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Past, Present, and Future of Healthy Life Expectancy

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The success of the current biomedical paradigm based on a "disease model" may be limited in the future because of large number of comorbidities inflicting older people. In recent years, there has been growing empirical evidence, based on animal models, suggesting that the aging process could be delayed and that this process may lead to increases in life expectancy accompanied by improvements in health at older ages. In this review, we explore past, present, and future prospects of healthy life expectancy and examine whether increases in average length of life associated with delayed aging link with additional years lived disability-free at older ages. Trends in healthy life expectancy suggest improvements among older people in the United States, although younger cohorts appear to be reaching old age with increasing levels of frailty and disability. Trends in health risk factors, such as obesity and smoking, show worrisome signs of negative impacts on adult health and mortality in the near future. However, results based on a simulation model of delayed aging in humans indicate that it has the potential to increase not only the length of life but also the fraction and number of years spent disability-free at older ages. Delayed aging would likely come with additional aggregate costs. These costs could be offset if delayed aging is widely applied and people are willing to convert their greater healthiness into more years of work.

How long we live and what proportion of that life is spent in good health have important implications for individuals and societies. The implications for individuals span a wide range of possibilities including potential social burden of caregiving from surviving family members, valuing life insurance premiums, and adequacy of retirement benefits and savings. The societal effects include a changing dependency ratio (the ratio of dependent [older] to independent [younger] people), which has major consequences on the fiscal viability of social transfer programs, such as Social Security and Medicare, and the size and demographic composition of the workforce.

Average years of life (life expectancy) have continuously increased in most countries over the last century with no apparent plateau (Vaupel 2010). In low-mortality countries, most of the recent rise in life expectancy has been attrib-

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uted to declining mortality rates at older ages (Rau et al. 2008). Whether additional years of life are also accompanied by years in good health has become a subject of intense interest. Many disciplines contribute answers to this question, and several frameworks for assessing healthy aging have emerged (Gruenberg 1977; Fries 1980; Manton 1982). Recent developments in the biology of aging suggest that the aging process could be delayed (Kirkwood and Austad 2000; Sierra et al. 2009; Miller 2012) and that this process may lead to faster increases in life expectancy accompanied by improvements in health at older ages (Goldman et al. 2013). Unlike current medical and health care policy approaches that typically focus on reducing progression and lethality of major chronic diseases one by one, delayed aging focuses on postponing age-dependent deterioration in dividing cells, nondividing cells, cell parts, and extracellular materials (Miller 2012). As a result, delayed aging has the potential to postpone both physiological deterioration and comorbidities over the life cycle, and extend healthy years of life (Goldman et al. 2013). If delayed aging occurs among populations as posited, the study of healthy aging may require either revamping standard theories or formulating new ones.

In this article, we provide a general overview on trends in healthy life expectancy in the United States and other high-income countries and further elaborate on the implications of delayed aging for the future of healthy life expectancy. In particular, we examine whether increases in average length of life associated with delayed aging link with additional years lived disability-free at older ages. The review is structured as follows: We describe empirical evidence on healthy life expectancy to assess trends in the past and present. Next, we evaluate the implications of delayed aging for the future of healthy life expectancy and, finally, we discuss prospects of healthy life expectancy in the near future and conclude.

HEALTHY LIFE EXPECTANCY IN THE PAST AND PRESENT

Mortality trends in high-income countries between 1900 and 1950 showed a clear age-pattern shift. Mortality at young ages and from infectious conditions was rapidly receding, whereas mortality at older ages and from chronic conditions began to dominate (Omran 1971; Preston 1976). By the 1960s, major medical improvements in cardiovascular survival led to an increasing prevalence of heart disease at older ages. These developments focused attention on the morbidity as well as the mortality of the increasing older population. By the late 1970s and early 1980s, researchers had devised theoretical frameworks as well as markers of morbidity for assessing healthy aging. We briefly review three of these frameworks—failure of success, compression of morbidity, and dynamic equilibrium—that have guided significant amounts of research on healthy life expectancy in the last decades.

