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From Life Span to Health Span: Declaring "Victory" in the Pursuit of Human Longevity

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A difficult dilemma has presented itself in the current era. Modern medicine and advances in the medical sciences are tightly focused on a quest to find ways to extend life—without considering either the consequences of success or the best way to pursue it. From the perspective of physicians treating their patients, it makes sense to help them overcome immediate health challenges, but further life extension in increasingly more aged bodies will expose the saved population to an elevated risk of even more disabling health conditions associated with aging. Extended survival brought forth by innovations designed to treat diseases will likely push more people into a "red zone"—a later phase in life when the risk of frailty and disability rises exponentially. The inescapable conclusion from these observations is that life extension should no longer be the primary goal of medicine when applied to long-lived populations. The principal outcome and most important metric of success should be the extension of health span, and the technological advances described herein that are most likely to make the extension of healthy life possible.

ON THE ORIGIN OF LIFE SPAN

How long people live as individuals, the expected duration of life of people of any age based on current death rates in a national population, and the demographic aging of national populations (e.g., proportion of the population aged 65 and older), are simple metrics that are colloquially understood as reflective of health and longevity. Someone that lives for 100 years had a life span of a century, and a life expectancy at birth of 80 years for men in the United States means that male babies born today will live to an average of 80 years if death rates at all ages today prevail throughout the life of the cohort. When life expectancy rises or declines, that is interpreted as an improvement or worsening of public health. These demographic and statistical metrics are reflective measurement tools only—they disclose little about why they change or vary, they reveal nothing about why they exist at all, and they are indirect and imprecise measures of the health of a population.

Understanding why there is a species-specific life span to begin with and what forces influence its presence, level, and the dynamics of variation and change (collectively referred to here as "life span determination") is critical to comprehending why the topic (e.g., the longevity dividend and geroscience) is now so important, why claims about forthcoming radical life extension are misguided positions of advocacy, why victory

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can now be declared in humanity's pursuit of longevity, and why biomedical research and modern medicine should now be focused on extending health span rather than exclusively trying to make us live longer.

WHY DO SPECIES-SPECIFIC LIFE SPANS EXIST?

This question was first asked and then answered in the nineteenth century by French physiologist Pierre Flourens who asked a simple question in his book *Human Longevity and the Amount of Life upon the Globe*—"What is the natural, usual, and normal duration of the life of man?" (Flourens 1855). This question was not new since the greatest thinkers of every era throughout history speculated about the human life span and devised what they believed were methods of modifying how long people are capable of living (Gruman 1966), but it was Flourens who provided a biological answer more than two centuries before the evolutionary theory of senescence laid down the principal answer to this question.

Questions of this sort are not esoteric—how long we live as individuals and populations has important public policy implications. For example, the future solvency of age-entitlement programs (such as those involving retirement and health) are heavily dependent on how many people live to retirement age and how long they draw benefits from such programs once they begin doing so. Current and future demands on health care resources are fundamentally influenced by length of life; planning for retirement and how long to remain in the labor force are all influenced by an answer to this seemingly simple question. As such, understanding the human life span has taken on new and important roles in the modern public policy arena.

To answer this question, I will draw on first principles from the field of evolutionary biology based on a famous quote from the geneticist Theodosius Dobzhansky (1973) who once stated, "… nothing in biology makes sense except in the light of evolution" (Dobzhansky 1973). To appreciate the first principles behind the human life span, consider the Renaissance view of humankind that was present for centuries before Flourens, evolutionary biology, and other biological sciences emerged. According to this view, humans are "perfect" physical specimens molded by the hand of a creator—with a life span potential purported to be close to 1000 years if the Old Testament is to be taken literally. The imagery that best exemplifies this view of humanity's perfection is Michelangelo's painting *The Creation of Adam* on the ceiling of the Sistine Chapel.

