Prize Winner

From Gompertz to AI: The Evolution of Mortality Modeling in an Age of Longevity Breakthroughs

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INTRODUCTION

In 1825, London insurance actuary Benjamin Gompertz observed a striking regularity in mortality patterns: after early adulthood, human death rates increase exponentially with age. Known as Gompertz's Law, this finding suggested that aging followed a predictable mathematical curve—one as inevitable as compound interest, yet even more consequential.

Imagine the human body as a bustling metropolis, with trillions of cells functioning like citizens going about their daily business. In Gompertz's time, aging was viewed much like the inevitable decay of a city's infrastructure—roads cracking, buildings weathering, power lines fraying. But a city is far more than its infrastructure. It is a highly interconnected ecosystem of transportation networks, power plants, waste management, communication lines, and millions of individual decisions and interactions. Similarly, we now know that aging isn't simply about wear and tear. It's about the gradual breakdown of cellular communication networks, the accumulation of molecular garbage in our biological streets, the failing power plants of our mitochondria, and the emergence of problematic "neighborhoods" of senescent cells that poison their surroundings.

This richer understanding began emerging in mortality modeling in 1960, when Bernard Strehler and Albert Mildvan proposed their vitality theory of aging. Rather than viewing death as inevitable system failure, they suggested each individual possessed a certain level of "vitality" that could resist and recover from damage. Their theory recognized aging as a dynamic process, where the accumulation of damaged cells constantly competed with the body's repair mechanisms. This view gained mathematical sophistication through Anatoli Yashin's work introducing stochastic elements to capture the effect of myriad factors not explicitly included in the model.

Enter artificial intelligence (AI), and with it, a revolution in our understanding of the human body as a biological metropolis. In research laboratories worldwide, AI systems perform the arduous work of mapping complex relationships between cellular damage and systemic aging that help reveal how cascading failures contribute to the exponential rise in mortality rates that Gompertz observed. More importantly, these technologies suggest that such failures might be preventable or even reversible. This raises a profound question for actuarial science: how do we model mortality in a world where the aging process itself becomes increasingly negotiable?

THE DIVERGENCE OF CHRONOLOGICAL AND BIOLOGICAL AGE

The separation of chronological and biological age originates in cellular biology. AI systems have succeeded in explaining how nine fundamental hallmarks of aging interact to create the mortality patterns we observe in populations, ranging from genomic instability to altered intercellular communication, and each representing a potential target for intervention. This deep understanding reveals why traditional actuarial models, based on aggregate statistics, fail to capture the full complexity of human aging.

Cellular senescence represents one of the most promising targets for intervention. AI systems have identified protein signatures unique to these "zombie" cells, which cease dividing but release inflammatory compounds that damage neighboring tissues. These cells accumulate exponentially with age, providing a biological foundation for Gompertz's mortality law. AI-designed senolytics—drugs that selectively eliminate senescent cells—have been shown to reduce biological age markers by several years in early-stage research. Improvements in mitochondrial function appear to enhance energy production and stem cell performance, creating synergies with senolytic treatments.

Biological aging clocks incorporate hundreds of biomarkers, from blood parameters to epigenetic methylation patterns, revealing that individuals of the same chronological age can differ in biological age by decades. These metrics predict mortality more accurately than traditional actuarial factors. New mortality models must therefore incorporate both chronological and biological aging rates, with traditional mortality curves splitting into multiple trajectories based on access to and effectiveness of various interventions.

The temporal dynamics of these interventions pose particular challenges. Unlike conventional medical treatments, which often show diminishing returns, AI-designed longevity therapies exhibit compounding effects. Clearing senescent cells reduces inflammation, enhances stem cell function, and improves cognitive performance. Current research with AI systems has identified combinations of interventions that target multiple aging mechanisms simultaneously, producing mortality reductions greater than the sum of their individual effects.

The impact extends beyond measurement to fundamental questions about mortality projection. While traditional actuarial methods rely on past mortality trends, assuming continuity in improvement rates, AI-driven breakthroughs in both physical and cognitive aging signal a period of discontinuous change. As our ability to influence biological age advances, the basic relationship between chronological age and mortality risk may require thorough reconsideration.

THE TERM STRUCTURE OF LONGEVITY MODELING

AI-driven advances in longevity present uncharted territory for the actuarial profession. Any significant shifts in survival rates would likely unfold across multiple time horizons, each requiring distinct approaches to modeling, product design, and risk management.

In the immediate term, measurement and credibility take center stage. Early adopters of AI-guided health interventions may exhibit survival rates that diverge from population averages. Traditional actuarial theory provides tools for distinguishing genuine trends from statistical noise. The difficulty lies in gathering sufficient data from what are initially small, potentially unrepresentative populations while maintaining appropriate conservatism in estimates.

The intermediate horizon necessitates innovation in product design and risk transfer. Insurers and pension funds are already developing responsive solutions. Participating annuities now incorporate mortality-linked adjustments, while pension plans implement conditional indexation tied to funding status. These features create natural feedback mechanisms between longevity experience and benefit levels.

Legacy books demand particular attention during this period. Many insurers and pension funds hold substantial portfolios of annuities and pensions written without risk-sharing features, often extending decades into the future with guaranteed benefit levels. The reinsurance market is expanding its toolkit for transferring this longevity risk, though pricing reflects substantial uncertainty. These existing exposures could face severe impacts from AI-driven longevity gains, as their long-dated guaranteed benefits were priced without contemplating significant biological age reversal.

The long-term horizon raises fundamental questions about solvency and capital adequacy. Current regulatory frameworks, such as Solvency II in Europe, require insurers to evaluate mortality improvement scenarios in their capital modeling. However, these scenarios typically assume relatively stable progression. As evidence of accelerated improvements materializes, stress testing approaches and capital requirements may need revision.

Throughout this evolution, materiality remains the actuary's compass. The profession's historical experience provides valuable context: improvements in life expectancy, whether from medical advances or public health measures, have typically unfolded gradually enough for actuarial methods to evolve with them. And while AI-driven gains may require new approaches, the key principle of actuarial prudence endures. Success in this fluid landscape hinges on developing flexible frameworks that incorporate new evidence while maintaining the reliability that has long characterized actuarial work.

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