The first framework proposed by Gruenberg (1977) argued that declines in mortality from chronic disease would invariably lead to increase disease prevalence, which he termed "the failure of success." In his view, mortality declines would arise from higher survival of individuals with health problems thereby increasing disease prevalence and morbid life in the population. Others noted that the interaction of mortality declines with disease incidence (Fries 1980) and that disease progression and its severity (Manton 1982) had an important role for shaping the length of morbid life. The second framework developed by Fries (1980) introduced the idea of "compression of morbidity" in which he argued that the same forces that resulted in decreased mortality would be linked to lower incidence of chronic disease and higher age of onset of chronic disease resulting in a shortening of the length of morbid life. The third framework developed by Manton (1982) introduced the idea of "dynamic equilibrium" to highlight the link with disease progression and its severity. He argued that the severity and progression of chronic disease would change at the same pace as mortality improvements so that the progression of disease would be stopped at early stages, resulting in potentially more disease in the population but disease with decreased consequences.

Measuring Health at Older Adult Ages and Its Connection with Length of Life

Fries' hypothesis guided most empirical research since the 1980s. In his framework, he advocated the study of disability and functional mobility indicators as proxy markers to test compression of morbidity under the assumption that these indicators "represented" the morbidity status of the population. These indicators were initially developed in the 1970s by Nagi (1979), of which activities of daily living (ADLs)—eating, bathing, walking, toileting, and dressing by oneself—are the most commonly used, and adopted internationally by the World Health Organization (World Health Organization 1980) in the 1980s. They were further elaborated by Verbrugge and Jette (1994) under the framework of the "disablement process" in the early 1990s. Under this framework, disability is thought to be influenced by the interaction of physical ability (intraindividual) and environmental challenge (extraindividual), and the focus is on how chronic and acute conditions affect critical physical functions, such as ADLs (Verbrugge and Jette 1994). In addition to these internal and external factors, disability levels are also affected by the social roles used to define disability, and the environment in which it is measured. That is, disability is considered to be the end result of a pathologic process, and so the framework's goal is to assess the trajectory of functional consequences over time and the factors that may affect it. This approach has guided the majority of research on healthy life expectancy since the mid-1990s.

Since the 1980s, many national health surveys have begun collecting biological markers that appeared to be better suited for assessing underlying physiological damage as precursors of overt morbidity. These markers are thought to represent a latent trait of functioning of major organ systems and their physiological processes. The use of these markers in social science research is quite recent (since the early 2000s), and has opened a new gate of possibilities for studying healthy aging, and it is becoming the guide for current and future research on linking mortality improvements with health (Goldman et al. 2006, 2009; Crimmins et al. 2009, 2010). Most of these biomarkers were initially developed to assess individuals' risk of cardiovascular events (e.g., Framingham Risk Score) and cardiometabolic status (e.g., metabolic syndrome). Additional composite indexes have been created to incorporate a broader array of physiological factors linked with highly prevalent health outcomes at older ages, such as markers of stress and disease accumulation (e.g., allostatic load) (Seeman et al. 1997) and markers of inflammation. For instance, recent evidence suggests that inflammatory markers related to cardiovascular and metabolic disease, such as interleukin-6 (IL-6) and soluble intercellular adhesion molecule 1 (sICAM-1), are linked with survival among middle-aged and older adults (Crimmins et al. 2010; Glei et al. 2014).

Measuring morbidity at older ages requires data on individuals at multiple points in time to assess changes in health (e.g., transition probabilities) as they reach older ages. This data is difficult to come by at the national level except for a handful of longitudinal studies, such as the Health and Retirement Study (HRS) in the United States. Thus, most evidence on morbidity indicators comes from cross-sectional surveys in the form of prevalence rates, with a few exceptions (for example, see Cai and Lubitz 2007; Crimmins et al. 2009; Cai et al. 2010). The typical approach for estimating healthy life expectancy is the Sullivan method (Sullivan 1971)—a technique that allocates years of life into years lived with and without morbidity based on prevalence rates. Thus, trends in healthy life expectancy are largely driven by prevalence rates in a given morbidity indicator. In the following sections, we provide a brief overview on past and current trends of the most commonly used morbidity indicators when they are measured by traditional disability and functional mobility as well as those related to chronic disease and biomarkers of health.

Functional Mobility-Based Indicators

Empirical evidence on past and current trends in disability and functional mobility indicators

