The Value of Health and Longevity

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Abstract

We develop a framework for valuing improvements to health and life expectancy, based on individuals' willingness to pay. We then apply the framework to past and prospective reductions in mortality, both overall and for specific life-threatening diseases. We calculate the social values of (i) increased longevity for men and women over the 20th century; (ii) progress against various diseases after 1970; and (iii) potential future progress against various major categories of disease. The historical gains from increased longevity have been enormous. Over the 20th century, cumulative gains in life expectancy were worth over $1.2 million per person for both men and women. Between 1970 and 2000 increased longevity added about $3.2 trillion per year to national wealth, an uncounted value equal to about half of average annual GDP over the period. Reduced mortality from heart disease alone has increased the value of life by about $1.5 trillion per year since 1970. Rough estimates of value of improvements in the health-related quality of life are comparably large. The potential gains from future innovations in health care are also extremely large. Even a modest 1 percent reduction in cancer mortality would be worth nearly $500 billion.

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I. Introduction

During the 20th century life expectancy at birth for a representative American increased by roughly 30 years. In 1900, nearly 18 percent of males born in the United States died before their first birthday – today, it isn't until *age 62* that cumulative mortality reaches 18 percent.[1] This remarkable increase in longevity reflects progress against a variety of afflictions, driving reductions in mortality at all ages. It illustrates a substantial, but unmeasured, increase in social welfare due to improved health.

This paper develops and applies an economic framework for valuing improvements in health, based on individuals' willingness to pay. We estimate the economic gains from declining mortality in the United States over the 20th century, and we value the prospective gains that could be obtained from further progress against major diseases. These values are enormous. Gains in life expectancy over the century were worth over $1.2 million per person to the current population. From 1970 to 2000 gains in life expectancy added about $3.2 trillion *per year* to national wealth, with half of these gains due to progress against heart disease alone. Looking ahead, we estimate that even modest progress against major diseases would be extremely valuable. For example, a permanent 1 percent reduction in mortality from cancer has a present value to current and future generations of Americans of nearly $500 billion, while a cure (if one is feasible) would be worth about $50 *trillion.*

Our analysis of the value of health improvements is founded on individuals' maximization of lifetime expected utility. We distinguish two types of health

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[1] Death rates by age are recorded in *Vital Statistics of the United States.* Longer term data are scant, but suggest that progress accelerated up until about 1950. Swedish data since 1751 show an increase in life expectancy of 6 years between 1800 and 1850, 9 years between 1850 and 1900, 17 years between 1900 and 1950, and 9 years between 1950 and 2000 (*Statistics Sweden, Program for Population Statistics).*

improvements – those that extend life and those that raise the quality of life. Life extension is valued because utility from goods and leisure is enjoyed longer, and improvements in the quality of life raise utility from given amounts of goods and leisure. This framework delivers precise expressions for the value of a life-year, for the value of remaining life, and for changes in these values when health improves. We show that the social value of improvements in health is greater: (a) the larger the population, (b) the higher are lifetime incomes, (c) the greater the existing level of health, and (d) the closer are the ages in the population to the age of onset of disease. These factors underlie a rising valuation of health improvements over the 20th century and into the future. As the population grows, as incomes grow, as health levels improve and as the baby-boom generation approaches the primary ages of disease-related death, the social value of improvements in health will continue to rise.

We also show that improvements in health tend to be complementary; for example, improvements in life expectancy raise willingness to pay for further health improvements by increasing the value of remaining life. This means that advances against one disease, say heart disease, raise the value of progress against other age-related ailments such as cancer or Alzheimer's. This is of significant empirical relevance—we find that reductions in mortality since 1970 have raised the value of further health progress by about 18 percent.

An analysis of the value of health improvements is a first step toward evaluating the social returns to medical research and health-augmenting innovations. Improvements in health are partially determined by society's stock of medical knowledge, for which basic medical research is a key input. The U.S. invests about $60 billion annually in medical research, of which about 40 percent is federally funded, accounting for 25 percent of government research and development outlays.[2] The $27 billion federal expenditure for health related research in FY 2003 represented a real dollar doubling over 1993 outlays. Are these expenditures warranted? Our analysis suggests that the returns to basic research may be quite large, so that substantially greater expenditures may be worthwhile. For example, take our estimate that a 1 percent reduction in cancer mortality would be worth about $500 billion. Then a "war on cancer" that would spend an additional $100 billion on cancer research and treatment would be worthwhile if it has a 1-in-5 chance of reducing mortality by 1 percent, and a 4-in-5 chance of doing nothing at all.

Our analysis highlights some of the important economic issues surrounding the valuation of improvements in health, health research and the growth in health expenditures. Many of these issues have significant policy implications. For example, the annuitization of many public and private retirement benefits (Social Security, private pensions, Medicare and private medical insurance) and the prevalence of third party payers increase incentives to spend on medical care, even when benefits are far smaller than costs. These distortions also skew investments in research away from cost-decreasing improvements in technology, as the demand for care is artificially price insensitive. This creates "second-best" considerations in valuing medical advances: innovations that would otherwise be welfare improving may be socially wasteful because *ex-post* utilization decisions are distorted. Then a correct valuation of health advances

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[2] The distribution of health R&D expenditure is reported by the National Institutes of Health. See http://www.cdc.gov/nchs/products/pubs/pubd/hus/tables/2001/01hus126.pdf. Pharmaceutical industry R&D expenditures are reported in www.phrma.org/publications/publications/profile02/chapter2.pdf.

must account for the induced effect on future costs. Our methodology does this, and we provide evidence on the value of improving health relative to increased health care expenditures since 1970. Even ignoring health-induced changes in the quality of life, we find that the aggregate value of increased longevity since 1970 has greatly exceeded additional costs of health care. In some groups, however, especially elderly women, we find that additional costs exceed that value of life-years gained.

The Setting: Long-Term Evidence of Improvements in Health

Figure 1 shows life expectancy at birth and age 50 in the United States since 1900. These and other estimates that follow are based on cross sectional age-specific death rates at each date, so (when health is improving) they will underestimate life expectancy for a given birth cohort. The figure shows that life expectancy over the century increased by about 30 years. Progress during the first half of the century was rapid and concentrated at younger ages—remaining life expectancy at age 50 grew only slightly. Progress slowed between 1950 and 1970, especially for men, but the upward trend began again after 1970. Late century gains were especially prominent for older individuals—expected remaining life of 50 year old men has increased by over 5 years since 1970. [3]

This shift in the age distribution of rising longevity reflects differential progress against life-threatening ailments, shown in Table 1. Since 1950 the largest single contributor is reduced mortality from heart disease, which added more than 3.5 years to the expected lifetimes of both men and women. When combined with strokes, progress

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Government expenditures for health R&D are reported by the National Science Foundation; see www.nsf.gov/sbe/srs/nsf02330/historic.htm

[3] Evidence for other developed countries is similar. For OECD countries, from 1960 to 2000 the average at-birth life expectancy of women increased by 9 years and that of men by 8 years. OECD Health Data, Table 1, Life Expectancy in Years, http://www.oecd.org/xls/M00031000/M00031357.xls

against cardiovascular diseases added 4.7 and 5.1 years to the expected lifetimes of men and women, with most of the gain occurring after 1970.

These data are well known to demographers and health researchers, but their implications for economic well being have not been widely studied.[4] Health improvements are a form of economic progress, and their valuation is important for two reasons. First, traditional measures of economic growth and welfare, based on national income accounts, make no attempt to account for this source of rising living standards. They count neither the value to the existing population of living longer nor of living "better." They therefore underestimate increases in well-being when health is improving. Second, public expenditure accounts for a large portion of both medical research and the provision of medical care. Efficient decisions require a framework for measuring the value of treatment, and of research-based medical progress.

II. Economic Framework: Valuing Improvements in Health

Advances in health-related knowledge affect the quality of life and the risks of mortality over the lifecycle. We assume these effects are channeled through the intangible "health" of individuals, of which we distinguish two types. The first, *H(t)*, raises the quality of life without affecting mortality. For example, technologies that improve mental health or reduce the effects of arthritis may increase instantaneous utility without affecting longevity. The other, *G(t)*, affects mortality without affecting the quality of life. New methods of detecting treatable diseases or advances in surgical

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[4] Related literature includes the papers collected in Murphy and Topel (2003), especially Murphy and Topel (2003a) and Nordhaus (2003). Usher (1973) is an early attempt to include health in national income acccounts, while Arthur (1981), Rosen (1988, 1994) and Ehrlich and Chuma (1990) develop frameworks for valuing life extension.

techniques are examples. Many advances affect both types of health—e.g. medicines that reduce blood pressure or retard the advance of cancer. *H(t)* and *G(t)* are also affected by environmental factors, the state of health technologies and individuals' choices. We relegate these choices to the background, so health is determined outside the model.

We build on the life-expectancy analyses of Arthur (1981) and Rosen (1988, 1994) by assuming that willingness to pay for health is determined by maximization of lifetime utility. Remaining lifetime expected utility for an individual of age *a* is

$$\int_a^\infty H(t)u(c(t),l(t))\tilde{S}(t,a)e^{-\rho(t-a)}dt \tag{1}$$

where ρ is the rate of time preference and we have normalized the utility of death at zero. *H(t)* enters multiplicatively in (1), so we assume that type-*H* health enhances the "quality" of life by increasing utility from consumption, *c(t)*, and non-market time, *l(t)*.[5] Type-*G* health enters through the survivor function:

$$\tilde{S}(t,a) = \exp[-\int_a^t \lambda(\tau,G(\tau))d\tau] \tag{2}$$

where $\lambda(\tau,G(\tau))$ is the instantaneous mortality (hazard) rate and $\tilde{S}(t,a)$ is the probability of survival from age *a* to *t*. We assume $\lambda_G' < 0$: greater type-*G* health reduces mortality. Then for any factor α that that affect mortality the impact on $\tilde{S}(t,a)$ is

$$\tilde{S}_\alpha'(t,a) \;=\; -\tilde{S}(t,a)\int_a^t \lambda_\alpha'(\tau,G(\tau))d\tau \;=\; \tilde{S}(t,a)\Gamma_\alpha(t,a) \tag{3}$$

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[5] This assumption has several important implications explored below. It is consistent with methods for evaluating the quality of life for persons with various ailments. The most popular asks individuals to index their quality of a life-year against "perfect" health. The resulting "Quality Adjusted Life Years" (QALY) gives values of *H≤1*, where *H=1* indexes perfect health.

A given change in the hazard at some age prior to *t* has a larger impact on $\tilde{S}(t,a)$ when $\tilde{S}(t,a)$ is itself large. This property has important implications for valuing health improvements, which we discuss below.

Assume a perfect annuity market, so the expected discounted value of future consumption equals expected wealth

$$A(a) + \int_a^\infty [y(t) - c(t)]\tilde{S}(t,a)e^{-r(t-a)}dt \;=\; 0 \tag{4}$$

where *r* is the interest rate, *A(a)* is initial assets, and *y(t)* is life-contingent income. With endogenous labor supply $y(t) = w(t)[1 - l(t)] + b(t)$ where *w(t)* is the wage and *b(t)* is life-contingent non-wage income such as social security or defined-benefit pension receipts.

The individual chooses *c(t)* and *l(t)* to maximize (1) subject to (4)

$$U(a) = \int_a^\infty \{H(t)u(c(t),l(t))e^{-\rho(t-a)} + \mu[y(t) - c(t)]e^{-r(t-a)}\}\tilde{S}(t,a)dt + \mu A(a) \tag{5}$$

Optimization yields the necessary conditions[6]

$$\begin{aligned} H(t)u'_c(c(t),l(t)) \;&=\; \mu e^{-(r-\rho)(t-a)} \\ H(t)u'_l(c(t),l(t)) \;&=\; w(t)\mu e^{-(r-\rho)(t-a)} \end{aligned} \tag{6}$$

Notice that *H(t)* and consumption of other goods are natural complements in our setup. For example, if type-*H* health declines at older then consumption will also fall.[7] This is consistent with evidence from studies of lifecycle consumption, and we exploit this feature below in calibrating the value of a life-year.

