41.9	-59.6
4)	$\Delta w = -50\% \& \Delta A = +50\%$	poorer person and high tech	-9.2	2.6	-41.0	-19.9	-38.5	-51.7
5)	$\Delta w = -50\% \& \Delta A = -50\%$	poorer person and low tech	24.5	-5.4	-87.7	-46.9	-44.4	-65.2
6)	$\Delta w = +50\%$	richer person	-5.0	1.6	90.8	46.9	43.9	61.7
7)	$\Delta w = +50\% \& \Delta A = +50\%$	richer person and high tech	-32.4	11.2	257.7	135.2	71.3	107.2
8)	$\Delta w = +50\% \& \Delta A = -50\%$	richer person and low tech	19.1	-4.2	-28.3	-16.1	25.1	29.6

Table 1: Medical Progress and Life Cycle Health Behavior and Health Outcomes

The table shows the predicted deviation of health behaviors and health outcomes from the calibrated benchmark individual.  $\Delta LE$  is the change in life expectancy measured in years. The other entries are (dimensionless) relative deviations from benchmark.  $\Delta D(65)$  is the relative deviation of health deficits at age 65;  $\Delta h_I$  is the relative deviation in expected life time health investments;  $\Delta h$  is the relative change of expected total health expenditure (including long-term care);  $\Delta k^*$  is the relative deviation of peak wealth;  $\Delta V(65)$  is the relative deviation of the value of life at age 65.

is less likely and health expenditure is lower in young and middle age and higher in old age (for given age).

Table 1 shows the comparative dynamics by using instructive quantitative moments:  $\Delta D(65)$ is the relative deviation of health deficits at age 65 from benchmark;  $\Delta LE$  is the deviation of life expectancy at 20 from benchmark, measured in years;  $\Delta h_I$  and  $\Delta h$  are the relative deviations of lifetime health investments and total lifetime health expenditure; and  $\Delta V(65)$  is the relative deviation of the value of life experienced at age 65. The response of savings is less easily summarized in one number. Here, we focus on a straightforward statistic, namely the relative deviation in peak wealth  $\Delta k^*$  (i.e. wealth around age 65 in Fig. 1).

The first two rows of Table 1 show these moments for the two cases considered in Figure 1. A 50% increase in medical efficacy is predicted to lead to a 22% decline of health deficits at age 65 and an increase of life expectancy of 7.3 years. Lifetime health investments increase by 84% and total lifetime health expenditure (including long-term care) increases by 46%. Peak wealth is predicted to be 13% higher and the individual experiences an 18% increase in the value of life at age 65. The response to 50% decline in medical efficacy is the mirror image: health deficits at age 65 decline by 20 percent, life expectancy declines by 4.7 years, and the value of life declines by 16 percent.<sup>6</sup>

Case 3–5 repeat these experiments for a poorer person who earns 50 percent less than benchmark income. Facing the calibrated level of medical technology, this person displays 9.2 percent more health deficits at age 65 and expects to die 2.1 years earlier. Due to higher morbidity and mortality the value of life at age 65 is 60 percent below benchmark level. Facing a 50% higher level of medical technology, the poorer person develops 9.2 percent fewer health deficits than benchmark (i.e. 18.4 percent fewer health deficits compared to his status quo) and lives 2.6 years longer than benchmark (i.e. 2.1 + 2.4 = 4.5 years longer compared to his status quo). This means that medical progress improves health and longevity of the poorer individual by less than for the benchmark individual.

<sup>&</sup>lt;sup>6</sup>In absolute terms, the response of health and longevity to an increase of medical efficacy is stronger than that to an equiproportionate decline. This is because the rate of health deficit accumulation declines with increasing A, implying that the deficit-by age curve becomes "less exponential" and the force of aging  $\mu$  becomes less dominant in the determination of health deficits.

Richer persons, in turn, benefit more from medical progress. This is shown in Case 6–8 by considering an individual with 50% more than benchmark income. Given benchmark technology, the rich person displays 6 percent fewer deficits at age 65 and lives 1.6 years longer. Facing the improved technology, the rich person, displays 27.4 percent fewer health deficits and expects to live 9.6 years longer, compared to his own status quo.

The model thus suggests that medical progress is in part responsible for the observation of an increasing income gradient of health and longevity. The *proximate* explanation for this outcome is that richer individuals respond to improved technology more strongly with health investments (h). In the example, the benchmark individual increases health investments by 45 percent, the poor individual by 35.2 - 19.9 = 15.3 percent, and the rich individual by 135.2 - 46.9 = 88.3 percent. The *deep* explanation for these different behavioral responses is the feature that instantaneous utility is concave in consumption while lifetime utility is linear in the length of life. Richer persons therefore experience a smaller loss of utility from consumption for any extra unit invested in health and respond more strongly with health investments to medical progress and the prospect of greater longevity.

In order to decompose the direct effect of medical progress on health and longevity, I ran the model under the assumption that individuals make their life cycle choices believing that technological progress stays constant at benchmark level while actually it is 50 percent higher than benchmark. In this case, life expectancy increases by 4.9 years (instead of 7.5 years), which suggests that 2/3 of the increase in health and longevity can be attributed directly to technology and 1/3 is explained by the elicited behavioral changes.<sup>7</sup>

There exists a rich literature on the socioeconomic gradient of health and its development over time. In a study for the U.S., Bothworth et al. (2016) compare cohorts born 1920 and 1940 stratified by lifetime income. They estimate a difference in life expectancy between the 5th and lowest deciles of 2.4 years for the 1920s cohort and 5.0 years for the 1940s cohort. The difference in life expectancy between the top decile and the 5th decile increased from 2.6 to 7.0 years from the 1920s cohort to the 1940s cohort. Similar trends are estimated in other studies (e.g. Chetty et al., 2022). The health deficit model suggests that a large part of the increasing gradient can be explained by the fact that later born generations were exposed to more efficient medical technology. According to the predictions from Table 1, a 50 percent increase in medical efficacy increases differential life expectancy between the average American and a 50 percent person by 7.3 - 2.6 = 4.7 years and differential life expectancy between the average American and a 50 percent richer person by 11.2 - 7.3 = 3.9 years.

By distinguishing health investments and necessary health expenditure the model also contributes to resolving the debate as to whether health care is a luxury good (see e.g. Hall and Jones, 2007, and Acemoglu et al., 2013). The (lifetime-) income elasticity of health investment implied by case 7) is 90.8/50 = 1.8 while the income elasticity of total health expenditure is

<sup>&</sup>lt;sup>7</sup>This assessment is robust to an alternative decomposition method. When the lifetime paths for consumption and health investments as predicted for the benchmark calibration are represented by functions of age and are used to replace optimal behavior in another run of the model with 50 percent higher medical technology, life expectancy is found to exceed the benchmark prediction by 5.0 years (i.e by 2/3 of the original effect).

46.9/50 = 0.94. Similarly, we obtain from case 3) an income elasticity of health investment larger than 1 and an income elasticity of total health expenditure smaller than 1.