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is mixed. In the United States, there is evidence that ADL disability prevalence declined among those older than age 65 until the 1990s (Freedman et al. 2013), with a decline in the severity of ADL disability among people aged 65 and older between 1992 and 2002, a decline in the prevalence of people unable to complete at least three ADLs, but no significant change in moderate disability (disabled in one or two ADLs) (Cai and Lubitz 2007). Data from Medicare Current Beneficiary Survey (Cutler et al. 2013) and from the Health and Retirement Study (Smith et al. 2013) show that ADL disability is increasingly compressed within the last 2 years before death. Other research, however, does not indicate declines in disability. Data from early 2000s show stagnation and even deterioration in mobility functioning and disability (Crimmins and Beltrán-Sánchez 2011; Freedman et al. 2013). Additional evidence indicates increasing disability rates in recent years among younger American adults aged 40–64 years (Seeman et al. 2010). Similarly, results from two major studies of aging, the Longitudinal Studies of Aging and the Medicare Current Beneficiary Survey, show no changes in age at onset of disability between 1984 and 1994 (Crimmins et al. 1994) and between 1992 and 2002 (Cai and Lubitz 2007). In Europe, trends in disability[4] at age 65 are similarly mixed with some studies indicating increases in disability rates in nine out of 13 European countries,[5] with reductions in two countries (Austria and Italy) and stable rates in two countries (Belgium and Spain) (European Health Expectancy Monitoring Unit 2009; Bowling 2011). Finally, a large-scale study of 187 countries from the global burden of disease indicates that as life expectancy has increased between 1990 and 2010, the number of healthy years lost to disability has also increased (Salomon et al. 2012).

[4]Disability is estimated from the question: "Are you hampered in your daily activities by any physical or mental health problem, illness or disability"?

[5]Countries included: Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, the Netherlands, Portugal, Spain, and the United Kingdom.

Chronic Disease Indicators and Health Risk Factors

Arthritis is the leading cause of disability in the United States, especially common among adults with multiple chronic conditions (Barbour et al. 2013). In 2005, 19% of adults who reported disabilities indicated arthritis or rheumatism as the main cause of their disability (Brault et al. 2013). Among the 53 million adults who reported doctor-diagnosed arthritis, 23 million also reported arthritis-attributable activity limitation. Arthritis is an especially common chronic condition among adults with heart disease, diabetes, and obesity. For example, 49% of adults with heart disease also had arthritis between 2010 and 2012 (Centers for Disease Control and Prevention 2013).

In addition to arthritis, major chronic conditions and cognitive impairments appear to be on the rise among U.S. older adults. Nearly half of all Medicare beneficiaries during the 1990s and early 2000s received care for at least one of the following: cancer, chronic kidney disease, chronic obstructive pulmonary disease, depression, diabetes, or heart failure (Schneider et al. 2009). Moreover, it is estimated that the prevalence of dementia in the early 2000s at ages 71+ was ~14% and ~10% for Alzheimer's disease specifically (Plassman et al. 2007), although some substantial portion of the increase is likely attributable to better diagnosis. Finally, lack of access to health insurance may exacerbate the future consequences on the health status of older adults. A substantial proportion of working-age adults with chronic conditions—who are not yet old enough to receive Medicare benefits—are uninsured (Wilper et al. 2008). These uninsured and chronically ill adults were less likely to visit a health professional and have a standard site of care (other than the emergency department) compared with their insured counterparts.

These patterns are not unique to the United States. Globally, chronic diseases are the leading cause of mortality and morbidity (World Health Organization 2002; Yach et al. 2004). The global prevalence of chronic conditions is projected to increase substantially over the next decade as the leading causes of death and dis-

ability shift from communicable disease to noncommunicable chronic diseases as described by the "epidemiological transition." Cardiovascular disease, cancer, and diabetes are among the chronic conditions projected to increase the most (Yach et al. 2004). Behavioral risk factors including alcohol abuse, tobacco use, and obesity contribute substantially to disability (Salomon et al. 2012). For example, 58% of diabetes, 21% of ischemic heart disease, and between 8% and 42% of cancers were attributable to obesity (body mass index $\geq$21 kg/m^2).

Physiological Status Indicators

Adverse levels in biomarkers of health slowly develop into chronic conditions over the individual's life cycle. There is little evidence from recent trends in markers of cardiometabolic risk of improvements in health as people approach old age. Trends in physiological indicators representing average functioning of multiple bodily systems indicate a deterioration in recent years in some markers of inflammation and glucose levels (diabetes indicator), but improvements in average lipid levels and markers of cardiovascular health (e.g., hypertension) (Crimmins et al. 2010; Beltrán-Sánchez et al. 2013). From the late 1980s to about 2005, time trends were stable for C-reactive protein (CRP), a marker of inflammation, and for glycosylated hemoglobin, a marker for diabetes, among people aged 65 and older (Crimmins et al. 2010). In the same time period, there were also reductions in the prevalence of high-risk cholesterol level and hypertension (Crimmins et al. 2010). Among younger adults aged 40 to 64, some evidence indicates increasing prevalence of CRP among males and higher levels of glycosylated hemoglobin for females between 1999 and 2006 (Martin et al. 2010). Importantly, declines in lipid levels and hypertension appeared to be driven by increased use and efficacy of medications, rather than reductions in the incidence of these conditions (Beltrán-Sánchez et al. 2013). For example, among the adult U.S. population aged 20 and older, the use of lipid-modifying agents almost doubled between 1999 and 2010, whereas the use of antihypertensive medications reached ~28% in 2010 (Beltrán-Sánchez et al. 2013).