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[6] We have ignored personal medical expenditures, which might be treated as a non-consumption expense. We return to a consideration of medical expenditures and the costs of health care in our empirical work.

[7] A sufficient condition is $u_{cl}(c,l) \geq 0$. If u_{cl} <0 consumption can rise with *H.*

Equation (5) is our basic building block for valuing health improvements, and it provides a monetary expression for the "value of life." Consider a small change $d\lambda(a)$ in the instantaneous hazard rate. From (2) $d\lambda(a) < 0$ increases survivorship at all subsequent ages. The impact on expected lifetime utility is

$$dU(a) = -d\lambda(a)\int_a^\infty \{H(t)u(c(t),l(t))e^{-\rho(t-a)} + \mu[y(t)-c(t)]e^{-r(t-a)}\}\tilde{S}(t)dt$$

The value of life at *a* is the marginal rate of substitution between $\lambda(a)$ and assets, *A(a)*:

$$V_\lambda(a) \equiv -\frac{\partial U(a)/\partial\lambda(a)}{\partial U(a)/\partial A(a)} = \frac{1}{\mu}\int_a^\infty \{H(t)u(c(t),l(t))e^{-\rho(t-a)} + \mu[y(t)-c(t)]e^{-r(t-a)}\}\tilde{S}(t)dt$$

Using (6) the value of life at age *a* is

$$V_\lambda(a) = \int_a^\infty v(t)e^{-r(t-a)}\tilde{S}(t,a)dt \tag{7}$$

where

$$v(t) = \frac{u(c(t),l(t))}{u_c'} - c(t) + y(t) \tag{8}$$

is the "value of a life-year"—the value of utility and net savings at age *t*.[8] Savings affect *v(t)* because they finance consumption in other periods, with marginal utility μ. Note the rate of time preference, ρ, does not appear in (7): the ability to borrow and lend causes future life years to be discounted at the rate of interest. As both interest and mortality contribute to discounting the future we define $S(t,a) \equiv e^{-r(t-a)}\tilde{S}(t,a)$.

H(t) does not appear explicitly in the value of life formula (7) because we assumed that type-*H* health raises total utility and the marginal utility of consumption by the same proportional amount. So *H* is valuable, as we will see, yet willingness to pay for additional life-years does not depend on *H*. For example, suppose a physical limitation such as partial paralysis reduces a person's *H* by a uniform proportion at all ages. Then (7) and (8) imply that her value of life is the same as for an otherwise identical individual without such limitation, though she would of course still pay to eliminate her physical limitation. This property accords with empirical evidence, as summarized by the Environmental Protection Agency's Science Advisory Board (2000):

> "There are no published studies that show that persons with physical limitations or chronic illnesses are willing to pay less to increase their longevity than persons without those limitations. People with physical limitations appear to adjust to their conditions, and their willingness to pay to reduce fatal risks is therefore not affected."[9]

Life-Cycle Changes in the Value of Life

While different levels of *H* between individuals do not affect the values of life or of life-years, relative levels of *H(t)* within a lifetime do affect relative values of life-years. The rate of change in the value of a life-year as a person ages is:

$$(9) \qquad \dot{v}(t) = \frac{y(t)}{v(t)}\left(s_w(t)\,\dot{w}(t) + (1-s_w(t))\,\dot{b}(t) \right) \; + \; \left(1 - \frac{y(t)-c(t)}{v(t)}\right)\left(\dot{H}(t) + r - \rho\right)$$

where s_w is the share of earnings in life-contingent income. The first term in (9) ties the age profile of *v(t)* to changes in income. Pre-retirement we can set s_w=1, so *v(t)* tracks wages, while indexing of post-retirement annuities suggests $\dot{b}$ =0. The second term ties *v(t)* to the lifecycle shape of *H(t)*: life-years become less valuable as health deteriorates, and persons in declining health are more impatient. This again follows from

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[8] Rosen (1988) gets a similar expression for the value of longevity in a model without saving or non-market time. Topel and Welch (1988) derive the effect of saving on instantaneous utility.

complementarity—*within* a lifetime planned consumption is low when health is expected to be poor, so *v(t)* is also low.

Estimates of the "value of a statistical life" (*VSL*) typically assume that *VSL*s do not depend on age—it is just as valuable to "save" a 60 year old as a 40 year old. In our framework $V_\lambda(a)$ follows the usual law of motion for an asset price:

$$\frac{\partial V_\lambda(a)}{\partial a} = (r + \lambda(a))V_\lambda(a) - v(a)$$

Letting *R(a)* represent the (discounted) length of remaining life at age *a*, this becomes

$$\frac{\partial V_\lambda(a)}{\partial a} = (r + \lambda(a))\int_a^\infty \left[v(t) - v(a)\right]S(t,a)dt + v(a)\frac{\partial R(a)}{\partial a} \tag{10}$$

Life tables for developed economies indicate the last term is negative at all ages. From (9) the first term will be positive at younger ages because wages rise with age and *H* is unlikely to deteriorate much among the young. Later in life $V_\lambda(a)$ declines because wage growth is negligible, *H* deteriorates and *R(a)* is falling.

Willingness to Pay for Improvements in Health

Consider some factor, α, that can affect both type-*H* and type-*G* health. We can think of α as the state of "medical knowledge"—techniques, medicines, and so on—though it can equally represent environmental improvements, improved nutrition or access to medical care. The value of a medical advance follows from displacement of (5):

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[9] http://www.epa.gov/sab/pdf/eeacf013.pdf . Other forms of specifying the utility from *H* would not deliver this property. For example, if *H* is additive willingness to pay for longevity rises with *H*.

$$V_\alpha(a) \equiv \frac{U'_\alpha(a)}{\mu} = \int_a^\infty v(t)S(t,a)\Gamma_\alpha(t,a)dt + \int_a^\infty \frac{H'_\alpha(t)}{H(t)}\frac{u(c(t),l(t))}{u_c}S(t,a)dt \tag{11}$$

Equation (11) measures willingness to pay for any factor that affects health. The first term is the value of additional lifetime utility from changes in mortality, where $S(t,a)\Gamma_\alpha(t,a) = S_\alpha(t,a)$. The second term is the value of changes in type-*H* health. If savings are negligible, proportional changes in *H* and in the survivor function are valued in the same way. Then living a bit better is like living a bit longer.

Equation (11) is our tool for valuing past and prospective changes in health. To make empirical headway we restrict utility to be homothetic, so $u(c,l) \equiv u(z(c,l))$ where z is linear homogeneous. Then the value of a life-year is

$$v = y + \frac{u(c,l)}{u_c(c,l)} - c = y + \frac{u(z_c c + z_l l)}{z_c u'(z)} - c \tag{12}$$

so z is a composite good that aggregates consumption and leisure. Define *full consumption* and *full income* by adding the shadow value of non-market time to each:

$$c^F = c + \frac{z_l}{z_c} l = z_c^{-1} z$$

$$y^F = y + \frac{z_l}{z_c} l$$

where for labor force participants we know that $\frac{u_l(z)}{u_c(z)} = \frac{z_l}{z_c} = w$, the wage. Then

$$v = y + \frac{u(z_c c + z_l l)}{z_c u'(z)} - c = y^F + c^F\left(\frac{u(z)}{zu'(z)} - 1\right)$$

$$v = y^F + c^F \Phi(z) \tag{13}$$

$\Phi(z)$ is consumer surplus per unit of *z*, or surplus per dollar of full consumption. It is positive when average utility of *z* exceeds marginal utility. We do not require $\Phi(z) \geq 0$, however. Positive utility may require composite consumption above some subsistence level, z_0, where $u(z_0) = 0$. Then $\Phi(z_0) = -1$ and there is a $z_1 > z_0$ where $\Phi(z_1) = 0$.[10]

Equation (13) demonstrates two important points about the value of a life-year. First, even if $\Phi(z) = 0$ the value of being alive exceeds measured income because of the value of non-market time. This is especially important for persons without wage and salary income—such as the retired—for whom the value of non-market time accounts for most of y^F. Pre-retirement, non-working hours are valued at *w* and annual hours of leisure are (reasonably) greater than hours worked, so y^F may be more than double earned income. Second, full consumption adds to this value if $\Phi(z) > 0$. For example, if $\Phi(z) = 1$ (surplus equals consumption expenditure) and *y=c* (no savings) the value of a life year is over 4 times annual income. For a typical male at peak lifecycle earnings—roughly $45,000 per year—this puts *v(t)* above $180,000.

Now use (13) to rewrite (7) and (11):

$$V_\lambda(a) = \int_a^\infty [y^F(t) + c^F(t)\Phi(z(t))]S(t,a)dt \tag{14}$$

$$V_\alpha(a) = \int_a^\infty [y^F(t) + c^F(t)\Phi(z(t))]S(t,a)\Gamma_\alpha(t,a)dt + \int_a^\infty \frac{H'_\alpha(t)}{H(t)} c^F(t)[1+\Phi(z(t))]S(t,a)dt \tag{15}$$

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[10] Rosen (1988) uses this property in a one-period model, emphasizing the convexity introduced by z_0 and its implications for risk-taking. In a multi-period setting *v(t)<0* doesn't mean that death is preferred, as the value of continued life at *a* is determined by $V_\lambda(a)$, which will be positive if future prospects are brighter.

Equation (14) is the value of an age-*a* statistical life—the expected discounted value of full income and surplus on full consumption. Equation (15) is the age-*a* willingness to pay for improving health. Both are proportional to full income and consumption, so health is perhaps the ultimate "normal" good. To pursue this point, let $\sigma(z) = -\frac{u'(z)}{zu''(z)}$ be the elasticity of intertemporal substitution (*EIS*), and consider the impact of increased income on *v(t).* Abstracting from saving by setting $y=c$, the income elasticity of v is

$$\frac{\partial \log v}{\partial \log y} = 1 + \frac{1}{\sigma(z)} - \frac{1}{1+\Phi(z)^{-1}} \tag{16}$$

which exceeds 1.0 if $\sigma(z) < 1 + \Phi(z)^{-1}$. Later evidence indicates $\Phi(z) \approx 2$ in middle age, and empirical studies suggest $\sigma(z) \leq 1.0$. Then the income elasticity of the value of a life year exceeds 1.33.

Inspection of (14)-(16) offers several implications for valuing health improvements:

- Willingness to pay for health rises with wealth, so growth is a boon to health-related investments. This is especially important when willingness to pay is income elastic, as suggested by (16). Then richer societies are likely to invest proportionally more.[11]
- The value of a life year includes the value of non-market time. Common attempts to value life-years based on income or consumption expenditures alone neglect much of what people value, especially when health improvements are concentrated at older ages, as has occurred in recent decades.[12]
- Wealth constant, health improvements are more valuable when surplus, Φ, is large. This occurs when the demand for *current* consumption is inelastic, so consumption expenditures at different ages are poor substitutes—$\sigma(z)$ is small. Then loss of a year of life cannot be offset by simply reallocating consumption to other years. We exploit

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[11] Whether health spending is income elastic depends on (16) as well as on the rate of diminishing returns in health production and in consumption. Hall and Jones (2005) provide a related discussion.

[12] For example, the Conference Board of Canada (2001) estimates the "costs" of excess mortality from what a decedent would have produced, not the value to the individual of remaining alive.

this notion in the next section, gauging Φ from evidence on intertemporal substitution in consumption.

- The value of progress against a disease is greatest when the current age, *a*, is close to, but before, the typical age of onset of the disease.

Complementarity of Health Improvements: Increasing Returns

Suppose a medical advance reduces mortality from heart disease, so a 30 year old is more likely to survive to age 60. This increases the value of progress against cancer, because the individual is more likely to be around to enjoy the benefits. Progress against cancer isn't worth much if you are sure to die of a heart attack first.