A sensitivity analysis of these results is provided in Table A.1. It shows robustness of the results when the key parameters A,  $\gamma$ ,  $\sigma$ , and  $\pi$  vary around their benchmark values within plausible magnitudes. For example, when  $\gamma$  ( $\sigma$ ) varies from -20% to +20% of its benchmark value, the predicted gain in life expectancy elicited by a 50% increase of medical efficacy A varies from 7.9 to 6.9 (from 6.6 to 7.5). Health behavior is independent from the imposed rate of time preference  $\rho$ . The reason is that  $\rho$  equally affects the marginal cost and marginal benefit of health investments. In the Appendix, I explain this feature in more detail.<sup>8</sup> Furthermore, Appendix Table A.2 shows results from an exercise of comparative dynamics that places the benchmark American in an environment where health care is less expensive such that life expectancy is predicted to be 2 years higher than in the U.S. In this 'stylized Canada', individuals are healthier although they spend less on health and technological progress has a larger impact on health improvements than in the U.S. calibration. A 50% increase in medical efficacy is predicted to increase life expectancy by 10.3 years (instead of 7.3 years). Here, we focussed on health of American men. Schüenemann et al. (2017a) calibrate a health deficit model for men and women and predict that economic growth will lead to a (mildly) widening gender gap in health and longevity. The reason is that the calibrated women value health more strongly than men and thus use a greater part of increasing income for health investments. With the same intuition, it can be assumed that women will benefit more from medical progress than men.

## 3. Occupational Choice, Retirement, and Unhealthy Consumption

3.1. Setup. In order to extend the model by occupational choice, we consider individuals endowed with a certain level of education s who can chose the proportion of their working time in blue collar occupation z and white collar occupations (1 - z). Blue collar work is characterized by a low return to education  $\theta_B$  and a hazard (or strength) premium  $\psi$  that is paid because the job involves more physical stress on health (Strulik, 2022b). Specifically, an individual of age tand frailty index D is assumed to earn the wage

$$w(t,D) = w_0 \left[ z\psi \exp(\theta_B s) + (1-z)\exp(\theta_W s) \right] \exp(\lambda t) \exp(-\nu D)$$
(4)

in which  $\theta_W > \theta_B$  is the return to education in white collar occupations and  $\lambda$  is the return to experience. In contrast to the canonical Mincer (1974) model, the return to experience (chronological age) is always positive for all ages and wages decline in old age because of deteriorating health (increasing frailty index D).

The retirement decision is captured by a modification of the utility function as  $U(c, \ell) = U(c) - \Lambda \ell$  with  $\ell = 1$  if working and 0 otherwise. After retirement, individuals receive a pension in terms

<sup>&</sup>lt;sup>8</sup>The independence of health behavior from time preference does not depend on the assumed functional forms, but it is not robust to extensions of the model. It disappears when health deficits enter utility directly, for example, through pain (Strulik, 2021), and when individuals adapt to deteriorating health (Schünemann et al., 2017b) or anticipate deteriorating health in the future (Schünemann et al., 2022b). Moreover, health behavior and health deficits accumulation are affected by other notions of human impatience. This has been shown for hyperbolic discounting (Strulik and Trimborn, 2018; Strulik and Werner, 2021) and limited self-control (Strulik, 2019a,b).

of  $\zeta$  percent of the last wage. Optimal retirement then occurs at age R when, for the first time, the disutility of work exceeds the utility from working, i.e. when  $\Lambda > c(R)^{-\sigma}(1-\zeta)w(R, D(R))$ , in which  $c(R)^{-\sigma}$  is the marginal utility of income (spent on consumption).

A unit of work in blue collar occupation increases health deficit accumulation by E units. The linearity assumption ensures that working individuals at any given age work either in blue or white collar occupation (and not both at the same time) and that, over the course of life, individuals change the collar color of their occupation at most twice (Strulik, 2022b).

Additionally, we consider the possibility of unhealthy consumption by conceptualizing c as a weighted compound  $c = \tilde{c} + \alpha u$ , in which  $\tilde{c}$  is health neutral consumption and u is healthdamaging consumption. The preference for health damaging consumption is measured by  $\alpha$ . Summarizing, health deficits evolve according to

$$\dot{D} = \mu [D - Ah_I^{\gamma} + Ez + \Omega D^{\delta} u^{\omega} + a],$$

in which the parameter  $\Omega$  reflects the general unhealthiness of consuming u and the parameters  $\omega$  and  $\delta$  capture the feature that unhealthiness increases in the level of consumption and the frailty status of the individual. The budget constraint of the extended model is given by

$$\dot{k} = (r+m)k + w\ell + w_R(1-\ell) - \tilde{c} - qu - \pi (h_I + h_N),$$
(5)

in which  $w_R$  is pension income and q is the price of unhealthy goods.

3.2. Calibration. The benchmark individual is endowed with 13 years of education, which was about the average level of education of white men aged 25-29 in 2010 (US Census, 2010). The return to education is set to  $\theta_B = 0.024$  and  $\theta_W = 0.070$ , according to the estimates of Keane and Wolpin (1997). The calibration targets all the moments from the benchmark run and the following targets: the wage-by-age profile of men without a bachelors degree (US Census, 2019); average wage income of single men (same as for basic model); the feature that men with 12 years of education earn as much in blue collar work as in white collar work (DataUSA, 2020); the estimate that men who worked in blue collar occupations have accumulated at age 65 about 12 percent more health deficits than men in white collar occupation (Abeliansky and Strulik, 2022); and a retirement age of 65.5. The replacement rate is set to 47 percent of the last wage before retirement (as in the basic model). Unhealthy consumption u is conceptualized as smoking and q is set to one. The calibration targets that single male Americans spend on average \$ 360 p.a. on cigarettes (BLS, 2012); that the smoking intensity (including quitting) declines with age by about factor 5 from age 25 to age 50 (Holford et al., 2014); and that smoking shortens the length of life of the benchmark American by 2.2 years. The estimated parameter values are shown in the notes to Figure  $2.^9$ 

The predicted life cycle trajectories are shown by blue (solid) lines in Figure 2. The calibration implies that the benchmark American spends his whole working life in white collar occupation. Red (dashed) lines show life cycle outcomes for an otherwise identical individual with 9 years

 $<sup>^{9}</sup>$ Notice that the average American smokes substantially less than the average American smoker. The calibration implies the prediction that an average smoker who spends about 3 times as much on cigarettes as the average American faces a health toll of 5 years of life expectancy. See Strulik (2022b) for details on the calibration.

of education. This individual optimally decides to spend his whole working life in blue collar occupation and trades off health for income gains. At age 65 he has accumulated 17 percent more health deficits and due to physiological aging and the entailed productivity losses, he decides to retire 3.4 years earlier. However, due to the self-productive nature of health deficits accumulation, health continues to deteriorate faster also after retirement. As a result, health expenditure rises faster and life expectancy is 3.8 years shorter compared to benchmark levels. An anyway shorter life expectancy reduces the opportunity cost of unhealthy behavior and the low educated individual is predicted to spend 27 percent more on unhealthy consumption.