By contrast, the underlying principle of Darwin's theory of evolution was not the Renaissance view of perfection, but rather the exact opposite. Darwin's view of evolution originated with imperfections in the anatomic structures and functions of the human body that led to evolutionary change across long time periods, sexual reproduction as a means to maintain the immortality of the germ line, a "disposable" soma, and, ultimately, an explanation for why humans live as long as we do.

A case can be made that both Michelangelo and Darwin were right. On the one hand, there is an artistic-like perfection of the human body exemplified by the near flawless maintenance and repair mechanisms of nuclear DNA (Kirkwood 2005; Maynard et al. 2015). It is difficult to fathom that each cell in the human body confronts more than 10,000 potentially damaging chemical and radiation-based hits every day (Ames et al. 1993)—and yet the DNA contained within the 3.72×10^{13} cells in our bodies (Bianconi et al. 2013) is maintained and repaired continuously, 24/7, with *close to* flawless perfection. In this regard, it is hard to argue with Michelangelo's view of humanity's perfection.

Yet, Darwin focused on the minutia—the *close to* part of humanity's "perfect" DNA repair story—the tiny imperfections that make their way through from one generation to the next (rather than the level of perfection present), as the basis upon which evolution takes place. According to both Darwin and Stephen J. Gould (1977), evolution takes places in fits and starts rather than gradually, which means eons of evolutionarily quiescent time is punctuated by rapid evolutionary events. Over time, sexual reproduction evolved as a mechanism through which DNA has become immortalized. As Dawkins

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(2016) eloquently stated with his selfish gene hypothesis, somas (our bodies) are the vehicles through which DNA achieved immortality. This also means that somas, the vehicles that transport genes across time, are eventually disposable (Kirkwood 1977). The subsequent "discarding" of the soma (which is a passive, not an active process—and the timing with which it occurs), is why there is a life span.

Details of the evolutionary theory of senescence are contained in detail in the literature, so there is no need to engage that line of reasoning any further here. Suffice it to say that the price paid for the immortality of the germ line is a suite of anatomic structures and functions within our bodies that, when used beyond what may be thought of as their biological or Darwinian warranty period (Olshansky et al. 2001a; Carnes et al. 2003), leads to many of the diseases and disorders now commonly associated with aging or senescence. The divergent but intimately linked views of Michelangelo and Darwin exemplify the importance of a biological perspective on aging, the diseases that accompany it, and, ultimately, the forces that influence and limit the life span of our species.

ARE THERE TICKING BIOLOGICAL TIME BOMBS IN OUR BODIES?

Given the consistent message that death eventually comes to all living things, and the highly predictable timing with which it occurs for every species, it would be easy to conclude that a clock is ticking in each of us that measures biological time from conception, and which directly causes us to age and eventually die. Yet, if aging is indeed an inadvertent byproduct of genetically fixed programs for growth, development, and reproduction, then there can be neither death genes nor longevity genes that evolved under the direct force of natural selection. Why is that?

Death programs cannot exist as a direct product of evolution because the end result would be the systematic demise of all living things at an age beyond which almost every member of a species would ordinarily be expected to live. Aging programs cannot exist for the same reason. A biological time bomb driven by genes designed exclusively to kill at older ages is equivalent to automobile manufacturers building in an explosive device that is set off only when the car reaches 1 million miles. Since cars are not ordinarily driven that far, such a death program would rarely if ever be triggered—rendering it useless. In humans and other living things, genetically fixed life span programs that cause aging or death would be equally useless—and for the exact same reason. There is no point in building (or having natural selection expend precious biological resources) in a genetic program that would rarely if ever be used under normal conditions.

Does the absence of aging and death programs mean humans can live forever, or at least much longer than we do now as some claim? (Wilmoth 1998; Oeppen and Vaupel 2002). As it turns out, this question about a "limit" to life or finite amount of measured survival time is one of the most misunderstood topics in the field of aging today. Let us clear up this issue once and for all.