This example suggests a form of increasing returns inherent to health: past advances raise the value of further improvements. To formalize the point, assume two diseases, *A* and *B,* that only affect mortality. By the nature of competing risks $\lambda(t) = \lambda^A(t) + \lambda^B(t)$ where $\lambda^j(t)$ is the death rate from disease *j.* Let $d\alpha$ $(d\beta)$ be an advance that reduces mortality from *A* (*B*), so $\lambda_\alpha^A < 0$. Differentiation of (15) yields[13]

$$V_{\alpha\beta}(a) \equiv \frac{\partial V_\alpha(a)}{\partial \beta} = \int_a^\infty [y^F(t) + \Phi(z)c^F(t)]S(t,a)\Gamma_\alpha(t,a)\Gamma_\beta(t,a)dt > 0 \tag{17}$$

The functions $\Gamma_\alpha \geq 0$ and $\Gamma_\beta \geq 0$ are derivatives of $\ln S(t,a)$; see (3). They are non-decreasing and strictly positive for some *t*, so (17) is positive. Progress against heart disease (*A*) raises future values of *S(t,a)*. Then progress against cancer (*B*) is more valuable because the individual is more likely to be alive when cancer threatens.

Equation (17) treats the case where *A* and *B* affect mortality. If one or both ailments affect the quality of life the effect will be channeled though the assumed complementarity of *H* with consumption: a medical advance that raises *H(t)* at some ages causes a reallocation of lifecycle consumption, raising $v(t)$ at those ages as well. So suppose A affects mortality (cancer) but B affects the quality of life in old age (Alzheimer's). By raising the value of life years in old age, progress against Alzheimer's is complementary with advances that raise the probability of remaining alive. So, *mortality-reducing advances raise the value of type-H health improvements that increase with age*. Similarly, if both A and B affect the quality of life they will be complementary if they raise H at similar stages of life. So advances against arthritis and Alzheimer's are complementary because they both improve the lot of older people.

These complementarities in willingness to pay for health have important implications for private and social health expenditures. Improvements in health raise the value of further improvements. So the large health improvements of recent decades should increase the demand for health by individuals and also raise the social value of health infrastructure and research. We estimate this effect below.

The Social Value of Improvements in Health

An important application of our method is in assessing the value of medical advances or improvements in public health that increase society's "output" of health. These typically affect both current and future populations, so to measure their social value we must aggregate over the current and expected future populations that benefit. Individual willingness to pay is given by (15), so the social value of an advance that improves health from date τ onward is:

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[13] We simplify and neglect wealth effects in this discussion; see Murphy and Topel (2005)

$$W_{\alpha}(\tau) = \int_{a=0}^{\infty} N(a,\tau)V_{\alpha}(a)da \ + \ N^{f}(\tau)V_{\alpha}(0) \tag{18}$$

Here $N(a, \tau)$ is the population of age a at date τ and $N^{f}(\tau)$ is the present value of future births. These enter the calculation because medical advances that improve health will also apply to future generations, for whom value is measured at birth. When combined with (15), (18) yields two additional implications.

- The current social value of a health advance is proportional to the size of the current and future populations to which it applies.
- Aggregate willingness to pay for progress against a disease will be highest when the age distribution of the population is concentrated near, but before, the typical age of onset of the disease. For example, the aging of the baby-boom generation has raised the social value of medical advances against age-related ailments.

In our empirical applications we will apply (18) in three ways. First, treating reductions in mortality at any past date τ as the outcome of technical improvements that increase health output, we will augment date-τ national income to include the value of life-years "produced". Second, we use (18) to calculate what past reductions in mortality are worth today. For example, we calculate the current value of reductions in mortality from heart disease that occurred between 1970 and 2000. Third, we use (18) to calculate the prospective value of medical progress that would, say, reduce the average likelihood of dying from cancer or AIDs by some amount.

III. Calibration: The Value of a Life-year

Our calibration strategy begins with estimates of the value of a statistical life.[14] Empirical studies typically estimate the *VSL* from wage differences on jobs with varying probabilities of accidental death, or from market prices for products that reduce the likelihood of fatal injury. Suppose workers require a \$500 annual wage premium in order to accept a 1 in 10,000 greater annual probability of accidental death. Among 10,000 workers this would raise expected deaths by 1 each year, so the *VSL* is \$500×10,000=\$5 million. This is the conceptual equivalent of $V_\lambda(a)$ in (14). Viscusi's (1993) survey offers a "reasonable range" of \$4-\$9 million per statistical life, expressed in 2004 dollars, while Viscusi and Aldy (2003) suggest a narrower range of \$5.5-\$7.5 million. Government agencies regularly update these estimates to account for economic growth and new methods and evidence; for example the U.S. Environmental Protection Agency has used \$6.3 million in cost-benefit analyses since 1999.[15] As these values are derived from risk-income tradeoffs for working-age individuals, we assume that the survivorship-weighted average of $V_\lambda(a)$ between ages 25 and 55 is \$6.3 million. Readers who prefer a different value may adjust things accordingly, as our estimates are scalable.

Given this value it remains to impute a lifecycle shape for *v(t)*. We construct *v(t)* from the model's structure and empirical evidence on key parameters. Values of $y^F(t)$ can be constructed from lifecycle wages, while paths of $c(t)$ and $c^F(t)$ follow

$$\dot{c} = \sigma(r-\rho) + \sigma\dot{H} - (\eta-\sigma)s_L\dot{w} \tag{19a}$$

$$\dot{c}^F = \sigma(r-\rho) + \sigma\dot{H} - (1-\sigma)s_L\dot{w} \tag{19b}$$

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[14] See Viscusi (1993) for a survey or Thaler and Rosen (1975) for an original analysis.

[15] See Dockins et. al. (2004) for a review.

where s_L is the share of leisure in $c^F(t)$ and η is the elasticity of substitution between consumption and leisure in $z(c,l)$. Assume σ and η are constants, so $z(c,l)$ is CES and

$$(20) \qquad u(z)=\frac{z^{1-\sigma^{-1}}-z_0^{1-\sigma^{-1}}}{1-\sigma^{-1}} \quad \Rightarrow \quad \Phi(z)=\frac{1}{\sigma-1}\left(1-\sigma(\frac{z_0}{z})^{1-\sigma^{-1}}\right)$$

The value of a life-year will be larger when demand for current full consumption is more inelastic, which occurs when σ is small.

Many studies estimate σ based on versions of (19a). Most find that aggregate consumption growth is insensitive to the real interest rate, suggesting σ is close to zero.[16] Then $\Phi(z)$ would be huge. Browning, Hansen, and Heckman (1999) survey estimates of σ from micro-data and conclude that σ is “a bit” larger than 1.0. The ratio z_0/z asks how much of current composite consumption individuals would sacrifice before they would rather be dead. We know of no formal evidence on this, though comparisons of living standards over time and across countries and individuals suggest the ratio is quite small. Table 2 shows values of a life-year $v(t)$ under various assumptions on σ and z_0/z for a 50 year-old male who earns \$60,000 annually.[17] We assume $y=c$, which is reasonable at this age.[18] The implied values of $v(t)$ are large—when $\sigma=1.0$ the value of an age-50 life-year ranges from \$193,000 ($\Phi=0.61$) for z_0/z=.2 to \$360,000 ($\Phi=2.0$) for z_0/z=.05. For our calculations we assume $\sigma=.80$ at all ages and z_0/z =.10 at age 50, yielding $v(50)$=\$373,000 ($\Phi=2.11$).

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[16] Hansen and Singleton (1983), Hall (1988), and Campbell and Mankiw (1989). Barsky et. al. (1997), use questionnaires to estimate an upper bound on σ of 0.36. Notice that z_0/z must be sufficiently positive for values of $\sigma<1$ to generate positive surplus in (20).

[17] Median annual earnings of men aged 45-54 who worked full time in 1999 were about \$45,000, http://www.census.gov/hhes/income/earnings/call1usmale.html . Non-wage benefits average about 29% of total compensation for a typical worker, http://www.bls.gov/news.release/ecec.t01.htm .

[18] In Consumer Expenditure Survey data for 2003, men aged 45-54 had average after tax incomes of \$53,195 and consumption expenditures of \$46,353. http://www.bls.gov/cex/home.htm , Table 29.

To complete the calibration of *v(t)* we choose parameters of (19) to fit empirical evidence on lifecycle consumption and *y(t)* to match lifecycle wages.[19] Empirical studies indicate that consumption peaks around age 50 and declines thereafter by about 2% annually.[20] This is consistent with declining health after middle-age and $r > \rho$, which we assume. Figure 2a shows the shape of *H(t)* implied by these studies and (19a)—*H(t)* is stable until age 40, but declines rapidly in late middle-age. Given this profile for *H(t)* Figure 2b shows profiles of *v(t),* $y^F(t)$ and $c^F(t)$ that yield an average *VSL* of $6.3 million between ages 25 and 55.[21] The value of a life-year peaks at over $350,000 around age 50, but falls by more than half by age 80 because consumption (health) declines.[22]

Figure 3 plots values of remaining life $V_\lambda(a)$ using *v(t)* from Figure 2b.[23] Women have higher values because we apply gender-specific survivor functions, and women live longer. The effects of discounting and future mortality are apparent: $V_\lambda(a)$ reaches $7 million near age 30 and then falls, but Figure 2b showed that the value of a life-year rises until age 50. $V_\lambda(a)$ declines to $5 million at age 50 and $2 million by age 70.

IV. Estimating the Value of Past and Prospective Health Improvements

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[19] For *y(t)* we estimated a wage equation with a 4th order polynomial in age.

[20] Fernandez-Villaverde and Krueger's (2004) relative consumption index peaks at 1.3 at age 50, then declines by about 2 percent annually. Banks et al. (1998) also find a peak at age 50, a subsequent rate of decline of 2% pre-retirement and about 1% post-retirement. In our calibrations, relative consumption peaks at 1.29 at age 50, with a rate of decline of 2 percent at age 60 and 1.5-2 percent thereafter.

[21] We also assume $r - \rho = .02, \eta = .50$ and that retirement income replaces half of earnings from age 65.

[22] Lichtenberg (2001) and Cutler et. al. (1998) use $25,000 per life year saved in valuing gains from new drugs and advances against heart disease. This is less than *income* for a typical worker, and certainly less than full income. Moore and Viscusi (1988) place the value of a life-year at $175,000, while Miller et. al (1990) find a value of $120,000. None of these studies allow for age effects.

[23] For all of the following calculations we value life-years for men and women equally, and years from birth to age 20 at their age 20 value.

This section measures long-term gains in health, the sources of those gains, and the prospective values of future progress against life-threatening diseases. We also account for changes in medical expenditures that accompany life-extending medical progress, which is a central feature of cost-benefit analyses of improving health care.

Valuing Longevity Gains over the 20th Century

Using mortality tables for the U.S., Figures 4a-b show the timing and age distribution of increases in the value of life over the 20th century. These are values received by individuals *today* from health-improving advances achieved in the past. Vertical differences between two curves represent the present value of changes in survivor rates accruing to individuals of a particular age for a particular decade, so the top curve (2000) shows cumulative gains from 1900 to 2000, and so on.

The largest gains are at birth and at young ages. Health advances over the 20th century yielded additional life years for a newborn with a present value of nearly $2 million. Most of this occurred early—more than half occurred by 1930 and more than 80 percent by 1950, reflecting progress against infant mortality and childhood diseases. But gains are also very substantial for adults. Men aged 20 to 40 gained life-years worth roughly $1 million. Women's gains were greater because we value life years for men and women equally, but women gained more years. Notice that Figures 4a-b show negligible progress for women after 1980, though men enjoyed substantial gains over this period.