These results are also shown in Table 2, which uses the same notation as Table 1. Additionally, Avg(z) reports the share of the working life in blue collar occupation,  $\Delta R$  is the change in retirement age, compared to benchmark, and  $\Delta u$  is the relative deviation of unhealthy consumption. The individual with 9 years of education and a working life in blue collar is shown as case 6). Case 3) shows an individual with 11 years of education and a work life in both occupations. At a certain age and level of health deficits, the individual leaves better paid but more strenuous blue collar work in order to slow down health deficit accumulation. Having spend 72 percent of the work life in health-demanding occupations the predicted deviations for health outcomes are similar but somewhat more muted than those of case 6).



Figure 2: Life Cycle Health Behavior and Health Outcomes: Extended Model

Solid blue lines: benchmark: 13 years education, optimally chosen white collar work; dots: targeted data (Abeliansky et al., 2020, for health deficits; MEPS, 2010, and De Nardi et al., 2016, for health expenditure; Strulik and Vollmer, 2013, for survival probability; BLS, 2012, for wage profile. Dashed red lines: Individual with 9 years education, optimally choosing blue collar work. Parameters:  $\alpha = 4.8$ ,  $\beta = 1.58$ ,  $\gamma = 0.27$ ,  $\delta = 0.38$ ,  $\eta = 200$ ,  $\sigma = 1.07$ ,  $\rho = 0.07$ ,  $\lambda = 0.039$ ;  $\mu = 0.043$ ,  $\nu = 10.8$ ,  $\psi = 2.2$ ,  $\xi = 16$ ,  $\zeta = 0.047$ ,  $\omega = 1.4$ ;  $\Omega = 10^{(}-6)$ ;  $\Lambda = 0.345$ , A = 0.0010, r = 0.07,  $w_0 = 9120$ , a = -0.0036, D(0) = 0.027,  $\overline{D} = 0.5$ .

As for the main counterfactual experiment, the results for the benchmark individual facing a 50% improved health technology are shown in row 2) of Table 2. With respect to health outcomes, the extended model corroborates the predictions from the simple model. Additionally, the model predicts a substantial increase of the optimal age at retirement of more than 10 years. Life cycle models investigating aging in chronological terms, typically find that higher life expectancy leads to later retirement, but with an elasticity less than unity (e.g. Bloom et al., 2014). This mechanism is at work here as well. Additionally, the model of physiological aging takes into account that longevity increases because health deficits are lower at given age. At age 65, the individual displays 23 percent fewer health deficits and thus substantially higher productivity, which creates a further incentive to retire later and pushes the longevity elasticity of retirement above unity.

case	par. change	remark	Avg(z)	$\Delta D(65)$	$\Delta LE$	$\Delta R$	$\Delta u$	$\Delta h_I$	$\Delta h$	$\Delta k^*$	$\Delta V(65)$
1)	$\Delta A = +50\%$	higher med. tech	0.0	-23.2	7.5	10.7	-1.0	109.1	53.6	-0.8	9.0
2)	$\Delta A = -50\%$	lower med. tech	0.0	19.3	-4.5	-3.6	-0.6	-65.4	-32.4	-7.5	-5.8
3)	s = 11	11 years edu	71.9	10.3	-2.4	-3.3	22.8	-15.8	-8.2	-6.2	-10.7
4)	$s = 11 \& \Delta A = +50\%$	11y edu and high tech	84.1	-10.8	3.5	5.1	20.0	72.0	35.0	1.2	-5.2
5)	$s=11$ & $\Delta A=-50\%$	11y edu and low tech	40.8	27.5	-5.9	-3.4	25.0	-70.7	-35.3	-13.0	-17.6
6)	s = 9	9 years edu	100.0	17.1	-3.8	-3.4	26.9	-20.8	-11.0	-9.5	-15.9
7)	$s = 9 \& \Delta A = +50\%$	9y edu and high tech	100.0	-6.1	1.9	2.1	25.9	59.4	28.7	-2.5	-8.6
8)	$s = 9 \& \Delta A = -50\%$	9y edu and low tech	100.0	35.7	-7.3	-3.6	26.2	-72.1	-36.5	-14.3	-21.0

Table 2: Medical Progress and Life Cycle Outcomes: Extended Model

The table shows the predicted deviation of health behaviors and health outcomes from the calibrated benchmark individual. Avg(z) is the percent of work life spent in blue collar work; Other entries compared to benchmark:  $\Delta LE$  is the change in life expectancy measured in years.  $\Delta R$  is the change in retirement age measured in years. The other entries are (dimensionless) relative deviations from benchmark.  $\Delta D(65)$  is the relative deviation of health deficits at age 65;  $\Delta u$  is the relative deviation in lifetime unhealthy consumption;  $\Delta h_I$  is the relative deviation in expected life time health investments;  $\Delta h$  is the relative change of expected total health expenditure (including long-term care);  $\Delta k^*$  is the relative deviation of peak wealth;  $\Delta V(65)$  is the relative deviation of the value of life at age 65.

In contrast to the prediction from the simple model, peak wealth  $k_{max}$  responds very little to medical progress. Because individuals can adjust to improving health with more labor supply there is less need to adjust with savings to fund health expenditure in old age. This observation, however is not robust. Less educated individuals responds to medical progress with somewhat increased savings. The reason is that individuals with lower income respond less strongly with health investments to medical progress and thus they benefit less from medical progress in terms of morbidity and mortality (see discussion of the basic model). A smaller improvement of health at 65 means that the desired age at retirement increases by less than for the benchmark case. Notice also that individuals with medium education (case 3–5) respond to medical progress by working longer in health-demanding occupations. This mechanism is perhaps most intuitive for careers in professional sports.

Another remarkable result is that medical progress causes only small changes in unhealthy consumption ( $\Delta u$ ). This outcome is explained by two countervailing forces: On the one hand, medical progress reduces the opportunity cost of unhealthy consumption because health deficits are more easily repaired. On the other hand, medical progress increases the survival probability at all ages and the prospective of a potentially longer life reduces the incentive for unhealthy behavior. A balancing of these forces is observed at all levels of education.

The robustness of results to variation of the key parameters  $\gamma$ , A, and  $\sigma$  is shown in Appendix Table A.3. It may be argued, however, that the model is overly optimistic by assuming that

all of the downward bending branch of productivity is due to declining health, implying nondecreasing returns to experience. As shown Appendix Section A.4, very similar results are obtained under an alternative calibration strategy with decreasing (and eventually negative) returns to experience. Assuming that the disutility of work depends on the state of health would further amplify the response of retirement age. The results suggest that the observation of a muted upward trend of retirement age despite continued improvements in longevity and health is explained by political, institutional, or cultural mechanisms that are not captured by the life cycle model of optimal aging.