There is a limit to life; it is fundamentally rooted in biology, and, provided in the next section, is a simple explanation for why this is so. In fact, it is more than a bit surprising that anyone would question the presence of a human life span or "limit to life" given the ubiquitous presence of death all around us. If the wrong tools of science are used it becomes easy to believe that radical life extension or immortality are almost within the grasp of science's hand.

WHAT IS THE HUMAN LIFE SPAN?

As a reminder, *life expectancy* is a demographic term used to represent the expected remaining years of life based on a current life table—it is a population statistic that takes into account observed death rates at all ages in a given country in a calendar year. Life expectancy can be calculated for people of any age, but it is most often reported at birth. *Life span* is the observed duration of life of an individual. *Maximum life span* is the observed duration of life of the longest-lived member of the species—defined by how long one person lived. Life expectancy and maximum life span are often used interchangeably, but they are vastly different

numbers. The term "life expectancy" is defined here as "period life expectancy at birth."

One of the best and earliest explanations of why there are species-specific life spans comes from French naturalist Georges Buffon (1747). He speculated that every person has the same allotment of time from birth to death, and that duration of life depends not on our habits, customs, or quality of food, but rather on physical laws that regulate the number of our years. This concept of a physical law regulating duration of life is nearly identical to Gompertz's (1872) view about physical laws governing what he called the Law of Mortality. However, Buffon was not aware of the importance of genetic heterogeneity in the eighteenth century, so his view of equal allotments of time for everyone was misguided. Buffon further stated that each species possesses a suite of fixed biological attributes (e.g., gestation period, age patterns of growth, and constant physical form), so if all biological phenomena conform to fixed laws like those governing the timing of gestation and sexual maturity, then duration of life must also be fixed accordingly.

Buffon's language about a linkage between reproduction and the timing of death preceded the evolutionary theory of senescence by more than two centuries and Gompertz's Law of Mortality by more than one century. Buffon's interest in life span was based on an extensive database of life history characteristics that he collected for a variety of species (e.g., dogs, cats, rabbits, humans, etc.). Based on these data, Buffon reasoned that a species' life span is a product of interconnected chains of functional relationships between biological attributes. He envisioned a fixed duration of gestation giving rise to a fixed duration of growth, which, in turn, leads to a fixed duration of life. Thus, Buffon was the first to articulate that life span is calibrated to the onset and length of a species' reproductive window. He went on to suggest that the life span (e.g., life expectancy) of a species is consistently six to seven times greater than the time required to reach puberty. In humans, this would be ~85 years.

The maximum life expectancy of humans has often been associated with the number 85 in the scientific literature. For example, Fries (1980) speculated that the upper limit to human life expectancy at birth is 85 years based on an extension of historical trends in life expectancy at birth and at older ages where they converge on or about age 85. Olshansky et al. (1990) used complete life tables for the U.S. population, and later included data from other countries (Olshansky et al. 2001b) to demonstrate that the metric of life expectancy at birth becomes less sensitive to declining mortality the higher it rises. Once it reaches 85 (82 for men and 85 for women), the magnitude of the decline in mortality required to nudge life expectancy higher becomes particularly onerous, although not impossible. This line of reasoning was further supported by arguments about how the anatomical structures of the human body make it difficult to justify life expectancies for national populations much beyond 85 since components of the body consistently wear out over time, and not all of them can be repaired or replaced by medical intervention (Olshansky et al. 2001a, 2007). A far more detailed look into the proximate biological forces that influence duration of life in humans (Carnes et al. 2013) supported the same conclusion that Buffon came to in the eighteenth century—that life expectancy at birth is unlikely to exceed about 85 for men and women combined any time soon—unless technological advances occur that slow the biological rate of aging.

With regard to the human life span, there is theoretical, empirical, and biological justification to conclude that the human life span is about 85 years for men and women combined and maximum life span is currently 122 (Robine et al. 2019)—but this maximum might increase slightly in the coming decades with larger cohorts moving through the age structure (de Beer et al. 2017). There is empirical evidence to suggest that it will continue to be rare to have humans live beyond the age of 115 (Dong et al. 2016).