To evaluate whether these estimates are reasonable, consider the $1 million gain enjoyed by a 30 year old male. Over the century, the expected remaining duration of life for 30 year old men increased by 11.3 years, from 34.9 to 46.2. So think of a current 30 year old who is offered the choice of (a) his current standard of living and health or (b) a lump sum of \$1 million and the life-expectancy of 30 year old in 1900, which is 11.3 years shorter. Our estimates imply that the choice is a close call, but for a payment of less than \$1 million he would keep his current health. For women, the corresponding gain in life expectancy is 14.9 years, from 36.4 to 50.5, which is worth nearly \$1.2 million.[24]

Figure 5 further documents the difference in timing between men's and women's gains. We graph age-weighted average gains for men and women over the entire century, using end-of-century population weights. These cumulate to about \$1.3 million for the representative individual of each sex. Women's gains started to outpace men's in the 1930s and progress for both men and women decelerated in the early 1950s, reflecting the near exhaustion of progress against infant and child mortality. For men, health progress stalled for 20 years and the female-male gap reached nearly \$180,000 by 1970. Male progress resumed after 1970, reflecting advances against adult ailments, and the gender disparity had vanished by the end of the century.[25]

Figures 4 and 5 value past gains at current willingness to pay, so they represent the current value of past progress—what people alive today gained from earlier improvements. An alternative is to value progress at the date it occurred, so newly "produced" life years at date τ are a component of output—health capital—that will be enjoyed in future years and by future populations, but which are uncounted in per-capita national income.[26] The result is an augmented measure of per-capita income that counts the present value of reduced mortality at the date it is observed.

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[24] Nordhaus (2003) poses a related hypothetical—if offered only one of post-1950 gains in health or living standards, which would you choose? He estimates that gains in health and living standards after 1950 are of roughly equal value.

[25] Murphy and Topel (2003b) apply these methods to racial disparities in health, showing convergence in the value of health outcomes for blacks relative to whites.

[26] Nordhaus (2003) has a useful discussion of income accounting issues; see also Usher (1973). To value gains at date τ we use the shape of $v(t)$ in 2000, but rescale it by the ratio of GDP per capita in years τ and

Table 3 reports the results. From 1900 to 1950 the per-capita value of new life-years "produced" was roughly equal to output of goods and services. The decade 1910-20 is an exception due to the flu pandemic of 1917-19. Gains after 1950 form a smaller share of income because other forms of productivity grew faster. This accounting may also change one's perspective on relative growth rates from different decades: per-capita GDP grew rapidly during the 1960s and slowly during the 1970s, yet production of health stagnated in the 1960s—the lowest in the century—but boomed in the 1970s.

Post-1970 Gains

We now turn to a more detailed examination of the post-1970 period, where mortality-reducing progress among adults accelerated. Figures 6a-b show that the largest gains accrued to persons aged 40 to 60. Males enjoyed steady progress, with peak gains of \$460,000 for 50 year olds (who gained 5 years of life-expectancy), about double the peak gains of women (2.8 years). Most of men's gain is due to progress against heart disease alone (Figure 7). This partly accounts for the late-century "convergence" between men and women, because women's progress stalled after 1980 (Figure 6b).

Table 4 reports the social value of these advances, using (18) to aggregate over end-of-century and expected future populations.[27] The numbers are huge because the relevant populations are large. For men, mortality reductions between 1970 and 1980 were worth \$27 *trillion.* Progress slowed after 1980, but even so the cumulative gains for men total \$61 trillion. Women gained "only" \$34 trillion because of stalled progress after

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2000. We count reductions in mortality when they are observed, which may not be when they were produced. For example, improved neo-natal care in year τ may reduce heart attacks in $\tau + 50$. To obtain new health capital per capita, we include the value to future cohorts of a date-τ reduction in mortality, as in (18), and divide by the date-τ population. This "capital" approach is consistent with methods of national income accounting, where output is consumption plus the value of new capital.

1980. Combining men's and women's gains, reductions in mortality after 1970 had an end-of-century value of $95 trillion, or a flow of about $3.2 trillion per year. Separate calculations show that about two-thirds ($64 trillion) of this accrued to persons alive in 2000, and one-third will be enjoyed by future birth cohorts.

Net Gains: Accounting for Costs of Improving Health

Health improvements are worthwhile if their value offsets additional costs, and we have counted only the value side of the ledger. Some costs take the form of changes in consumption or behavior, such as reductions in smoking or increased exercise in light of new information about health consequences. For example, suppose the post-1970 decline in mortality among middle aged men was entirely due to reduced smoking, caused by new knowledge that smoking promotes heart disease and other ailments. As smoking evidently provides enjoyment, the benefits of improved health came at a cost and our estimates overstate net gains. In this case the usual welfare analysis indicates that net gains are about half the value of improved health.[28] Similar arguments apply to exercise, moderate drinking and other choices that may have improved health.

Other (flow) costs are those associated with implementing new procedures and treatments, or simply greater consumption of existing services. These costs can either rise or fall as a consequence of technical advances, depending on the nature of the advance and the nature of demand for medical services. To incorporate them, assume that health expenditures at age *t*, *k(t)*, provide no direct utility beyond that necessity for maintaining

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[27] Equation (2) requires an estimate of future birth cohorts. We use the discounted value (at 3.5%) of projected births, as estimated by the Bureau of the Census: http://www.census.gov/ipc/www/usinterimproj/. In using this discount rate we ignore anticipated economic growth, which would make our estimates larger.

[28] Let h be the previously unknown health cost per cigarette and Q be quantity smoked. Then the gain in health is $h\Delta Q$ and the lost value of smoking is $.5\ h\Delta Q$. If consumers knew smoking was harmful, but had underestimated the harm, the foregone benefits of smoking are less than half the value of new health.

health. An advance may improve longevity and quality of life while also changing costs. Willingness to pay is an extension of (15):

$$
\begin{aligned}
V_\alpha(a) &= \int_a^\infty [y^F(t) - k(t) + c^F(t)\Phi(z(t))](S_\alpha(t,a) + S_k(t,a)k_\alpha(t))dt \\
&\quad - \int_a^\infty k_\alpha(t)S(t,a)dt \; + \; \int_a^\infty \frac{H'_\alpha(t) + H'_k(t)k_\alpha(t)}{H(t)} c^F(t)[1 + \Phi(z(t))]S(t,a)dt
\end{aligned}
\tag{21}
$$

In (21) $k_\alpha(t)$ is the change in health spending at age *t*. If *k(t)* is chosen efficiently then terms involving $k_\alpha(t)$ vanish because the net return to a marginal increase in expenditure is zero. Then the balance of benefits and costs is surely positive and (21) is equivalent to (15). But third-party payers for medical services can distort these decisions, so the benefits of medical advances can be smaller than the costs of supplying them. This can be important on certain margins, as when large medical costs are incurred very near the end of life, allegedly to little benefit.

Our empirical analogue of (21) compares the value of increased longevity to changes health expenditures. We use data on individuals' expenditures from the Medical Expenditure Surveys, collected in 1977, 1987, and then as a panel starting in 1996. As is typical with survey data, survey-predicted medical spending underestimates actual national expenditure for medical services. So we use the age profile of relative spending from the survey data to allocate national medical expenditures. This yields estimates of aggregate health care spending by age and gender from 1970 to 2000.

Table 5 shows that medical spending grew from 11.3% of total consumption in 1970 to 19.6% in 2000. Calculating the present value of aggregate medical expenditures using 2000 population weights and survival probabilities, and assuming that the same level of expenditure applies to future years and birth cohorts, the capital value of medical spending grew from $16.2 trillion in 1970 to over $50 trillion by 2000.

Table 6 calculates net social gains from increased longevity. Note that our allocation of costs is only a rough analogue of (21), where $k_{\alpha}(t)$ represents the change in expenditures that are the direct consequence of implementing a new technology. We actually measure the value of increased longevity and changes in medical expenditures from all sources. This may cause either an overestimate or underestimate of the social value of health improvements, for several reasons. First, changes in spending include expenditures that raise the quality of life, which we ignore. Second, current expenditures may yield future benefits, leading to an underestimate of net gains, or benefits we observe may be the outcome of past events, yielding an overestimate. Finally, some observed gains may be due to things unrelated to medical spending—cleaner air or water, for example. We don't count the costs of these things.

With these caveats, we estimate that increased longevity after 1970 yielded a "gross" social value of $95 trillion and the capitalized value of medical expenditures grew by $34 trillion, for a net gain of $61 trillion. Two-thirds of this "occurred" in the 1970s, when both gross benefits were highest and additional costs were lowest. Overall, rising medical expenditures absorb only 36% of the value of increased longevity.

While overall gains exceed costs, many critiques of the efficacy of rising medical expenditures focus on marginal decisions to expend resources when benefits are smaller than costs (e.g Meltzer, 2003, Fuchs, 1972), especially on life-extending procedures for persons near death.[29] Table 7 shows how average net gains vary with age. For men, net

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[29] For example, over a quarter of all Medicare expenditures are spent in the last year of life, a proportion that has remained stable since the 1970s. See Hogan, Lunney, Gabel, and Lynn (2001)

gains are positive overall and in each sub-period for all but the oldest (85+) age category. Incremental costs as a proportion of gross benefits are fairly constant until old age, when the cost share rises sharply. The cost share is uniformly larger for women, for whom we estimate negative average net benefits above age 65—the life years they gained were worth less than their incremental health spending. In the 1990s we estimate net losses for women of all ages except infants, and deficits rise sharply with age. Though these deficits may surely be offset by uncounted improvements in the quality of life, they provide a cautionary tale that even large values may be swamped by increased costs.

What's on the Table? Prospective Gains from Medical Progress

We now turn to estimates of what can be gained from future progress against particular diseases. We make no attempt to deduct prospective costs, so our estimates should be interpreted as the value of life-years that could be gained from a given reduction in mortality. This value must be large enough to cover the costs of developing and implementing new methods that would save lives. Our benchmark is a 10 percent reduction in mortality from a disease.

Figures 8a-b show individual values resulting from a permanent reduction in mortality from five major causes. The largest values are for cardiovascular diseases, which peak at nearly $35,000 for men and $28,000 for women. The value of progress against cancer is nearly as large, with a noteworthy 20-year earlier peak for women that reflects the incidence of breast cancer. Progress against infectious diseases—of which mortality from AIDS accounts for about a third—has far lower value because of lower incidence, and it peaks early reflecting the typical age of onset.

To get the current social values of potential progress we aggregate over the age distribution of the 2000 U.S. population and future birth cohorts, as in (18). These are shown in Table 8. A 10 percent reduction in all-cause mortality would have a present social value of \$18.5 trillion. About 30 percent of this (\$5.7 trillion) is due to potential progress against cardiovascular diseases. Similar progress against cancer would be worth \$4.7 trillion, with roughly equal benefits for men and women. A ten percent reduction in mortality from infectious diseases, including AIDS, is of roughly the same value to men (\$500 billion) that progress against breast cancer would be for women (\$444 billion). For women, mortality-reducing progress against heart disease is four times more valuable than equivalent progress against breast cancer.

To put these values in perspective, total federal support for health research in the United States for fiscal 2005 was about \$28 billion. If we capitalize this flow over the indefinite future at 3 percent interest, it is roughly equal to the \$1 trillion value of a *one* percent reduction in mortality from cancer and cardiovascular disease. Even if we offset these gains by substantial increases in the cost of the treatments required to implement potential new technologies, potential net gains appear large.

Complementarity and Increasing Returns

Our earlier discussion emphasized the importance of complementarity as a source of increasing returns in the value of health. The right hand column of Table 8 illustrates this effect by calculating the impact of 1970-2000 health progress on prospective values. The estimates show the increase in the current social value of *future* progress that is due to the decline in mortality between 1970 and 2000. Formally we calculate:

$$\text{(22)} \qquad \Delta W_\alpha = \int_{a=0}^{\infty} \{N^1(a)[V_\alpha^1(a) - V_\alpha^0(a)] + V_\alpha^0(a)[N^1(a) - N^0(a)]\}da$$

The social value of health complementarity has two components. The first is how much more *today's* population (N^1) will pay for future progress when that value is based on current survival rates (V_α^1) than on past ones (V_α^0). The second reflects the fact that today's population (N^1) is larger than had people lived their lives under mortality rates from 1970 (N^0).