As for income, the results can be related to empirical observations of an increasing socioeconomic gradient of health with respect to education. Luy et al. (2019), for example, estimate for the U.S. that differential life expectancy at age 30 between men with lower secondary education or less and men with tertiary education increased from 1.5 years in 1990 to 5.5 years in 2010. Similar results are obtained in other studies (e.g. Meara et al., 2008). According to the results from Table 2, a 50 percent increase in efficacy of medical technology causes an additional difference in life expectancy of 7.5 - 3.8 = 3.7 years between the benchmark American (with 13 years of education) and an individual with 9 years of education. The extended model thus suggests that a substantial part of the increasing education gradient of health can be explained the fact that later born generations are exposed to improved medical technology.

Finally, I estimated again the direct and indirect effects of medical technology by solving the model under the assumption that individuals counterfactually believe that medical technology stays constant at benchmark level. When medical technology improves by 50 percent, life expectancy is predicted to increase by 5.0 years (instead of 7.5). This suggests that, as for the basic model, 2/3 of the total change in life expectancy is due to the direct effect of medical technology on health deficit reduction and 1/3 is due to the behavioral changes induced by improved medical technology.

# 4. Conclusion

Since the mid 19th century, we observe an unprecedented and steady trend of increasing human longevity. In this paper, I have argued, based on empirical evidence, that the observed trends in longevity are an expression of improving health at all ages. This insight implies that a serious discussion of the behavioral adjustments to improving longevity needs to abandon the view that death and mortality are exogenous objects or simple functions of chronological age. The health deficit model of Dalgaard and Strulik (2014) provides a gerontologically founded tool to discuss life cycle economics of physiological aging and endogenous longevity. Physiological aging is expressed as self-productive accumulation of health deficits that can be slowed down or accelerated by human behavior. Health deficits are measured by an established metric in gerontology, the frailty index, and models can be calibrated with real data and used for counterfactual analysis.

Here, I used the methodology to investigate the behavioral responses to medical progress defined as increasing efficacy of health care expenditure. The general takeaway is that behavioral adjustments *amplify* the impact of medical progress on health and longevity: people respond by investing more in their health, saving more for health expenditure in old age, and by retiring later, but not by consuming more unhealthy goods. For a calibrated average American, the model predicts that a 50% increase in medical efficacy leads to a reduction of health deficits at age 65 by more than 20% and an increase of life expectancy at age 20 by more than 7 years.

While the direction of behavioral responses is independent from socioeconomic status, individuals with higher income and more education are predicted to benefit more from medical progress. The reason for this is that at higher levels of income and consumption, the marginal utility from instantaneous consumption and thus the opportunity costs of health investment and savings (for later health investment) are lower. The differentiated individual responses imply the prediction that medical advances, although always individually beneficial, widen the income and education gap of health and longevity.

Health inequality caused by medical progress is not easily remedied by the provision of public health care. This is shown by Grossmann and Strulik (2019) who discuss the welfare-maximizing provision of tax-funded public health care in a health deficit model and a society stratified by idiosyncratic paths of deficit accumulation. In this context, medical innovations trigger an optimal increase in public health expenditure, which improves average health but leads to *more* health inequalities. The reason is that people with only a few health deficits benefit relatively more from the expansion of public health care than those who have already accumulated a large number of health deficits.

The health deficit model captures the empirical finding of self-productivity of health deficits, i.e. the feature that the presence of many health deficits leads to a faster accumulation of new health deficits (Mitnitski et al., 2006). Self-productivity explains why health deficits accumulate at almost constant rate, i.e. exponentially, with age (Mitnitski and Rockwood, 2016) and why a health innovation of a certain size (e.g. the cure of one health deficit) is more effective in terms of improved future health and longevity when it is experienced early in life (Dalgaard et al., 2021). With perpetual medical progress, later born generations are exposed to the same level of medical technology at younger age, which explains why continuing medical progress is reflected in a trend of increasing longevity.

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#### Appendix

A.1 Sensitivity Analysis of the Basic Model. In this section, I show the sensitivity of results with respect to key parameters of the model. We first consider the degree of declining returns to health investment  $\gamma$  and begin with an increase of  $\gamma$  by 20 percent (from 0.27 to 0.324). If the model would be left unadjusted, this change would have substantial effects on health outcomes. Life expectancy, for example, would increase by 9.8 years (and no longer represent the average American). Since the best value of  $\gamma$  was endogenously obtained, any recalibration of the model is suboptimal since it needs additionally to fit an exogenously set value of  $\gamma$ . Here, I go one step further and adjust only one other parameter, medical productivity, such that the model continues to predict the same life expectancy as the benchmark model from the main text. This minimal-invasive way of recalibration is appealing since it preserves all other parameters and helps to identify the changes caused by altering the health technology. The calibration implies a 37 percent reduction of A. The numerical experiment can thus be alternatively interpreted as a sensitivity analysis of medical efficacy.

Results are shown in the first block of Table A.1, which is constructed as Table 1. A comparison with Table 1 shows that that the change of  $\gamma$  and A elicits no substantial changes in the model predictions. For example, the predicted reduction of health deficits at age 65 caused by a 50% increases in efficacy of medical technology, is now 24.9 percent (instead of 22.1), the caused increase in life expectancy is 7.9 years (instead of 7.1) and the caused increase in health investments is 52.8 percent (instead of 45.7).

The results shown in the second block of Table A.1 document that the benchmark results from Table 1 are also robust to a change of health technology in the opposite direction, i.e. a decline of  $\gamma$  by 20 percent and an increase of A by 47 percent.

We next consider an increase of the (inverse of the) elasticity of intertemporal substitution  $\sigma$  by 20% (to 1.28). A greater  $\sigma$  implies that individuals experience less marginal utility from instantaneous consumption and are thus willing to forego more consumption for investment in health and a long life (see the detailed discussion in Dalgaard and Strulik, 2014). If unadjusted, such an increase of  $\sigma$  would lead to a substantial increase in health investments. In keeping with the minimal-invasive recalibration strategy introduced above, I adjust the price of health goods  $\pi$  such that the model continues to predict the same life expectancy as the benchmark model. This leads to increase of  $\pi$  by 310 percent. The experiment can thus alternatively be interpreted as a sensitivity analysis with respect to the price of health goods.

The results, shown in the third block of Table A.1, document again the robustness of results from the benchmark model. For example, the predicted change of life expectancy is 6.6 (-4.5) years for a 50% increase (decline) in medical technology, compared to 7.3 (-4.7) years in the benchmark model. The greatest modification of results is obtained for the predicted change in the value of life, which is now more muted than in the benchmark model. The reason is the significantly higher price of health goods, which requires a substantially greater reduction in consumption to finance a unit of health expenditure.