As originally stated by Olshansky et al. (1990), this life expectancy limit should be viewed as a glass ceiling that can be broken through with the use of technological advances that modify the rate at which biological aging occurs. While efforts are underway now to do just that, currently there are no biomedical interventions that have been documented to extend life beyond the limits described here. How far

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humanity can raise the life expectancy ceiling beyond the current limit is unknown.

ARGUMENTS FOR AND AGAINST RADICAL LIFE EXTENSION

Scientists who speculate on forthcoming radical increases in human longevity have generated a range of views from the promise of immortality to modest increases in this century. Four unique arguments have formed along these lines. The first is the "One More Day of Life" argument set forth by Wilmoth (1997) where the case was made that there are no biological or demographic constraints on generating one more day of life indefinitely. The central question asked was how death rates or life expectancy would behave if a limit to life was being approached. If the expected statistical behavior is not observed using the tools at his disposal, he reasoned, then the hypothesized limit must be too far beyond the observed longevity horizon to be detected.

The evidence presented by Wilmoth includes (1) data from Sweden for the period 1851–1990 that, despite a high degree of variation in the age of the longest-lived person, exhibit an increasing trend over this time period (based on data from one man and one woman from Sweden in each calendar year); (2) the hypothesis that a limited life span requires death rates to rise exponentially throughout the entire age structure—a pattern of mortality he suggested does not appear in humans (some evidence indicates otherwise) (Gavrilov and Gavrilova 2011); (3) the hypothesis that a decrease in the variability of death rates at older ages is not sufficient proof of a limit to life; and (4) the suggestion that the absence of a positive correlation between mortality level and the pace of mortality decline in some countries means a lower limit to the hazard function cannot be detected using demographic methods. The conclusion drawn from this analysis was that demographic/statistical/biological evidence for a limit to life could not be detected—even though there was no measure of any biological force of longevity determination in this analysis.

Wilmoth (1998) then carried his line of reasoning significantly further by concluding that "over sufficiently long time periods, it is not at all unusual for death rates to decline by half or more," and therefore "there is simply no convincing evidence (demographic, biological, or otherwise) of a lower bound on death rates other than zero." Wilmoth used a purely demographic tool to declare that immortality is plausible—there was no biology in this assessment. Wilmoth's reasoning is predicated on the assumption that demographic/statistical conditions are legitimate guideposts that can be used to reveal proximity to a limit to life. However, there are no a priori reasons why death rates must rise exponentially for a limit to be observed, or that mortality has to compress into a narrower age range, or that a positive correlation between level of mortality and pace of mortality decline is a defining characteristic of limits. Wilmoth declared those defining limits himself.

The obstacle to this line of reasoning is the consistent message imposed by the force of mortality. Even when annual death rates of 50% are applied to a hardy group of survivors to extreme old age, everyone in every birth cohort eventually dies within a short time frame, even though statistical reasoning might lead some to believe otherwise. Very few people survive past age 115 and most deaths in any given cohort occur at highly regular ages that are tightly compressed within a few decades between ages 60 and 90.

A simple analogy reveals the serious flaw in this argument. Consider the world record for the one-mile run—which is currently 3 min 43 sec. This record has declined steadily, in linear fashion since the middle of the nineteenth century when it was 4 min 28 sec (it is worth noting that this running record has not changed since it was last broken in 1999). Using Wilmoth's line of reasoning, it may be argued that there are no demonstrable reasons why one more second cannot always be shaved off this record—leading to the statistically logical but biologically untenable forecast that someone will eventually run one mile instantaneously. This argument could even be bolstered by a well-known biological fact—there is no genetic program in humans that precludes shaving time from the world record for the one-mile run. Yet, we need nothing more than common sense to inform us that the human body design will not allow this to happen

(Olshansky et al. 1990). In similar fashion, while Wilmoth is correct in assuming that there is no genetic program that precludes the indefinite addition of one more day of life, in identical fashion, the biomechanics of the human body will not allow this to happen.