Socioeconomic and Racial Differences in Healthy Life Expectancy in the United States

Period-based evidence consistently shows disparities in healthy life expectancy by sex, race/ethnicity, and socioeconomic status. Generally, the proportion of remaining life spent in good health is higher for men compared with women, for whites compared with racial and ethnic minorities, and for the most educated compared with the least educated (Crimmins et al. 1989; Manton and Stallard 1991; Guralnik et al. 1993; Hayward and Heron 1999; Crimmins and Saito 2001; Molla et al. 2004; Solé-Auró et al. 2015). Period-based studies have also found evidence of widening racial and sex disparities in healthy life expectancy over time, although these studies are based on tenuous assumptions of constant age-specific mortality and disability rates over time (Dowd and Bengtson 1978; Chappell and Havens 1980; Carreon and Noymer 2011).

Cohort studies, which are not subject to these assumptions, produce mixed results about whether racial and sex gaps in healthy life expectancy narrow, persist, or expand over age and time. For example, Kelley-Moore and Ferraro (2004) found evidence of persistent racial and sex disparities in disability, and Ferraro and Farmer (1996) found similar patterns of persistent disparities in subjective health. In contrast, Ferraro et al. (1997) found widening racial disparities in self-assessed health. Soneji (2006) concluded that cohort patterns in racial disparities in healthy life expectancy may depend on the severity level of disability, which is consistent with Manton's hypothesis of dynamic equilibrium.

Three theories in aging may help to explain the varying results from cohort studies. First, the "age as leveler" theory rests on selective survival and posits that earlier gaps in healthy life will narrow in advanced age (Kent 1971; Dowd and Bengtson 1978). Indeed, convergence in racial and sex gaps has been observed among the oldest old in chronic disease prevalence and physical disability, as well as functional health (Gibson 1991; Clark et al. 1993; Johnson 2000;

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Manton and Gu 2001). Second, the theory of "persistent inequality" asserts that sex and racial gaps in earlier life will continue throughout life. Stable sex and racial gaps have been found in physical disability (Ferraro and Farmer 1996; Kelley-Moore and Ferraro 2004). Finally, the "cumulative disadvantage theory" argues that the gap in healthy life expectancy experienced by racial and ethnic minorities and women will widen in advanced age. Such widening gaps have been noted in disability and institutionalization but not in mortality (Clark 1997; Liao et al. 1999).

OUTLOOKS FOR THE FUTURE: DELAYED AGING

An important tenet of delayed aging is that all fatal and disabling disease risks are lowered simultaneously, thereby leading to a postponement of the age at onset of these conditions. To provide a sense of the possible impact of delayed aging on future healthy life expectancy in the United States, we use projections of mortality and ADL disability prevalence from 2010 to 2060 by Goldman et al. (2013) based on a delayed aging model. Briefly, Goldman et al. created population projections using a microsimulation model, called the Future of Elderly Model (FEM), that takes into account time trends in disability, improved prevention of diseases, and impact of new medical technologies using data from cross-sectional national health surveys (e.g., National Health Interview Survey) and the largest longitudinal studies of aging in the United States (Health and Retirement Study and the Medicare Current Beneficiary Survey). Additionally, Goldman and colleagues also projected population counts for a baseline scenario using mortality projections from the Social Security Administration (for further details, see Goldman et al. 2013).