Analogously, a reduction of  $\sigma$  by 20 percent (to 0.89) requires a reduction of  $\pi$  by 56 percent in order to elicit behavior that generates benchmark life expectancy. Results are shown in the

$\Delta \gamma / \gamma = \cdot$	$+20\% (\Delta A/A = -37\%)$							
case	par. change	remark	$\Delta D(65)$	$\Delta LE$	$\Delta h_I$	$\Delta h$	$\Delta k^*$	$\Delta V(65)$
1)	$\Delta A = +50\%$	higher med. tech	-24.9	7.9	90.7	52.8	16.2	23.9
2)	$\Delta A = -50\%$	lower med. tech	20.1	-4.8	-64.6	-37.5	-9.9	-14.9
3)	$\Delta w = -50\%$	poorer person	9.8	-2.5	-70.1	-39.7	-42.1	-58.7
4)	$\Delta w = -50\% \& \Delta A = +50\%$	poorer person and high tech	-8.4	2.1	-44.0	-23.7	-38.5	-50.9
5)	$\Delta w = -50\% \& \Delta A = -50\%$	poorer person and low tech	24.9	-5.6	-89.4	-51.6	-44.5	-64.5
6)	$\Delta w = +50\%$	richer person	-8.5	2.1	99.9	56.1	48.1	73.5
7)	$\Delta w = +50\% \& \Delta A = +50\%$	richer person and high tech	-36.1	13.5	292.1	165.9	83.5	107.9
8)	$\Delta w = +50\% \& \Delta A = -50\%$	richer person and low tech	19.2	-4.2	-29.2	-17.7	24.1	30.8
$\Delta \gamma / \gamma = -$	$-20\% \ (\Delta A/A = +47\%)$							
case	par. change	remark	$\Delta D(65)$	$\Delta LE$	$\Delta h_I$	$\Delta h$	$\Delta k^*$	$\Delta V(65)$
1)	$\Delta A = +50\%$	higher med. tech	-21.8	6.9	80.0	40.1	11.9	20.0
2)	$\Delta A = -50\%$	lower med. tech	19.8	-4.6	-60.7	-30.4	-8.7	-17.0
3)	$\Delta w = -50\%$	poorer person	5.4	-1.7	-65.4	-31.4	-41.0	-56.6
4)	$\Delta w = -50\% \& \Delta A = +50\%$	poorer person and high tech	-12.5	3.1	-38.6	-16.9	-37.9	-48.3
5)	$\Delta w = -50\% \& \Delta A = -50\%$	poorer person and low tech	20.6	-5.2	-86.3	-42.7	-43.4	-62.4
6)	$\Delta w = +50\%$	richer person	-4.7	1.3	84.1	39.9	43.9	65.6
7)	$\Delta w = +50\% \& \Delta A = +50\%$	richer person and high tech	-29.4	10.0	235.6	114.1	67.9	103.0
8)	$\Delta w = +50\% \& \Delta A = -50\%$	$\% \& \Delta A = -50\%$ richer person and low tech		-4.2	-28.0	-14.9	28.1	30.3
$\Delta \sigma / \sigma = 0$	$+20\% (\Delta \pi/\pi = +310\%)$							
case	par. change	remark	$\Delta D(65)$	$\Delta LE$	$\Delta h_I$	$\Delta h$	$\Delta k^*$	$\Delta V(65)$
1)	$\Delta A = +50\%$	higher med. tech	-21.4	6.6	63.2	34.4	8.8	10.5
2)	$\Delta A = -50\%$	lower med. tech	19.7	-4.5	-56.2	-30.3	-5.8	-6.9
3)	$\Delta w = -50\%$	poorer person	9.5	-2.3	-71.5	-37.1	-26.9	-63.1
4)	$\Delta w = -50\% \& \Delta A = +50\%$	poorer person and high tech	-8.3	2.0	-52.5	-25.8	-25.5	-57.6
5)	$\Delta w = -50\% \& \Delta A = -50\%$	poorer person and low tech	24.6	-5.3	-88.3	-46.8	-28.0	-66.3
6)	$\Delta w = +50\%$	richer person	-5.1	1.7	97.7	50.1	34.3	66.8
7)	$\Delta w = +50\% \& \Delta A = +50\%$	richer person and high tech	-29.7	10.5	222.8	116.4	57.8	83.8
8)	$\Delta w = +50\% \& \Delta A = -50\%$	richer person and low tech	15.3	-3.9	-10.6	-6.9	19.9	67.3
$\Delta \sigma / \sigma =$	$-20\% \ (\Delta \pi / \pi = -56\%)$							
case	par. change	remark	$\Delta D(65)$	$\Delta LE$	$\Delta h_I$	$\Delta h$	$\Delta k^*$	$\Delta V(65)$
1)	$\Delta A = +50\%$	higher med. tech	-24.7	7.5	90.8	49.2	15.6	29.8
2)	$\Delta A = -50\%$	lower med. tech	19.9	-4.7	-63.7	-34.5	-10.6	-18.1
3)	$\Delta w = -50\%$	poorer person	9.1	-2.0	-64.7	-33.9	-47.1	-57.3
4)	$\Delta w = -50\% \& \Delta A = +50\%$	poorer person and high tech	-9.6	3.0	-34.3	-16.5	-42.3	-48.6
5)	$\Delta w = -50\% \& \Delta A = -50\%$	poorer person and low tech	24.6	-5.3	-87.0	-46.8	-50.6	-63.7
6) 7)	$\Delta w = +50\%$	richer person	-4.9	1.5	83.5	43.4	49.7	59.2 109.1
() 2)	$\Delta w = +50\% \& \Delta A = +50\%$	richer person and high tech	-32.0	11.4	258.2	130.4	79.2	108.1
8)	$\Delta w = +50\% \& \Delta A = -50\%$	richer person and low tech	19.3	-4.3	-34.1	-19.2	29.3	23.9
$\rho = 0.03$								
case	par. change	remark	$\Delta D(65)$	$\Delta LE$	$\Delta h_I$	$\Delta h$	$\Delta k^*$	$\Delta V(65)$
1)	$\Delta A = +50\%$	higher med. tech	-22.1	7.3	84.5	45.7	13.3	27.7
2)	$\Delta A = -50\%$	lower med. tech	19.8	-4.7	-62.4	-33.7	-9.1	-20.2
3)	$\Delta w = -50\%$	poorer person	9.2	-2.1	-67.5	-35.2	-41.6	-60.2
4)	$\Delta w = -50\% \& \Delta A = +50\%$	poorer person and high tech	-9.2	2.6	-41.0	-19.9	-38.2	-50.4
5)	$\Delta w = -50\% \& \Delta A = -50\%$	poorer person and low tech	24.5	-5.4	-87.7	-46.9	-44.0	-66.9
6) 	$\Delta w = +50\%$	richer person	-5.1	1.6	90.9	47.0	44.9	67.1
7)	$\Delta w = +50\% \& \Delta A = +50\%$	richer person and high tech	-32.5	11.3	258.0	135.5	74.0	131.5
8)	$\Delta w = +50\% \& \Delta A = -50\%$	richer person and low tech	19.1	-4.2	-28.4	-16.1	26.0	26.8

Table A.1: Medical Progress and Life Cycle Health: Sensitivity Analysis

The table is structured as Table 1 and shows results from sensitivity analysis. The imposed calibration target is that the benchmark model (to which comparisons are made) predicts the same life expectancy as the benchmark model from the main text. Parameter changes as indicated. All other parameters are as for the benchmark model from the main text. See notes of Table 1 for details on notation.

fourth block of Table A.1 and demonstrate again the robustness of the benchmark results. Again, the greatest modification is for the predicted change in the value of life, which is now greater due to the lower price of health goods and the lower cost in terms of foregone consumption to finance a unit of health expenditure.