The biology of life and death was disregarded in this purely quantitative analysis and the resulting conclusion was that demographic/statistical evidence for a limit to life cannot be detected using observed demographic data—and therefore such limits must not exist. The reason proponents of this view cannot see a life span limit is because demographic/statistical reasoning is not where the evidence for life span limits resides. This argument is akin to claiming that air does not exist because it cannot be seen directly with the naked eye; evidence for a limit to life is contained outside the statistical analysis of mortality events observed in just a handful of people.

A second line of reasoning used to support infinite or dramatically higher life spans was set forth by de Gray (2005a) where the argument was made that *everything* that goes wrong with the human body can be repaired continuously, to perfection, indefinitely, by rapidly approaching technology that, in fact, does not yet exist. These so-called rejuvenation technologies are predicted to occur with "90% confidence" sometime between 2015 and 2040 with a massive funding effort. The mathematical logic behind this notion of radical life extension is derived from a concept invented by de Gray called "actuarial escape velocity" (AEV)—which is described as a scenario where "mortality rates fall so fast that people's remaining (not merely total) life expectancy increases with time." That is, remaining life expectancy gets longer the older one gets. The audacious claim using this line of reasoning is that at the oldest ages (past age 105) where annual conditional probabilities of death have consistently remained in the range of 50%, the probability of death will "…fall to 5% or lower, and mostly to below 1%…" (De Gray 2005b).

This argument lacks empirical evidence or validity—which is a kind way of saying the survival probabilities and resulting life expectancy estimates were made up. In fact, the notion of AEV is so far from reality that this author views it as "voodoo demography." It is worth noting that about 5 years after this prediction was made by de Gray, life expectancy began stagnating or declining in most parts of the developed world; that is, life expectancy began heading in the exact opposite direction as that predicted using AEV (more on this point later) (Case and Deaton 2015). The suggestion that death rates at extreme old age will decline from 50% to mostly below 1%, is at best derisory.

A third argument in favor of both radical life extension and immortality comes from Kurzweil and Grossman (2005). They argue that there are three bridges to eternal life. The first bridge is represented by an estimated 20 years the authors claim will be added to life expectancy with the use of nutritional supplements; but just like AEV, there is no empirical evidence to support the claim of an additional 20 years. Bridge two technologies are anticipated biomedical advances like stem cell therapy and genetic engineering that are thought to add another 20 years to life expectancy (a number provided by the author without empirical support); and the third bridge is nanotechnology, which the authors claim will be able to repair everything that goes wrong in the body, indefinitely, yielding eternal life. The bridge analogy is appealing at one level because many of these technological advances are likely. The problem is that it is difficult at best to estimate life expectancy benefits for technologies that do not yet exist.

The last argument favoring radical life extension is appealing to some because the case is made that the phenomenon of greatly extended lives is already here (Oeppen and Vaupel 2002; Vaupel et al. 2021). In this case, the authors do not bother with biology, they do not mention any new technological advances that are forthcoming with hypothetical life expectancy gains, and they do not even come up with concepts like AEV. Instead, they simply declare that half the babies born today will live to 100, and base this on an extrapolation of the historical trend in "best practice" life expectancy. For those who do not know what this is, take the annual world record for longevity in all national populations and plot them on a graph from the past into the present, pull out a ruler to extend this into the next cen-

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tury, and then simply declare that there is empirical evidence supporting the claim that radical life extension is already here. This is analogous to declaring that half the babies born today in the United States will be able to run a 3-min mile in their lifetime because a handful of people beat a 4-min mile running record each year since the middle of the twentieth century.

The bottom line is that all of the arguments advocating for radical life extension with the claim that large increases in life span are forthcoming or are already here lack theoretical, biological, and empirical support. These resemble positions of advocacy rather than science-based estimates of human life expectancy.