We find that declining mortality between 1970 and 2000 raised the social value of future health progress by 18 percent, or by \$3.3 trillion for our benchmark case of a 10 percent reduction in death rates. Of this, \$2.2 trillion is due to increased willingness to pay for progress against heart disease and cancer. These estimates illustrate that the value of health progress will continue to rise simply because people are getting healthier, even in the absence of growing productivity and incomes. Economic growth and income-elastic willingness to pay for health progress will only reinforce this effect.

Changes in the Quality of Life

Our calculations have valued changes in longevity, ignoring gains in the quality of life—what we called *H*. This is because changes in mortality are directly measurable, while changes *H* are not. Though we have no direct measure of these improvements it seems obvious that they have occurred. We think it's important to provide a ballpark estimate of how valuable they might be. Here is one approach.

Assume that advances in longevity and quality of life are related. Let $\lambda_0(t)$ and $\lambda_1(t)$ denote mortality rates in 1970 and 2000, respectively. Because mortality fell, assume that if $\lambda_1(t) = \lambda_0(t-k)$ then persons of age *t* in 2000 are *k* years "younger" than in 1970. We then assign $H'(t)/H(t) = \ln H(t-k) - \ln H(t)$ from Figure 2a to calculate the second term of (15). Figure 9 shows the resulting value of post-1970 improvements in type-*H* health. Values reach $1.2 million for men and $820,000 for women in their late-40s. The estimates are large because people in middle age were much "younger" in 2000 than they were in 1970—a 55 year old male in 2000 had the same death rate as a 49 year old from 1970—and our estimate of $H(t)$ is steeply declining. These estimates are roughly triple the peak values from increased longevity shown in Figures 6a-b, suggesting that quality of life may be the more valuable dimension of recent health advances.[30]

V. Conclusions

We have developed a framework for valuing improvements in health, based on willingness to pay, and used this framework to estimate the value of past and prospective health advances. The resulting values are large. Reductions in mortality from 1970 to 2000 had an (uncounted) economic value to the 2000 U.S. population of about $3.2 trillion *per year.* Cumulative longevity gains during the 20th century were worth about $1.3 million per person to the representative member of the 2000 U.S. population. Valued at the date they occurred, the production of longevity-related "health capital" would raise estimates of per-capita output in the U.S. by from 10 to 50 percent, depending on the time period in question.

Prospectively, even modest progress against diseases such as cancer and heart disease would have enormous social values. A one percent reduction in mortality from cancer or heart disease would be worth nearly $500 billion to current and future Americans. These estimates ignore the value of health advances to individuals in other

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[30] Or that we have overstated the rate of decline in $H(t)$. If so, our estimates of the value of increased longevity would be larger.

countries, so they understate aggregate social values of possible innovations. They also ignore corresponding improvements in the quality of life—which evidence suggests may be even more valuable than gains in longevity—and for these reasons as well they are likely to be conservative. We show that these values will increase in the future because of economic growth and, more interestingly, because health itself continues to improve.

Large as they are, these values may be offset by the costs of developing and implementing health improvements. Current public and private spending on health-related research is a tiny fraction of potential benefits, yet such investments may not be worthwhile if the costs of implementing new technologies are large. Social transfer programs and other third-party methods of financing health care can distort both utilization decisions and research, with the result that some health improvements are socially inefficient.

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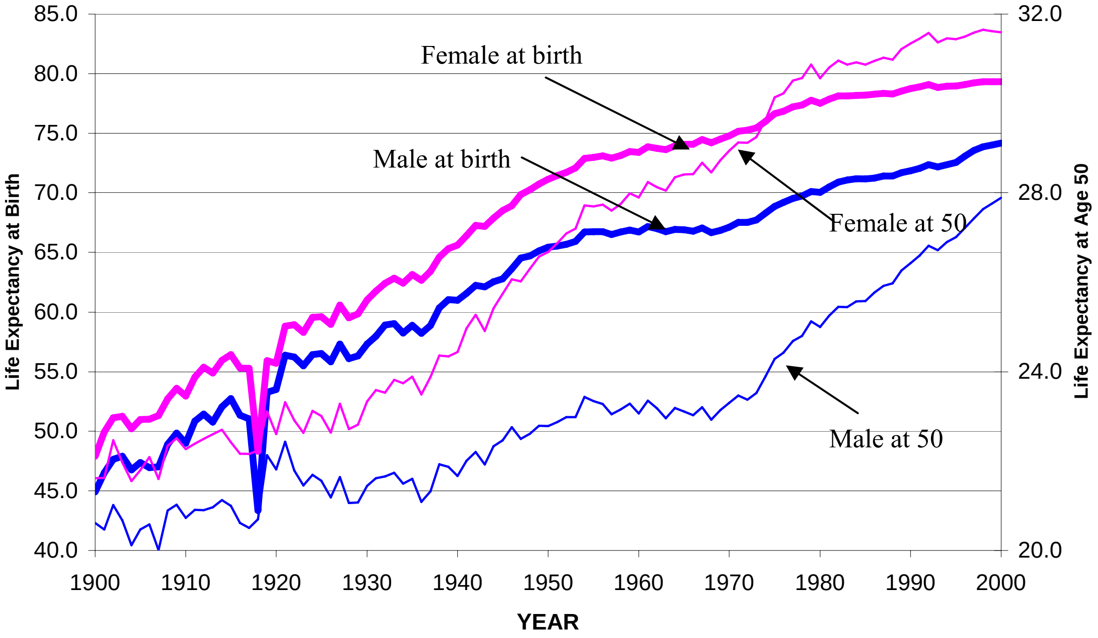
Figures and Tables

Figure 1

Life Expectancy at Birth and Age 50
United States, 1900-2000



Source: National Vital Statistics Reports, vol 52, #14, February 18, 2004, Table 12.

Table 1
Additional Life Years Due to Reduced Mortality From Selected Causes, by Decade, 1950-2000

Men

Disease	1950-60	1960-70	1970-80	1980-90	1990-00	Total
Infant Mortality	0.54	0.36	0.75	0.23	0.20	2.07
Heart Disease	0.16	0.38	1.05	1.26	0.88	3.73
Cancer	-0.19	-0.17	-0.08	0.02	0.43	0.01
Stroke	0.10	0.15	0.41	0.24	0.08	0.98
Accidents	0.18	-0.15	0.37	0.41	0.17	0.98
Other	0.54	-0.19	0.41	-0.31	0.85	1.30
Total	1.33	0.37	2.92	1.85	2.60	9.07

Women

Disease	1950-60	1960-70	1970-80	1980-90	1990-00	Total
Infant Mortality	0.40	0.35	0.59	0.22	0.13	1.68
Heart Disease	0.59	0.72	0.87	0.90	0.46	3.54
Cancer	0.20	0.07	-0.01	-0.11	0.17	0.31
Stroke	0.20	0.33	0.63	0.38	0.06	1.59
Accidents	0.10	-0.04	0.17	0.13	0.01	0.36
Other	0.77	0.19	0.69	-0.25	-0.04	1.36
Total	2.25	1.61	2.94	1.25	0.79	8.85

Notes: Figures are additional expected life-years calculated from *cross sectional* age-specific mortality rates in each year. Entries for each cause of death are contributions to additional expected life years over the decade due to changes in mortality rates from that cause. *Source:* Authors' calculations from Center for Disease Control, *Vital Statistics, Special Reports,* various years.

Table 2
Estimated Values of a Life-Year for 50 Year-Old Men

$$y^F + c^F \Phi(z) \; = \; y^F + c^F \frac{1}{\sigma - 1}[1 - \sigma(\frac{z_0}{z})^{\frac{\sigma-1}{\sigma}}]$$

	Elasticity of Intertemporal Substitution (σ)					
z_0/z	**1.2**	**1.1**	**1.0**	**.9**	**.8**	**.7**
.05	\$282	\$314	\$360	\$426	\$535	\$731
.10	\$229	\$249	\$276	\$314	\$373	\$471
.20	\$169	\$180	\$193	\$211	\$237	\$278

Note: The table assumes a value of full consumption of $y^F = c^F = \$120,000$ for a 50 year-old male with 4000 total available hours per year and wage of \$30/hour, including benefits.

Figure 2a: Implied Shape of H(t) Consistent with Consumption Data

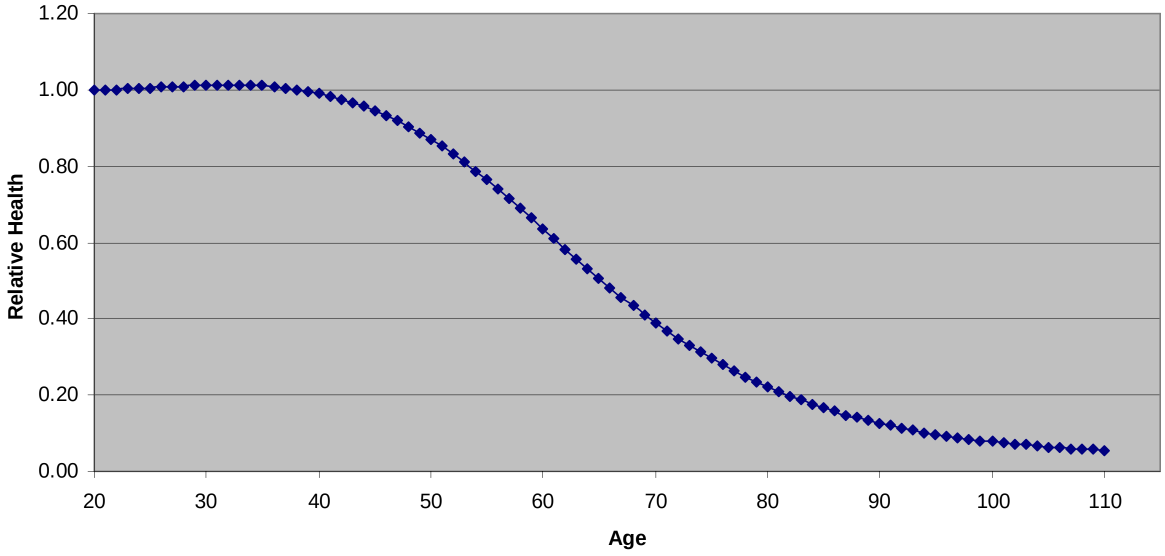
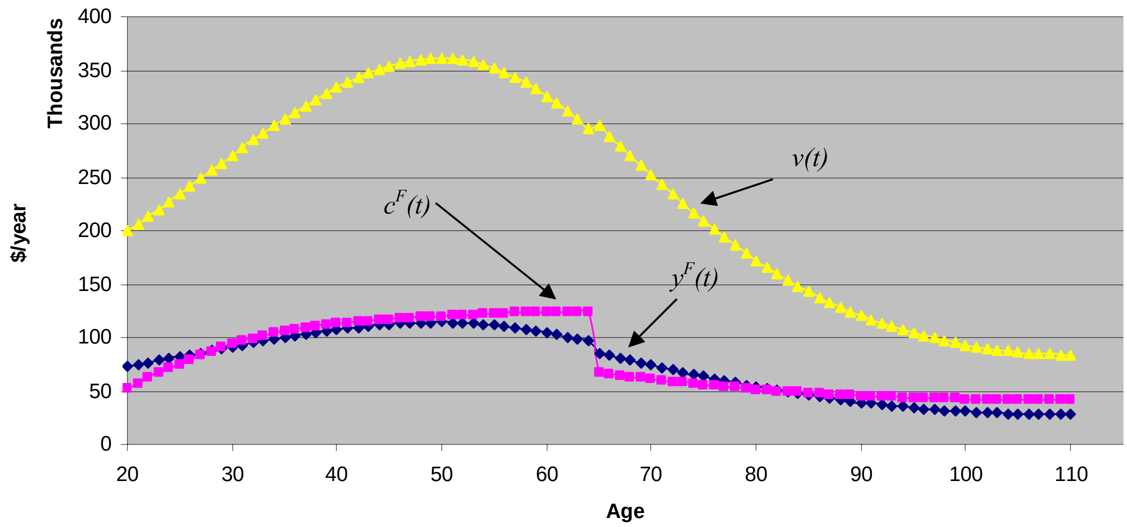


Figure 2b: Lifecycle Profiles of Full Income, Full Consumption and the Value of a Life-Year



Notes: See text for discussion of methods. Valuations assume $6.3 million average value of a statistical life, earnings of $60,000 at age 50, and peak consumption at age 50. Health profile is estimated residually from optimal consumption.