Finally, we consider a change in the rate of time preference to 0.03 (from 0.07). This change has a substantial impact on the age-consumption profile but does not affect health behavior and health outcomes. The reason for this perhaps surprising outcome is that the benefit of health investment and the cost of health investment are equally affected by a change of the time preference rate. To see this better, state the present value Hamiltonian associated with the individual life cycle problem (1) to (3) as:

$$H = e^{-\rho t} S(D) u(c) + \lambda_k \left[ (r+m)k + w - c - \pi (h_I + h_N) \right] + \lambda_D \mu \left[ D - Ah^{\gamma} - a \right], \qquad (A.1)$$

in which t is age,  $\lambda_k$  is the shadow price (costate) of capital and  $\lambda_D$  is the shadow price of health deficits. The first order condition for optimal health investment is

$$e^{-\rho t}\lambda_k \pi = -e^{-\rho t}\lambda_D \mu \gamma A h^{\gamma - 1}.$$
(A.2)

The cost of a unit of health investment is on the left-hand side. It consists of the price of a health good  $\pi$  evaluated at the price of a unit of foregone consumption  $\lambda_k$ . The benefit of a unit of health investment is on the right hand side. Notice that health deficits are 'liabilities' rather than assets such that the shadow price of a health deficit  $\lambda_D$  is negative. A unit of health investment provides a reduction in health deficit accumulation by  $\mu\gamma Ah^{\gamma-1}$  which is evaluated at shadow price  $\lambda_D$ . Aside from health investment and the shadow prices everything is constant in the first order condition. Finally, recall from the costate equation of dynamic optimization theory that the shadow prices evolve over time as  $\dot{\lambda}_j = -\partial H/\partial j$ , j = k, D and verify from A.1 that  $\partial H/\partial j$  does not depend on  $\rho$  for both k and D. Thus, optimal health investment is independent from time preference. Notice the generality of the result, which does not depend on the imposed functional forms.

These considerations are confirmed by the results presented in the last block of Table A.1, which document that predicted changes in behavior and health outcomes do not differ from those of Table 1 (aside from minuscule deviations stemming from the numerical solution procedure). Changes in the predicted value of life are larger, however, because, at a low rate of discounting, individuals benefit more in terms of lifetime utility from advancing medical technology.

A.2 Comparative Dynamics. As an exercise of comparative dynamics, we consider how results change when the calibrated benchmark American is placed in an environment where the price of health goods and aggregate health spending is lower while life expectancy is higher than in the U.S (i.e. a 'stylized Canada'). In the first exercise, I reduced the price of health  $\pi$  by 42 percent such that the model, in which everything else is kept as in the benchmark model of the main text, predicts a 2 years higher life expectancy. The calibration implies that the increase in life expectancy is observed together with 7 percent lower health expenditure than in the benchmark model.

$\Delta \pi/\pi = -0.42\%$									
case	par. change	remark	$\Delta D(65)$	$\Delta LE$	$\Delta h_I$	$\Delta h$	$\Delta k^*$	$\Delta V(65)$	
1)	$\Delta A = +50\%$	higher med. tech	-27.2	10.3	89.2	63.6	20.7	15.6	
2)	$\Delta A = -50\%$	lower med. tech	26.0	-6.1	-62.7	-44.7	-13.5	-18.6	
3)	$\Delta w = -50\%$	poorer person	13.6	-2.7	-67.0	-46.8	-47.4	-61.5	
4)	$\Delta w = -50\% \& \Delta A = +50\%$	poorer person and high tech	-10.4	3.7	-39.4	-26.4	-41.5	-52.9	
5)	$\Delta w = -50\% \& \Delta A = -50\%$	poorer person and low tech	31.2	-6.9	-87.6	-62.1	-51.1	-65.5	
6)	$\Delta w = +50\%$	richer person	-5.8	2.2	90.8	63.1	51.1	59.4	
7)	$\Delta w = +50\% \& \Delta A = +50\%$	richer person and high tech	-40.1	16.4	272.9	191.4	93.4	108.3	
8)	$\Delta w = +50\% \& \Delta A = -50\%$	richer person and low tech	25.0	-5.4	-29.4	-21.6	24.4	26.2	
$\Delta \pi / \tau$	$\pi = -0.80\% \& \Delta A/A = -25\%$								
case	par. change	remark	$\Delta D(65)$	$\Delta LE$	$\Delta h_I$	$\Delta h$	$\Delta k^*$	$\Delta V(65)$	
1)	$\Delta A = +50\%$	higher med. tech	-29.5	10.3	88.8	77.9	24.2	25.0	
2)	$\Delta A = -50\%$	lower med. tech	26.0	-6.1	-62.6	-54.9	-16.1	-18.5	
3)	$\Delta w = -50\%$	poorer person	13.6	-2.7	-66.6	-58.0	-52.0	-61.1	
4)	$\Delta w = -50\% \& \Delta A = +50\%$	poorer person and high tech	-10.5	3.7	-38.8	-33.3	-44.1	-52.7	
5)	$\Delta w = -50\% \& \Delta A = -50\%$	poorer person and low tech	31.2	-6.9	-87.4	-76.5	-56.7	-65.1	
6)	$\Delta w = +50\%$	richer person	-5.8	2.2	90.0	78.2	55.5	58.9	
7)	$\Delta w = +50\% \& \Delta A = +50\%$	richer person and high tech	-40.1	16.4	270.8	236.1	104.2	107.3	
8)	$\Delta w = +50\% \& \Delta A = -50\%$	richer person and low tech	25.0	-5.4	-29.6	-26.2	25.0	26.0	

Table A.2: Medical Progress and Life Cycle Health: Comparative Dynamics

The table is structured as Table 1 and shows results from comparative dynamics. The benchmark model (to which comparisons are made) predicts life expectancy at 20 of 59.1 (2 years in excess of male U.S. life expectancy) caused moderately lower lower prices for medical goods by 42 percent (first block) and by drastically lower prices for medical goods and moderately lower health technology (second block). All other parameters are as for the benchmark model from the main text. See notes of Table 1 for details on notation.