DECLARING VICTORY IN HUMANITY'S QUEST FOR LONGEVITY

Reductions in childhood diseases can occur only once for a population; once such gains are achieved, the only outlets for further significant gains in life expectancy must come from extending the lives of older people (Olshansky 2018). Given that multiple fatal conditions accrue in older people because of biological aging (e.g., a fundamental and inevitable risk that occurs independent of conventional behavioral risk factors for diseases) and once survival past age 65 years becomes common in a country, life expectancy gains must decelerate, even if medical advances and improved lifestyles continue to occur (Olshansky et al. 1990). Although unsupported claims have been made that the historic rise in life expectancy has been steady and has continued to the present (Vaupel et al. 2021), data from the *Human Mortality Database* demonstrate definitively that the rise in life expectancy at birth in most developed nations has been decelerating (mortality.org) as predicted (Olshansky et al. 1990).

In fact, trends in life expectancy in many developed nations since 2010 have shown a deceleration in the rate of increase, a stagnation, or even a decline (Ho and Hendi 2018). The COVID pandemic exacerbated this recent trend in life expectancy stagnation with extremely large drops observed in 2020–2021 (Mazzuco and Campostrini 2022; Stephenson 2022), but these are likely to be anomalies and some bounce back improvement in life expectancy is expected in the coming years.

Because the point of diminishing returns on life expectancy (~85 years for men and women combined) has been approached in many parts of the world, and because the change in life expectancy at birth is decelerating and approaching or has already reached a point of diminishing returns, there is reason to conclude that the goal of life extension for the human species has largely been achieved. The time has arrived to declare victory in humanity's quest to combat the scourges of mortality that precluded extended survival for the vast majority of our species throughout history. Now that most people born in the modern era have an excellent chance of survival past the age of 65, and, among these survivors, many will survive to ages 85 and older, the goal of life extension has been accomplished.

Do not interpret this declaration as justification to relax efforts to combat the plentiful causes of early mortality due to harmful behavioral risk factors such as smoking, obesity, lack of exercise, avoidance of life saving vaccines, drug use, violence, etc. Declines in death rates and additional gains in life expectancy from gaining control over these causes of death remain a high priority in public health. It is just that inroads against these causes of death will no longer yield significant gains in life expectancy for national populations—certainly nothing on the order of claims that radical life extension is forthcoming.

THE TIME HAS ARRIVED TO TARGET AGING

A rather difficult dilemma has presented itself in the modern era, and, in the final analysis, that is what this entire collection is all about. Modern medicine and advances in the medical sciences are laser focused on a constant quest for finding ways to extend people's lives—without considering either the consequences of success or the best way to pursue it. At one level—from the angle of the physician treating their patient—this makes perfect sense as their objective is to help their patients overcome the immediate health challenges they face. The current focus of most of modern medicine is on chronic, fatal age-related

diseases, in much the same way infectious diseases were confronted more than a century ago (i.e., one at a time as if independent of each other). Even though there have been many successes in efforts to combat aging-related diseases, further life extension in an aging world will expose the saved population to an elevated risk for all other aging-related diseases. That is, with extended survival brought forth by a suite of innovations designed to treat diseases that present themselves in older bodies, more people will survive into what may be thought of as a "red zone"—a later phase in life when the risk of frailty and disability rise exponentially—especially among those saved from dying at earlier ages as a byproduct of medical interventions (Fig. 1).

Keep in mind that the biological processes of aging force human bodies to become ever more susceptible to fatal and disabling conditions as survival extends further into the red zone; so unwanted health conditions emerge with greater frequency not so much because of how life has been lived (although harmful lifestyles can accelerate their emergence and progression) but because of how long life has already been lived. Time becomes the greatest challenge in aging bodies, so the target of medicine and public health should begin shifting to biological time (the aging process that gives rise to disease) rather than byproducts of aging—the diseases that modern medicine focuses on.