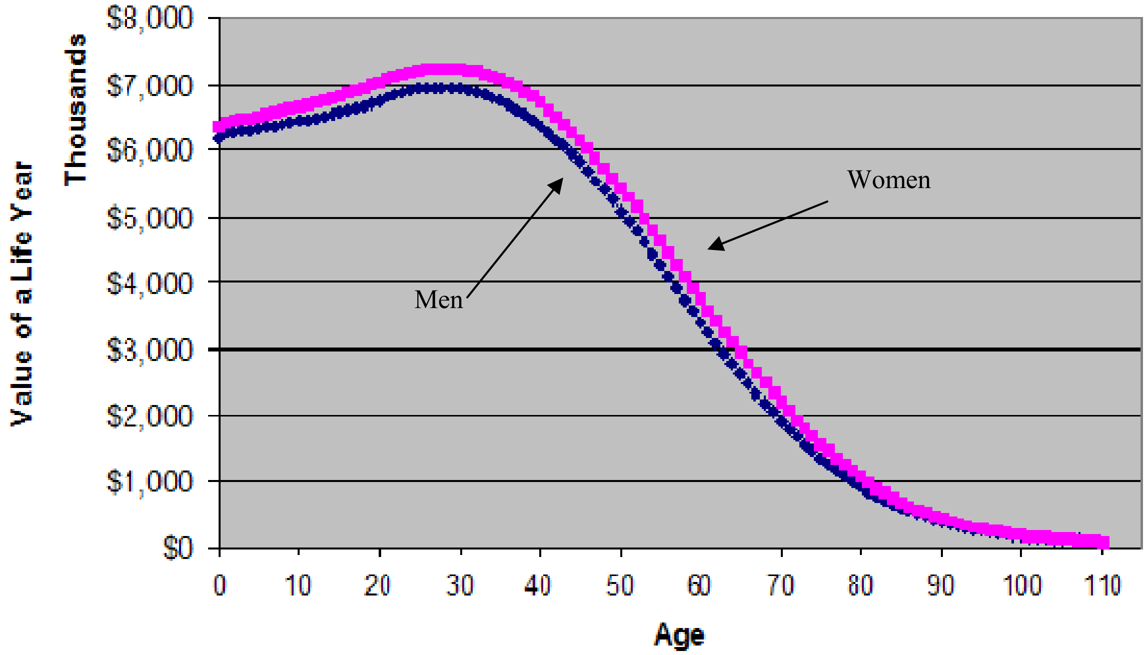


Figure 3: Values of Remaining Life Assuming $6.3 Million Value of a Statistical Life

Notes: See equation (14). Estimates are based on *v(t)* from Figure 2a, assuming an average value of a statistical life of $6.3 million between ages 25 and 55. Valuations of a life year are assumed identical for men and women.

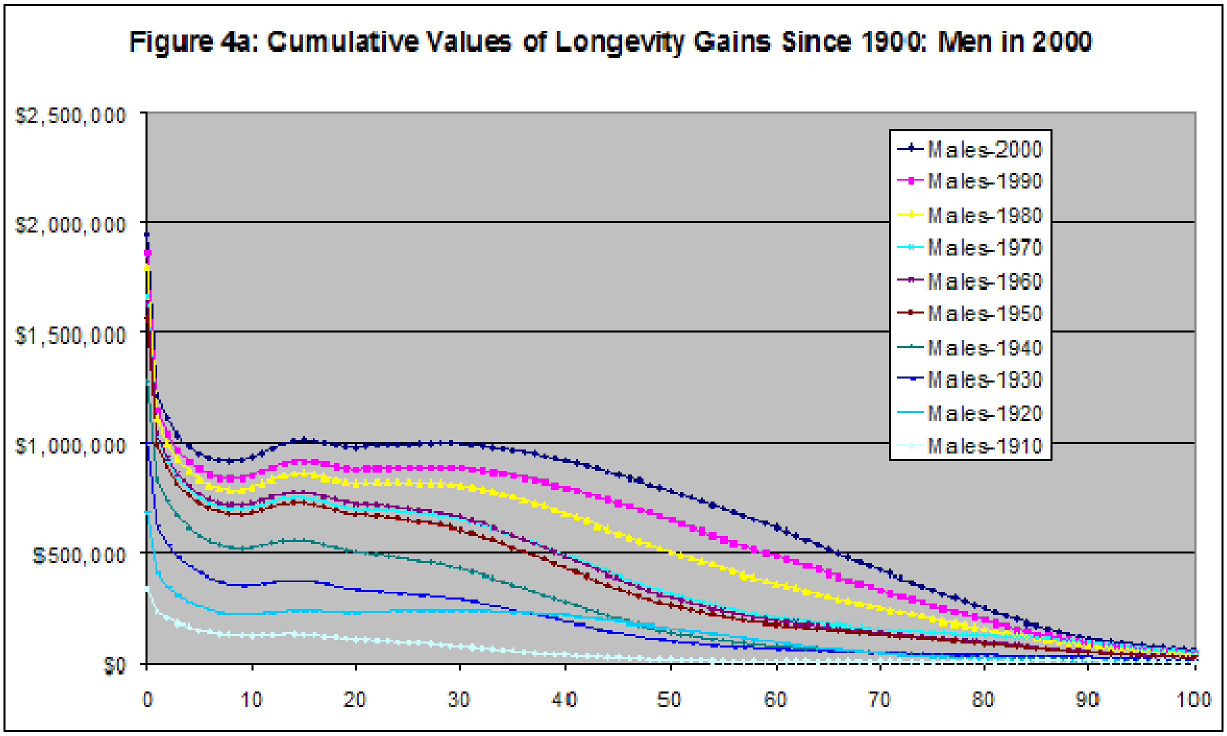


Figure 4a: Cumulative Values of Longevity Gains Since 1900: Men in 2000

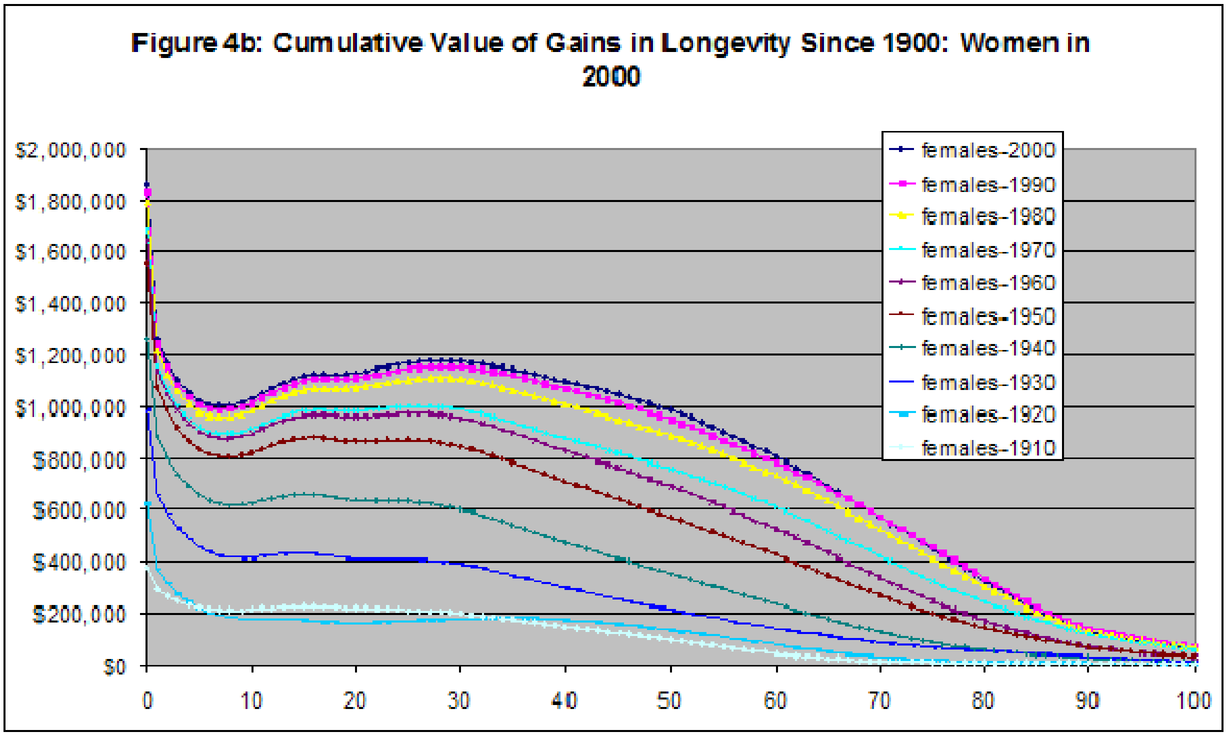


Figure 4b: Cumulative Value of Gains in Longevity Since 1900: Women in 2000

Notes: Each curve shows the cumulative value of increased longevity since 1900. Distance between curves represents gains in each decade.

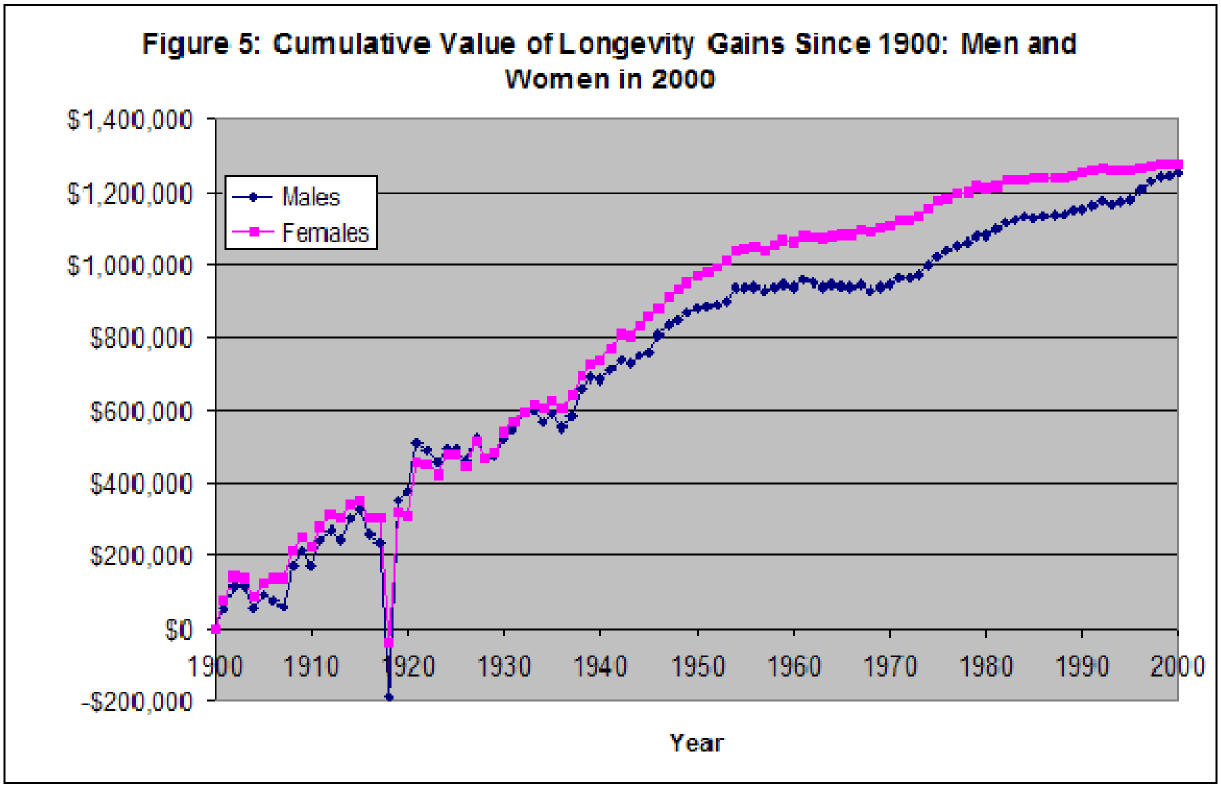


Figure 5: Cumulative Value of Longevity Gains Since 1900: Men and Women in 2000

Notes: Each curve represents the cumulative value to the indicated year due to increased longevity since 1900, as valued by persons in 2000. Age specific values are averaged using 2000 population weights.