Implications of Delayed Aging for Disability

Figure 1A shows the proportion of people aged 65 or older projected to be disability free between 2010 and 2060 in the delayed aging scenario and in the baseline scenario. Disability is defined as having one or more limitations in instrumental activities of daily living (IADLs), having one or more limitations in ADLs, living in a nursing home, or a combination of the three (Goldman et al. 2013). Results clearly show that under the delayed aging scenario there would be higher prevalence of disability-free older adults

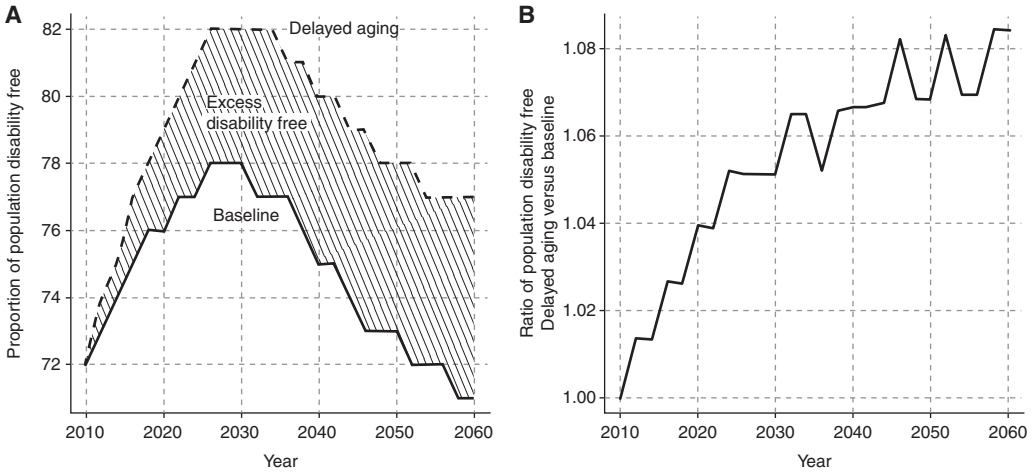

Figure 1. Effect of delayed aging on future population disability free. Proportion of people aged 65 or older projected to be disability free (*A*), and excess disability free (*B*), between 2010 and 2060 in the delayed aging scenario and in the baseline scenario, respectively. (From Goldman et al. 2013; with permission, from the authors.)

in every year between 2010 and 2060 with a peak in 2030, relative to the baseline scenario. Importantly, the magnitude of the difference between scenarios, that is, excess disability-free, slightly increases from 2030 to 2060 resulting from a lower annual rate of decline in disability-free prevalence in the delayed aging scenario (slope = −0.0020 in delaying aging vs. slope = −0.0025 in the baseline). Thus, there is an upward trend in excess of disability-free older adults in the delayed aging scenario (Fig.1B).

To highlight the impact of delayed aging on life expectancy, we estimate healthy life expectancy measured by years of life disability free at age 65 in 2030, the peak year of disability-free prevalence (Table 1). We use Sullivan's method (Sullivan 1971) to split remaining years of life at age 65 into years lived with disability and disability free using survival probabilities and disability prevalence from Goldman et al. (2013). According to the projections, delayed aging would lead to ∼9% (2.4 yr) higher life expectancy at age 65 in 2030 relative to the baseline scenario, from ∼25.5 yr in the baseline scenario to ∼27.9 yr in delayed aging. Estimates of healthy life expectancy also show higher number of reaming years of life disability free under the delayed aging scenario, ∼22.9 yr out of 27.9, relative to the baseline scenario. More importantly, however, is whether the additional 2.4 years of life under delayed aging are also accompanied by more years disability free. We use a simple and well-known decomposition approach (Kitagawa 1955) to assess how much of the additional 2.4 years are because of changes in prevalence of disability free and disability between scenarios. Our results indicate that ∼80% of the extra years of life (1.9 yr) under delayed aging would be disability free. This exercise highlights that delayed aging has the potential for increasing not only the length of life but also the fraction and number of years spend disability free at older ages.

Implications of Delayed Aging for Chronic Disease Morbidity

With a few exceptions (for example, see Goldman et al. 2013), most of the evidence of delayed aging is based on animal models and results show promising prospects for postponing the age at onset of chronic disease and disability accompanied by improved physiological status (Harrison et al. 2009). There is a growing literature of empirical studies showing viable interventions to slow aging and extend life including caloric restriction (Anderson and Weindruch 2012), single-gene mutations (Bartke 2011), inhibitors of the target of rapamycin pathways (Miller et al. 2010), senescent cell elimination (Baker et al. 2011), and transplants of stem cells from young to old mice (Conboy et al. 2005), to name a few.