With death inevitable, the modern attempt to counteract aging-related diseases reveals a phenomenon known as competing risks. When the risk of death from one disease decreases, the risk of death from other diseases increases or becomes more apparent. With advancing age, the period between the emergence of competing diseases shortens and rises exponentially with advancing age. The hazard in old age is not so much that one disease displaces another, but that the new diseases are often much more debilitating. For example, finding a cure for cancer may cause an unintended increase in the prevalence of Alzheimer disease.

The inescapable conclusion from these observations is that life extension should no longer be the primary goal of medicine when applied to long-lived populations. Pushing out the blue line may yield some modest increases in life expectancy, but the price paid for success could very well

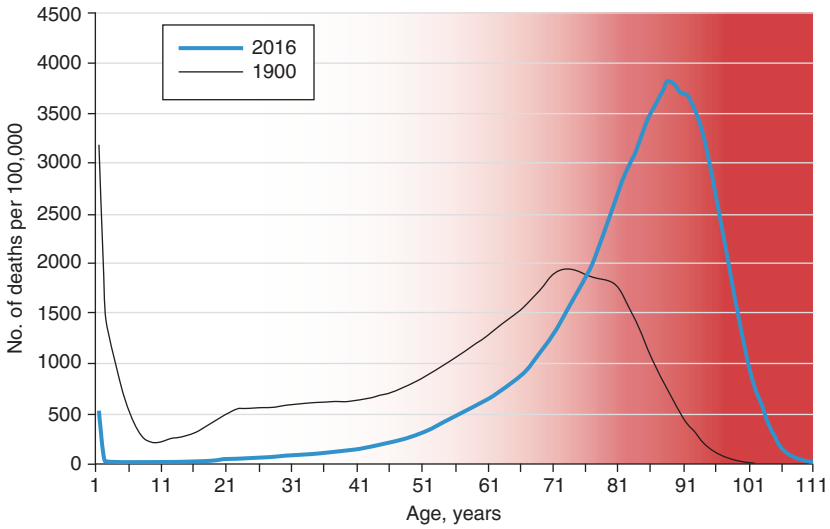

Figure 1. Age distribution of life table deaths for women in the United States, per 100,000 people, 1900–2016. (Source: Olshansky et al. 2020). The red zone represents a period in life when the risk of frailty and disability begins to increase rapidly. The goal of modern medicine is to push out the envelope of survival and extend the blue line to later ages. The goal of aging science, by contrast, is to delay and compress the red zone, which has the goal of extending the period of healthy life. The data used to generate this figure comes from the *Human Mortality Database* (mortality.org).

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be an expansion of morbidity. The principal outcome and most important metric of success, therefore, should be the extension of health span, and the technological advances that make the extension of a healthy life possible. The recommendation from this line of reasoning is that delaying and compressing the red zone should become the primary target of medicine and aging science.

While it is likely that an extended health span will be accompanied by an extension of life span, the primary metric of success in medicine and biology should be on what it takes to help humanity live healthier lives on the heels of a declared success in our effort to combat the challenges to extended survival faced by our ancestors.

WHAT IS HEALTH SPAN?

The conceptual formulation and measurement of health span in humans is not new. Sanders (1964) laid the conceptual groundwork for the idea behind measuring health span; Chiang (1965) developed the first mathematical models that measured the health of populations beyond those derived from vital statistics; Sullivan (1966) outlined the problems associated with the creation of a single index that combined measurements of health and mortality; and Moriyama (1968) further elaborated on the importance and measurement of population health rather than just mortality. These measurement issues were subsequently resolved, and Sullivan (1971) provided the first calculations of healthy life expectancy based on measures of survival time both free from disability and with disability.

The logic behind the use of health span is straightforward. Vital statistics such as death rates and resulting life tables used to estimate period life expectancy at birth and older ages, are indirect measures of a population's health. From Sanders to Sullivan, it was acknowledged that a more direct metric is required that combines measures of both health and mortality, into a single life table estimate that more accurately reflects the health of populations.