Table 3
Decade Averages of GDP and Production of Health Capital per Capita 1900-2000 ($2004)

	1900-10	1910-20	1920-30	1930-40	1940-50	1950-60	1960-70	1970-80	1980-90	1990-2000
GDP	$6,011	$7,239	$7,703	$7,578	$13,592	$15,856	$20,343	$25,342	$28,381	$32,057
Health Capital	$4,987	$2,754	$5,513	$6,062	$12,314	$4,951	$2,381	$12,839	$7,305	$8,240
Total	$10,998	$9,993	$13,216	$13,640	$25,906	$20,807	$22,724	$38,181	$35,685	$40,297
Share of Health Capital	0.45	0.28	0.42	0.44	0.48	0.24	0.10	0.34	0.20	0.20

Source: Average annual real ($2004) amounts. Author's calculations for health capital. GDP before 1929 from Kuznets as compiled by Jones and Obstfeld (2001), downloaded from NBER website. Post-1929 data from U.S. Department of Commerce, Bureau of Economic Analysis. Pre-1913 price index from Federal Reserve Bank of Minneapolis.

Figure 6a. Gains from Increased Longevity for Males 1970-2000

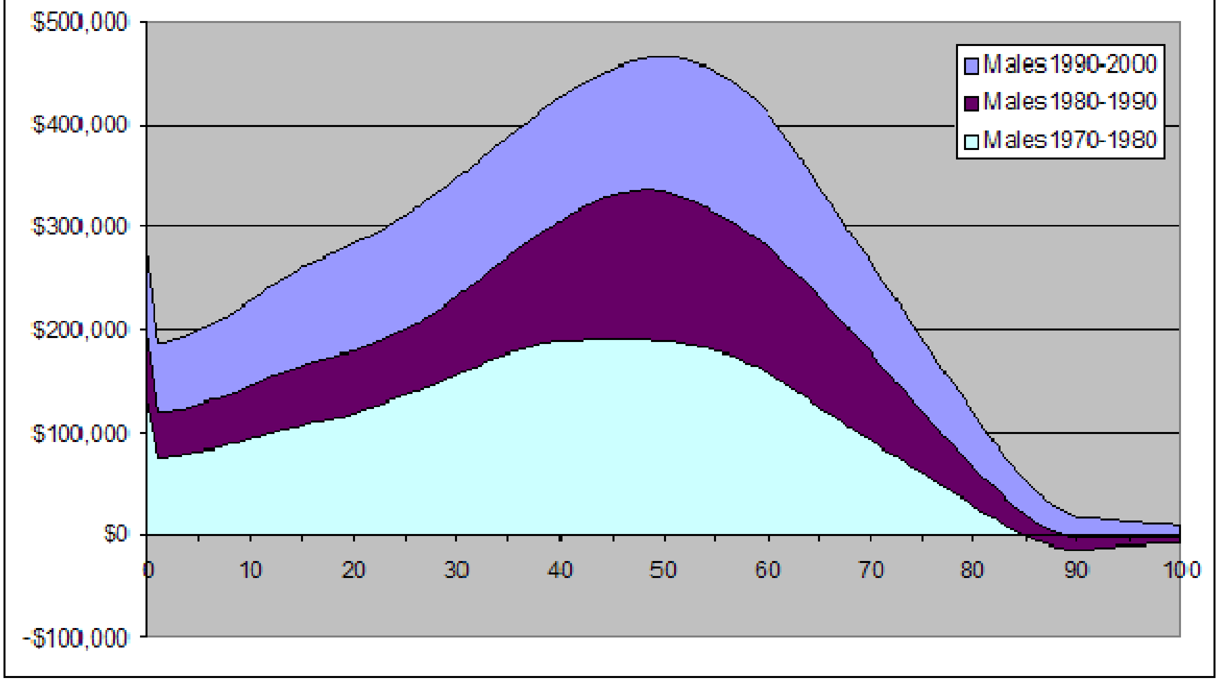
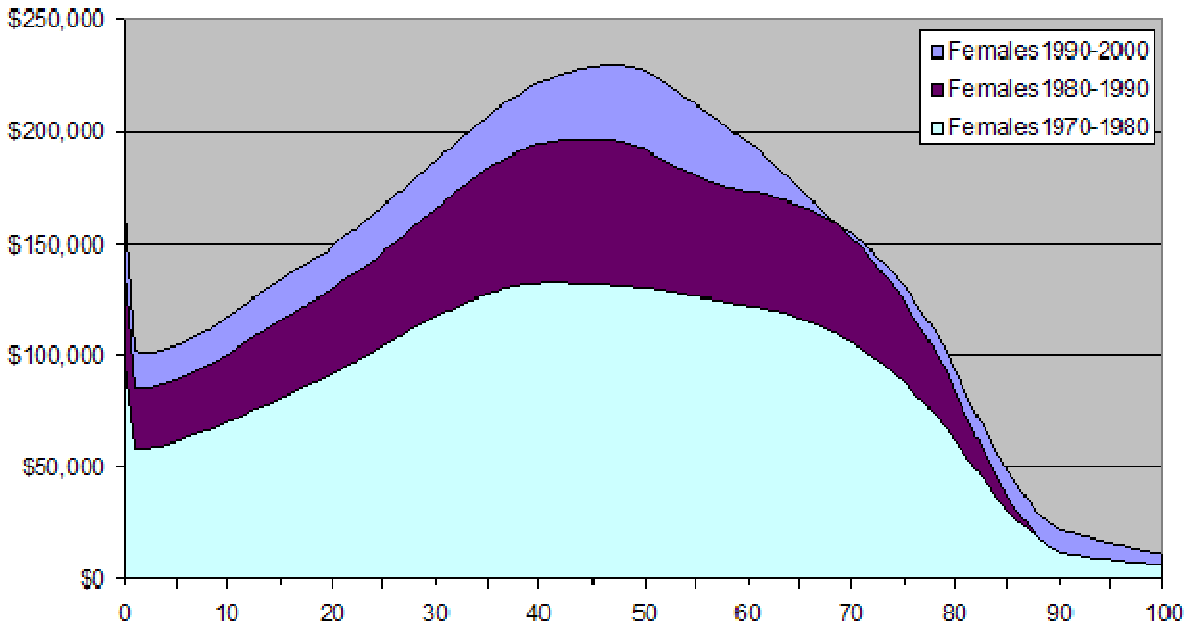
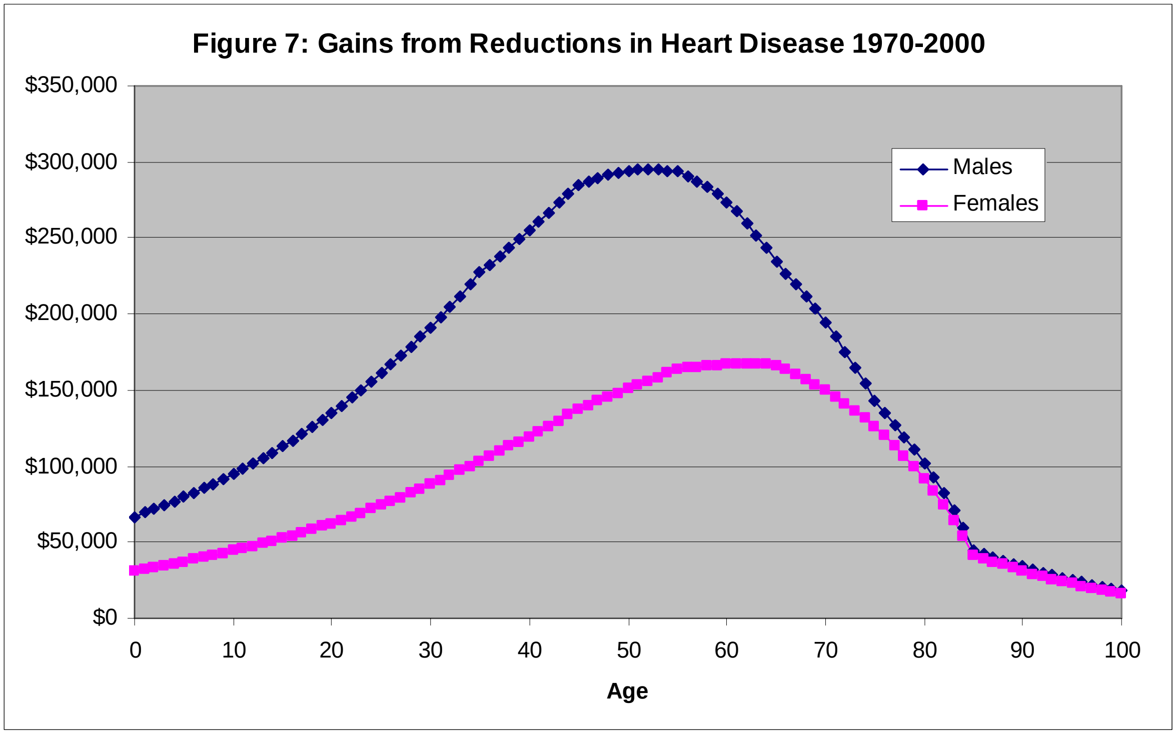


Figure 6b. Gains from Increased Longevity for Females 1970-2000



Notes: Each curve shows the cumulative value of increased longevity since 1970. Distance between curves represents gains in each decade.



Notes: See equation (15). Value to person of the indicated age in 2000 of reduced mortality from that age forward, 1970-2000.

Table 4
Economic Gains From Reductions in Mortality: 1970-2000
(Billions of $2004)

	1970-1980	1980-90	1990-2000	1970-2000
Males	$26,699	$15,471	$19,153	$61,323
Females	$20,515	$9,067	$4,440	$34,022
Total	$47,214	$24,538	$23,593	$95,345

Notes: Aggregate gains calculated using equation (24) and year 2000 U.S. population by age. Population at birth includes Census-predicted future birth cohorts discounted at 3.5 percent.

Table 5
U.S. Health Expenditures 1970-2000

	1970	**1980**	**1990**	**2000**
Nominal Expenditures ($Billions)	$73	$246	$696	$1,311
% of Total Consumption Expenditures	11.3%	13.9%	18.2%	19.6%
Real Expenditures ($Billions 2004)				
Current Year Population	$261	$445	$812	$1,221
Fixed Population	$369	$548	$883	$1,143
Per Capita Expenditures ($2004)				
Current Year Population	$1,537	$2,354	$3,911	$5,187
Fixed Population	$2,171	$2,897	$4,249	$4,855
Present Value of Total Expenditures ($Billions 2004, Fixed Population)	$16,209	$24,414	$39,342	$50,933

Source: Centers for Medicare and Medicaid Services, Office of the Actuary: National Health Statistics Group. “Fixed population” refers to the population in 2000.