The common theme in recent studies is the consistency of findings suggesting that these interventions improve both lifespan and healthspan in animal subjects. For instance, caloric restriction is thought to change the regulation metabolism, which in turn activates pathways leading to increase disease resistance with delays in the onset of chronic disease (Anderson and Weindruch 2012). Single-gene mutation that affects signaling of growth hormones (e.g., Pit1 and Prop-1 genes) and insulin (e.g., insulin-like growth factor [IGF]-1) has been shown to delay age-related diseases, such as oxidative stress resistance, cardiac and ocular pathology, and atherosclerosis (Bartke 2011). Results using rapamycin indicate that this inhibitor may play a major role in the target of rapamycin pathways in control of aging in mammals and in the pathogenesis of late-life illnesses (Harrison et al. 2009; Laplante and Sabatini 2009; Miller et al. 2010). Some studies show that rapamycin delays the age at onset of conditions, such as cancer (Blagosklonny 2008) and Alzheimer's disease (Caccamo et al. 2010), and reduces atherosclerotic plaque progression (Pakala et al. 2005). Additionally, there is evidence in humans that incidence of type 2 diabetes in older adults can be delayed through medication (metformin) (Knowler et al. 2002). Although there is limited empirical evidence that these interventions may have the same health benefits in humans, there is the potential that delayed aging through pharmacotherapy may lead to health improvements at older ages.

CONCLUSION

As we look into the future of healthy life expectancy, there are some concerns regarding trends in health risk factors, such as obesity and smoking, as well as large socioeconomic differences in health. In the United States, for example, a report of the National Academy of Sciences indicates that Americans have much higher rates of unhealthy behaviors (e.g., smoking and obesity) than their counterparts in high-income countries (Woolf et al. 2013). Some research predicts a slow down of life expectancy as a result of obesity (Olshansky et al. 2005; Stewart et al. 2009), whereas there is compelling evidence that smoking has had a great toll on adult mortality and will likely continue to do so in the near future, at least for females (Preston et al. 2010). Although recent evidence shows improvements in healthy life expectancy among recent cohorts of older people in the United States, there appears to be increasing levels of frailty and disability among younger generations, leading some researchers to believe that future cohorts of older people will likely show declining health expectancy (Martin et al. 2010). However, trends on obesity from 1999 to 2006 suggests a leveling off in the prevalence in adult females and children, with similar trends among adult males from 2003 to 2006. (Ogden et al. 2007, 2008). Educational attainment among older adults is likely to increase in the next decades as new cohorts of younger adults entering old age appear to have high average educational levels (Martin et al. 2010). Because education is positively linked with health and functioning through many mechanisms (e.g., healthier lifestyles), increasing educational levels among new cohorts of older adults is likely to lead to improvements in late-life health, including disability and functional mobility.

Continuing on the current biomedical paradigm based on a "disease model" is also likely to lead to health improvements, albeit with diminishing returns because of a large number of comorbidities inflicting older people. Results from Goldman et al. (2013) simulating two scenarios (cancer and heart disease) representing optimistic developments in medical research, disease treatment, and improvements in behavioral risk factors show a slight increase in older adults from 2010 to 2060 (0.8% and 2% more people in 2060 for cancer and heart disease, respectively, relative to a baseline scenario) with one-fourth (25%) of them having disability over the period when either cancer or heart disease are arrested. These values are ~20% higher than those under the delayed aging scenario. If these projections produce an accurate rendition of the near future, the current biomedical paradigm could potentially lead to an increasing fraction of the population with disability.

On the other hand, delayed aging appears to have important consequences on health and functioning of older mammals based on animal studies, although there is limited evidence on humans. As shown in the static exercise, delayed aging has the potential for increasing not only the length of life but also the fraction and number of years spent disability free at older ages. Although disability is only one dimension of health, results from animal models suggest that delayed aging could have far-reaching health benefits by delaying the age at onset of underlying physiological processes, reducing disease progression, or both. Nonetheless, delayed aging also poses important challenges. In high-income countries, population aging is already occurring or will inevitably occur in the next decades; this process could be exacerbated under a delayed aging scenario. Even if biomedical breakthroughs eventually provide means of slowing the rate of aging, they may not be applied on a wide scale. They may prove to be exceptionally expensive, so that only a small minority may benefit from them. But even if they are inexpensive to use on a personal level, the social costs may be prohibitive. As shown by Goldman and colleagues (2013), achieving delayed aging is likely to put pressure on public transfer programs (e.g., Social Security and Medicare) with additional aggregate costs resulting from a large number of people surviving to older ages. These costs could potentially be offset by changing the eligibility age for Medicare and the normal retirement age for Social Security (Goldman et al 2013). This is not an easy task. Changing eligibility of transfer pro-

grams is a core source of the current financial and political turmoil in Europe (e.g., France). The United States is likely to follow similar turmoil unless the benefits of delayed aging are applied on a wide scale and people are willing to convert their greater healthiness into more years of work.

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