Interest in measuring health span gained considerable interest in the ensuing decades as researchers from across the globe grappled with the difficulty in securing common methods of data and measurement metrics that would allow for valid comparisons across time and population subgroups. Excellent summaries of the history behind health span—including measurement issues and trends in national populations—may be found in Crimmins (2015) and Robine and Saito (2003). The metric of health span is now globally accepted, measured, and used routinely by the Global Burden of Disease Project and World Health Organization (GBD 2019 Demographics Collaborators 2020).

The use of a health span metric has now become central to the goals of geroscience because a successful effort to extend healthy life must be measured using standardized tools of science that have already been established in humans. Two main articles (Goldman et al. 2013; Scott et al. 2021) document the health and economic gains associated with successful efforts to slow aging and extend health span as a primary target and demonstrate that the absolute number of frail older individuals would be far fewer by mid-century (relative to byproducts of conventional disease-oriented treatments), accompanied by billions of dollars of health savings, with just a small successful effort to slow aging in people. A clarion call for a switch to health span extension over life span extension is now common in the various fields that inform aging science (Miller 2002; Fontana et al. 2010; Burch et al. 2014; Sierra et al. 2021; Olshansky et al. 2022).

A conceptual framework and detailed discussion of measurement and data issues involving health span metrics in animal models has been described by Seals and Melov (2014). The importance of this work in translational geroscience is that before clinical trials of geroprotective therapeutics can be tested in humans, animal models are required that mimic the effects of purported interventions on both length and quality of life. The image provided from the Seals and Melov paper (Fig. 2) conveys the conceptual model for health span extension involving both animal and human models of intervention.

CONCLUSIONS

The metrics of life span and health span are central to our understanding of human health.

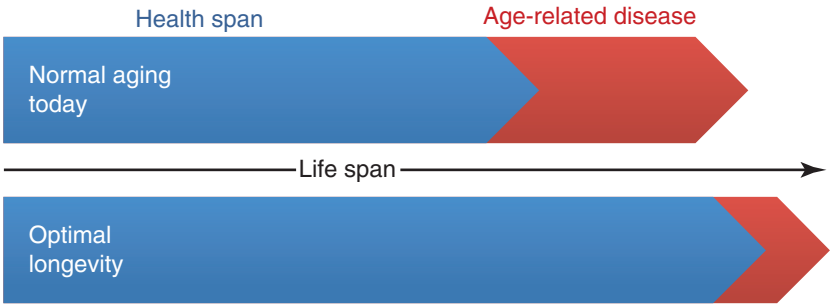

Figure 2. Increasing health span and optimal longevity. Comparisons versus ideal health span. Extending health span is a critical component of achieving optimal longevity, defined as living long but with good health, function, productivity, and independence.

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During the last two centuries, humanity experienced dramatic health changes that offered wonderful opportunities to explore later regions of the life span in ways never before experienced by previous generations. The benefits of life extension combined with demographic shifts that caused population aging have been so profound that scientists contend that a new map of life is warranted (Carstensen 2011). Figuring out how to navigate our way through the gift of additional survival time has led to wonderful new opportunities to explore life in ways rarely experienced by anyone in history (Rowe 2015).

However, life extension and population aging arrived with an equally difficult set of challenges. The medical cost of extended survival has skyrocketed as survival has extended into older regions of the life span where the cost of care and the avoidance of death is extremely high (Dieleman et al. 2020). Humanity has yet to come to terms with the inevitability of death and when to turn off or dampen the expensive medical machines that often end up yielding little more than additional weeks or months of life at an extremely high cost (Emanuel et al. 2002). Living up to one-third of life in retirement or some version of it is something that few are prepared to handle financially (Olshansky et al. 2020).

The modern medical machine is still centrally focused on a disease model that has been with us since public health began the battle with communicable diseases nearly two centuries ago. The question raised here is whether this disease model is still applicable in an aging world where there is reason to declare victory in humanity's effort to extend life. The literature will continue to zero in on the various pathways that scientists in the field of aging are pursuing to modulate biological time as a new method of primary prevention. There is reason for great optimism.

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