In the second exercise, I considered a more drastic comparative dynamic exercise. I required that the alternative country predicts a two years longer life for the benchmark American that is achieved with 25 percent lower health cost than predicted for the American calibration. This environment is constructed by a reduction of  $\pi$  by 80 percent and a reduction of A by 25 percent. The alternative country thus uses an inferior health technology compared to the U.S. and still achieves a 2 years higher life expectancy with 25 percent lower health spending.

The comparative dynamics for these exercises are shown in Table A.2. Interestingly, both exercises lead to about the same predictions. Specifically, they show that the calibrated benchmark American benefits more from medical technological progress when he is situated in the 'stylized Canada'. A 50% percent advancement of medical technology is now associated with an increase in life expectancy by 10.3 years and a 27.2 percent decline of health deficits at age 65. Advancing medical technology thus has a greater impact on health as health care becomes more affordable.

A.3 Sensitivity Analysis of the Extended Model. Results from sensitivity analysis for the key parameters  $\gamma$ , A, and  $\sigma$  are shown in Table A.3, which is structured as Table 2 from the main text. In the extended model a change of the intertemporal elasticity of substitution triggers a multitude of behavioral adjustments and can no longer be compensated by just adjusting  $\pi$ . In case of the 20 percent increase of  $\sigma$ , I recalibrated  $\pi = 4.3$ ,  $\Lambda = 0.035$ , and  $\alpha = 19.2$  in order to meet the benchmark calibration targets for lifetime health investment, age at retirement, and unhealthy consumption. In case of the 20 percent reduction in  $\sigma$ , the adjustment were  $\pi = 0.35$ ,  $\Lambda = 2.1$ ,  $\alpha = 2.6$  in order to meet the calibration targets. The results show that there is some variation in predicted behavior but the predicted health outcomes are close to those from

the benchmark calibration. For example, for the considered parametric changes, the predicted change of life expectancy in response to a 50 percent increase in medical efficacy varies between 6.6 and 8.4 years and the predicted reduction of health deficits at age 65 varies between 20.9 and 25 percent (compared to 7.5 years and 22.2 percent in case 1 from Table 2).

$\Delta \gamma / \gamma$	$\Delta\gamma/\gamma = +20\% \ (\Delta A/A = -36\%)$										
case	par. change	remark	Avg(z)	$\Delta D(65)$	$\Delta LE$	$\Delta R$	$\Delta u$	$\Delta h_I$	$\Delta h$	$\Delta k^*$	$\Delta V(65)$
1)	$\Delta A = +50\%$	higher med. tech	0.0	-25.0	8.4	12.4	0.7	121.8	65.4	-2.8	8.5
2)	$\Delta A = -50\%$	lower med. tech	0.0	19.5	-4.7	-3.8	-2.0	-67.9	-36.6	-8.2	-4.1
3)	s = 11	11 years edu	74.6	10.6	-2.5	-3.8	22.2	-16.8	-9.4	-6.3	-9.9
4)	$s = 11 \& \Delta A = +50\%$	11y edu and high tech	85.8	-12.5	3.9	5.5	21.0	79.3	42.3	0.5	-4.1
5)	$s=11$ & $\Delta A=-50\%$	11y edu and low tech	40.8	27.8	-6.1	-4.0	22.8	-73.1	-39.7	-13.6	-15.9
6)	s = 9	9 years edu	100.0	17.3	-3.9	-3.9	26.7	-22.0	-12.5	-9.6	-15.2
7)	$s = 9 \& \Delta A = +50\%$	9y edu and high tech	100.0	-8.0	2.3	3.2	27.6	65.3	34.7	-3.5	-7.7
8)	$s = 9 \& \Delta A = -50\%$	9y edu and low tech	100.0	35.9	-7.5	-3.8	24.2	-74.4	-40.9	-15.0	-19.6
$\Delta \gamma / \gamma$	$\gamma = -20\% \ (\Delta A/A = +44)$	1%)									
case	par. change	remark	Avg(z)	$\Delta D(65)$	$\Delta LE$	$\Delta R$	$\Delta u$	$\Delta h_I$	$\Delta h$	$\Delta k^*$	$\Delta V(65)$
1)	$\Delta A = +50\%$	higher med. tech	0.0	-21.4	6.8	9.4	-2.1	100.2	44.9	0.3	8.3
2)	$\Delta A = -50\%$	lower med. tech	0.0	19.1	-4.3	-3.5	0.7	-63.5	-28.7	-7.0	-7.1
3)	s = 11	11 years edu	70.8	10.2	-2.3	-3.7	23.3	-15.2	-7.2	-6.2	-11.3
4)	$s = 11 \& \Delta A = +50\%$	11y edu and high tech	82.3	-10.5	3.2	4.1	19.3	66.7	29.5	1.8	-3.9
5)	$s=11$ & $\Delta A=-50\%$	11y edu and low tech	40.8	27.4	-5.8	-3.3	26.7	-68.9	-31.4	-12.5	-18.7
6)	s = 9	9 years edu	100.0	15.3	-3.7	-3.4	27.1	-20.0	-9.8	-9.3	-13.8
7)	$s = 9 \& \Delta A = +50\%$	9y edu and high tech	100.0	-4.3	1.5	1.5	25.0	55.0	24.0	-2.5	-10.1
8)	$s = 9 \& \Delta A = -50\%$	9y edu and low tech	100.0	33.6	-7.2	-3.5	27.9	-70.3	-32.6	-13.8	-19.8
$\Delta \sigma / \sigma$	$\sigma = +20\%$										
case	par. change	remark	Avg(z)	$\Delta D(65)$	$\Delta LE$	$\Delta R$	$\Delta u$	$\Delta h_I$	$\Delta h$	$\Delta k^*$	$\Delta V(65)$
1)	$\Delta A = +50\%$	higher med. tech	0.0	-20.9	6.6	10.6	11.3	91.8	47.1	1.0	3.7
2)	$\Delta A = -50\%$	lower med. tech	0.0	18.8	-4.2	-3.8	-12.8	-62.4	-32.1	-8.5	-2.3
3)	s = 11	11 years edu	0.0	2.6	-0.7	-3.5	14.5	-9.1	-4.6	-2.7	-6.3
4)	$s = 11 \& \Delta A = +50\%$	11y edu and high tech	0.0	-17.1	5.5	6.9	25.7	74.1	38.3	1.9	-4.7
5)	$s=11$ & $\Delta A=-50\%$	11y edu and low tech	0.0	19.5	-4.6	-3.7	0.8	-65.8	-33.8	-10.5	-6.9
6)	s = 9	9 years edu	0.0	5.0	-1.2	-3.8	27.5	-15.8	-8.0	-4.6	-11.6
7)	$s = 9 \& \Delta A = +50\%$	9y edu and high tech	0.0	-14.6	4.6	2.6	39.4	60.1	31.2	3.1	-9.2
8)	$s = 9 \& \Delta A = -50\%$	9y edu and low tech	0.0	21.9	-5.0	-3.9	13.6	-68.4	-35.1	-12.0	-13.0
$\Delta \sigma / \sigma$	$\sigma = -20\%$										
case	par. change	remark	Avg(z)	$\Delta D(65)$	$\Delta LE$	$\Delta R$	$\Delta u$	$\Delta h_I$	$\Delta h$	$\Delta k^*$	$\Delta V(65)$
1)	$\Delta A = +50\%$	higher med. tech	0.0	-24.8	8.1	11.6	-0.7	110.3	60.5	-2.8	8.2
2)	$\Delta A = -50\%$	lower med. tech	0.0	19.9	-4.9	-3.1	3.3	-66.5	-36.7	-8.5	-4.1
3)	s = 11	11 years edu	100.0	14.8	-3.5	-3.3	15.3	-15.7	-9.4	-9.1	-8.8
4)	$s=11$ & $\Delta A=+50\%$	11y edu and high tech	100.0	-10.2	2.9	3.5	13.6	73.1	39.5	-2.7	-3.2
5)	$s=11$ & $\Delta A=-50\%$	11y edu and low tech	100.0	35.8	-7.6	-3.4	21.2	-71.6	-40.3	-15.4	-16.9
6)	s = 9	9 years edu	100.0	17.2	-4.0	-3.2	28.6	-21.9	-12.8	-13.2	-13.8
7)	$s = 9 \& \Delta A = +50\%$	9y edu and high tech	100.0	-7.9	2.1	2.6	25.9	60.0	32.4	-5.4	-7.7
8)	$s = 9 \& \Delta A = -50\%$	9y edu and low tech	100.0	36.3	-7.9	-3.3	35.3	-73.6	-41.5	-19.0	-19.3