Table 6
Estimated Gains Net of the Increase in Health Expenditures 1970-2000

	1970-1980	**1980-1990**	**1990-2000**	**1970-2000**
Gross Gains (from Table 4)	$47,214	$24,538	$23,593	$95,345
Increase in Expenditures	$8,206	$14,928	$11,591	$34,725
Gains Net of Expenditure Growth	$39,008	$9,611	$12,001	$60,620
Expenditure Increase as a % of Gains	17.4%	60.8%	49.1%	36.4%

Table 7
Economic Gains From Reductions in Mortality Net of Increased Health Care Expenditure, by Age and Gender, 1970-2000

Males	**Population**	**1970-1980**	**1980-1990**	**1990-2000**	**1970-2000**	**Cost/Value**
Birth	72,134	$119,958	$38,551	$61,967	$220,477	19.2%
1to4	7,938	$68,373	$20,716	$49,657	$138,746	26.9%
5to14	19,681	$81,703	$23,746	$60,995	$166,444	26.1%
15to24	18,618	$105,116	$28,576	$78,704	$212,396	24.7%
25to34	20,191	$139,412	$39,890	$86,580	$265,882	23.0%
35to44	21,569	$167,199	$73,290	$87,865	$328,354	21.7%
45to54	15,836	$166,351	$97,230	$95,943	$359,524	22.0%
55to64	10,166	$133,497	$78,043	$94,456	$305,996	25.8%
65to74	8,325	$69,395	$46,002	$59,350	$174,747	36.5%
75to84	4,486	$16,138	$11,866	$32,473	$60,477	55.9%
85+	1,070	-$21,094	-$5,191	$10,989	-$15,296	147.7%

Females	**Population**	**1970-1980**	**1980-1990**	**1990-2000**	**1970-2000**	**Cost/Value**
Birth	68,773	$83,703	$14,249	$4,743	$102,695	39.8%
1to4	7,578	$43,537	-$1,779	-$7,009	$34,749	65.8%
5to14	18,741	$51,176	-$2,832	-$9,736	$38,608	66.7%
15to24	17,604	$68,355	-$2,117	-$12,086	$54,153	63.2%
25to34	20,177	$88,985	$2,131	-$14,513	$76,603	58.8%
35to44	21,824	$98,440	$7,395	-$15,017	$90,818	58.5%
45to54	16,533	$90,914	$1,438	-$13,128	$79,224	65.0%
55to64	11,195	$75,543	-$13,315	-$27,842	$34,386	82.5%
65to74	10,345	$54,837	-$17,060	-$51,047	-$13,269	108.6%
75to84	6,944	$20,825	-$24,405	-$54,526	-$58,107	163.5%
85+	2,692	-$17,106	-$34,698	-$46,378	-$98,182	574.4%

Source: Values by age underlying Table 4 and imputations of health care spending by age and gender, as described in text.

Figure 8a. Value of a 10% Reduction in Death Rates from Selected Disease by Age for Males

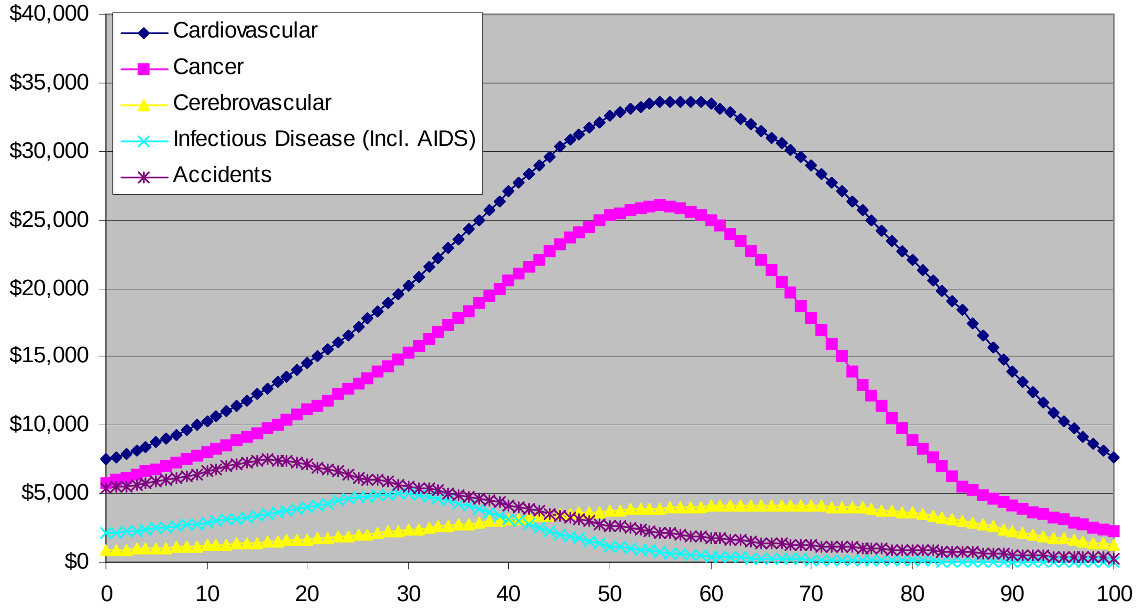
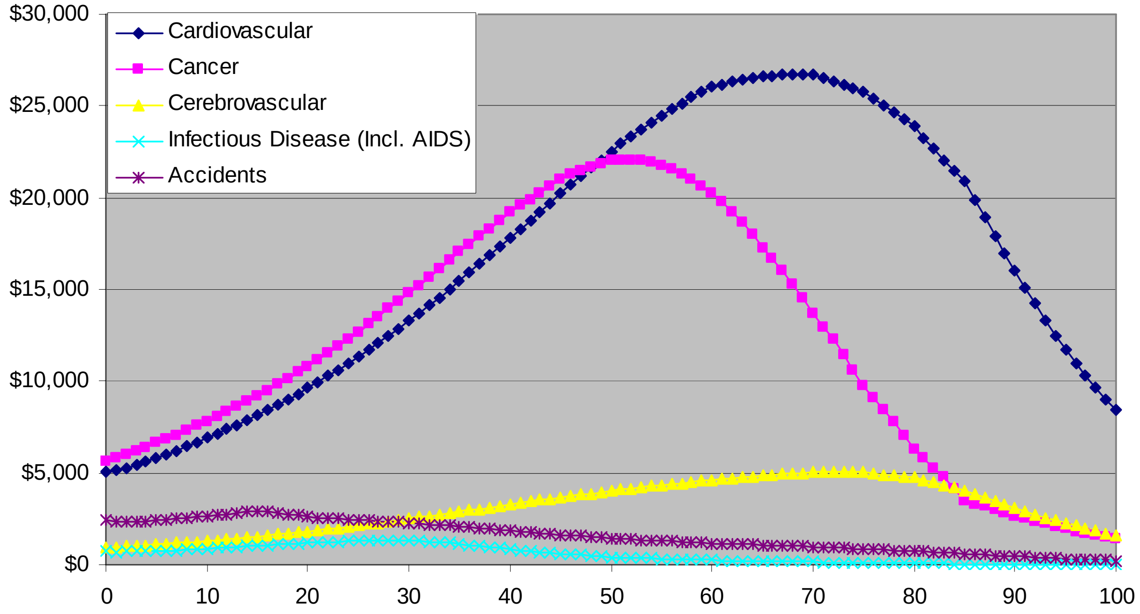


Figure 8b: Value of a 10% Reduction in Death Rates from Selected Disease by Age for Females



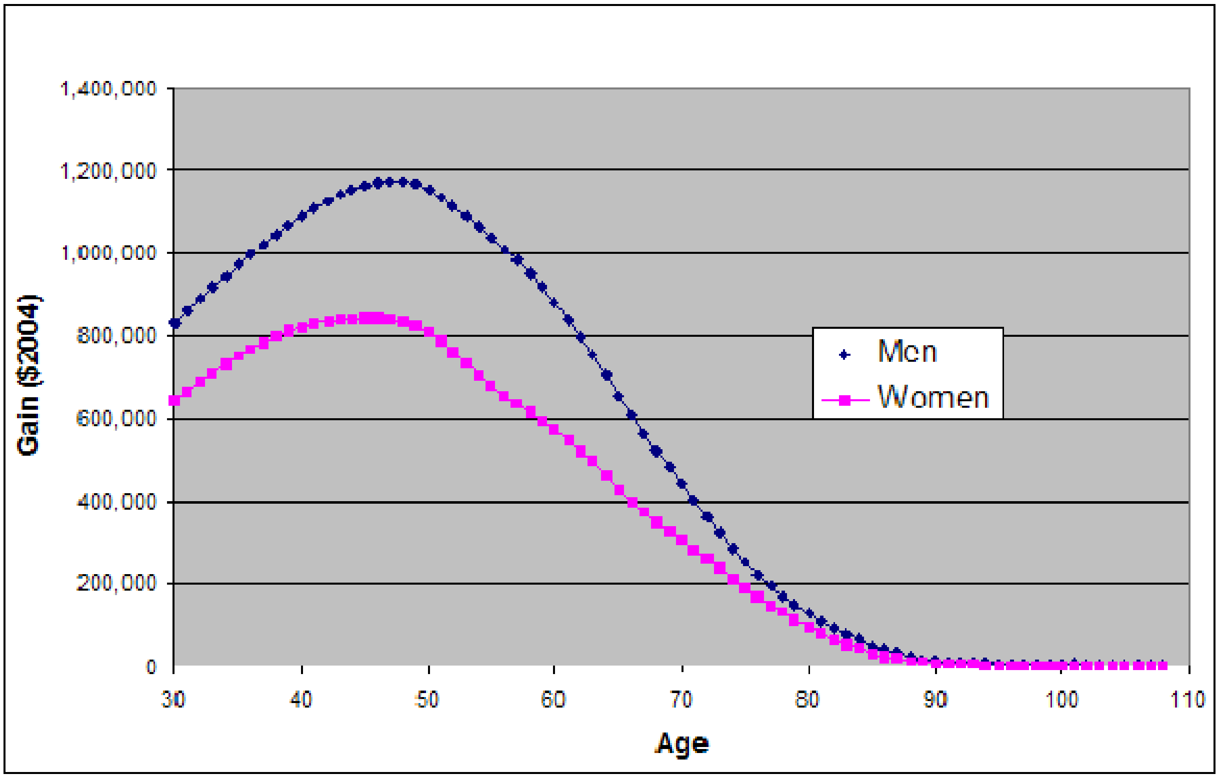
Notes: Curves show the per-capita value at the indicated age from a 10% reduction in mortality from the indicated disease, using equation (15)

Table 8
Current Value of a 10 Percent Reduction in Mortality from Major Diseases (Billions of $2004)

Major Cause of Death	Males	Females	Total	Complementarity Effect	
				Value	Share
All Causes	$10,651	$7,885	$18,536	$3,278	0.18
Cardiovascular Diseases	$3,254	$2,471	$5,725	$1,288	0.22
Heart Disease	$2,676	$1,852	$4,529	$1,013	0.22
Cerebrovascular Diseases	$393	$460	$852	$194	0.23
Malignant Neoplasms	$2,415	$2,261	$4,675	$863	0.18
Respiratory & Intrathoracic	$847	$557	$1,404	$278	0.20
Breast	$3	$444	$447	$51	0.11
Genital & Urinary	$301	$302	$603	$126	0.21
Digestive Organs	$575	$431	$1,006	$200	0.20
All Other Infectious Diseases	$500	$148	$649	$60	0.09
Obstructive Pulmonary Disease	$343	$331	$674	$153	0.23
Pneumonia & Influenza	$214	$194	$408	$98	0.24
Diabetes	$237	$249	$486	$91	0.19
Liver Disease & Cirrhosis	$217	$102	$319	$46	0.14
Accidents & Adverse Effects	$977	$421	$1,398	$133	0.10
Motor Vehicle Accidents	$519	$247	$767	$62	0.08
Homicide & Legal Intervention	$324	$90	$415	$29	0.07
Suicide	$411	$102	$513	$50	0.10

Notes: Social value of a 10% reduction in mortality from the indicated disease, calculated using equation (18). Calculations use 2000 population values and Census predictions of future birth cohorts, discounted at 3.5%.

Figure 9
Estimated Per-Capita Gain from Type-*H* Health Improvements
1970-2000



Notes: Value at each age of type-*H* health improvements between 1970 and 2000, using the second term in (15). See text for description of methods.