Table A.3: Extended Model: Sensitivity Analysis

The table shows the predicted deviation of health behaviors and health outcomes from the calibrated benchmark individual. Avg(z) is the percent of work life spent in blue collar work; Other entries compared to benchmark:  $\Delta LE$  is the change in life expectancy measured in years.  $\Delta R$  is the change in retirement age measured in years. The other entries are (dimensionless) relative deviations from benchmark.  $\Delta D(65)$  is the relative deviation of health deficits at age 65;  $\Delta u$  is the relative deviation in lifetime unhealthy consumption;  $\Delta h_I$  is the relative deviation in expected life time health investments;  $\Delta h$  is the relative change of expected total health expenditure (including long-term care);  $\Delta k^*$  is the relative deviation of peak wealth;  $\Delta V(65)$  is the relative deviation of the value of life at age 65. 4.1. A.4 Age-specific Decline of Experience. In this robustness check, we consider an alternative parameterization of the wage-by-age profile. Following Dalgaard and Strulik (2017), we assume that

$$w(t,D) = w_0 \left[ z\psi \exp(\theta_B s) + (1-z) \exp(\theta_W s) \right] \exp(\phi_1 t - \phi_2 t^2) D^{\nu_1}, \tag{A.3}$$

which replaces (??). This functional form implements decreasing returns to experience with respect to chronological age. Moreover, the parameter  $\nu_1$  is the wage elasticity with respect to health deficits. Its value can be fixed using macro estimates. Dalgaard et al. (2022) compute the frailty index of the workforce using data of the Global Burden of Disease Study (Vos et a., 2020). Using panel data for the period 1990-2019 they estimate the elasticity of GDP per capita with respect to the frailty index. When controlling for the age composition of the workforce and country and time fixed effects, this elasticity is obtained as -1.53. We use this estimate and calibrate  $\phi_1 = 0.0925$  and  $\phi_2 = 0.00053$  in order to fit the empirical wage-for-age curve used in the main text. Fitting the other calibration targets leads to new estimates of  $\Lambda$ ,  $w_0$ , and a. The other parameter values are kept from the main text. Figure A.1 shows the calibration result for the benchmark American with 13 years of education (blue lines) as well as the predicted life cycles choices and health outcomes of an otherwise identical individual with only 9 years of education. The life cycle trajectories are isomorph to those of Figure 2 from the main text.



Figure A.1: Robustness Check: Extended Model

Solid blue lines: benchmark: 13 years education, optimally chosen white collar work; dots: targeted data (Abeliansky et al., 2020, for health deficits; MEPS, 2010, and De Nardi et al., 2016, for health expenditure; Strulik and Vollmer, 2013, for survival probability; BLS, 2012, for wage profile. Dashed red lines: Individual with 9 years education, optimally choosing blue collar work.

Table A.4 shows the predicted responses to changes in medical technology. Results are very similar to those from the main text. In particular, the predicted responses of optimal retirement are of similar size as those obtained for the specification from the main text. This observation is true for all levels of education and irrespective of the direction of medical change.

case	par. change	remark	Avg(z)	$\Delta D(65)$	$\Delta LE$	$\Delta R$	$\Delta u$	$\Delta h_I$	$\Delta h$	$\Delta k^*$	$\Delta V(65)$
1)	$\Delta A = +50\%$	higher med. tech	0.0	-28.8	9.6	10.0	-24.1	156.1	77.0	10.7	27.5
2)	$\Delta A = -50\%$	lower med. tech	0.0	21.9	-4.9	-3.2	14.5	-68.4	-34.3	-8.5	-12.0
3)	s = 11	11 years edu	66.7	10.8	-2.7	-3.1	31.0	-19.5	-10.0	-3.3	-11.9
4)	$s = 11 \& \Delta A = +50\%$	11y edu and high tech	85.5	-14.6	4.4	5.3	4.9	90.1	44.3	7.3	4.5
5)	$s=11$ & $\Delta A=-50\%$	11y edu and low tech	37.5	25.6	-6.0	-3.1	55.6	-74.3	-37.3	-16.3	-22.4
6)	s = 9	9 years edu	100.0	17.8	-4.4	-3.1	45.1	-27.8	-14.7	-10.4	-17.9
7)	$s = 9 \& \Delta A = +50\%$	9y edu and high tech	100.0	-8.2	2.2	3.4	22.1	63.4	31.0	-5.7	-4.5
8)	$s = 9 \& \Delta A = -50\%$	9y edu and low tech	100.0	38.6	-8.1	-3.1	58.7	-76.1	-39.2	-19.3	-27.6

Table A.4: Robustness Check: Alternative Wage-for-Age Equation

The table shows the predicted deviation of health behaviors and health outcomes from the calibrated benchmark individual. Avg(z) is the percent of work life spent in blue collar work; Other entries compared to benchmark:  $\Delta LE$  is the change in life expectancy measured in years.  $\Delta R$  is the change in retirement age measured in years. The other entries are (dimensionless) relative deviations from benchmark.  $\Delta D(65)$  is the relative deviation of health deficits at age 65;  $\Delta u$  is the relative deviation in lifetime unhealthy consumption;  $\Delta h_I$  is the relative deviation in expected life time health investments;  $\Delta h$  is the relative change of expected total health expenditure (including long-term care);  $\Delta k^*$  is the relative deviation of peak wealth;  $\Delta V(65)$  is the relative deviation of the value of life at age 65.

# Additional References for Appendix

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