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Limitations of the Grossman Model and New Health Capital Production Model[1]

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Abstract. Health capital, as a core component of human capital, underpins both personal and social development. Michael Grossman's influential model of health capital production has shaped human capital theory, yet it contains fundamental flaws that remain inadequately addressed. This study critically examines these flaws and proposes an improved model. Using mathematical modeling and exponential functions, the authors reconstruct the Grossman model for intertemporal transactions, revealing the underlying mechanism of health capital production. They identify several key shortcomings: the model ignores the lifelong, continuous nature of health capital production; assumes unconditional returns on investment, when in reality excessive investment yields negative outcomes; overlooks the role of environmental factors in accelerating depreciation; and incorrectly assumes that health capital can be carried over between life periods. The authors argue that health capital production works by reducing depreciation rates, which rise due to external environmental pressures, to maximize available capital at any given time. Health-related events affect individual health capital solely through shifts in depreciation coefficients during maturation and aging. The study proposes a new theoretical framework that addresses these gaps, offering a foundation for more accurate forecasting of human capital and empirical research into health capital.

Keywords: human capital, health capital, Grossman model, health capital production, health capital depreciation, health investment

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ИССЛЕДОВАТЕЛЬСКАЯ СТАТЬЯ

Недостатки модели Гроссмана и новая модель производства капитала здоровья

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Аннотация. Капитал здоровья как компонент человеческого капитала служит основой личного и общественного развития. Модель Майкла Гроссмана, описывающая производство капитала здоровья, оказала значительное влияние на теорию человеческого капитала и широко применяется в экономических исследованиях. Однако она содержит фундаментальные изъяны, не получившие адекватного объяснения. Цель настоящего исследования — проанализировать причины несоответствия модели Гроссмана реальным практикам и эмпирическим данным, а также предложить её усовершенствование на основе полученных выводов. В рамках исследования модель Гроссмана подвергнута критическому теоретическому анализу и научной реконструкции с использованием математического моделирования. На основе экспоненциальных функций построена модель капитала здоровья для межпериодных транзакций, позволившая выявить механизм его производства. Основные недостатки модели Гроссмана касаются того, что она не учитывает некоторые практические аспекты производства капитала здоровья, а именно: непрерывный характер процесса производства на протяжении всей жизни индивида; условия эффективности инвестиций, так как отдача от инвестиций возможна только при определённых условиях, а чрезмерные вложения приводят к отрицательным результатам; необходимость непрерывных инвестиций; влияние внешней среды, усиливающее расходы на амортизацию капитала здоровья; невозможность полностью покрывать амортизационные расходы; непередаваемость капитала здоровья между периодами жизни индивида, что противоречит предположениям модели о межпериодной преемственности. В статье сделан вывод, что принцип производства капитала здоровья заключается в генерации большего объёма доступного капитала в определённый период за счёт снижения нормы амортизации, возросшей под влиянием внешнего давления окружающей среды. Установлено, что события, связанные со здоровьем, влияют на индивидуальный капитал здоровья лишь посредством изменения коэффициентов амортизации в периоды взросления и старения. В исследовании предложена новая теоретическая модель капитала здоровья, учитывающая обозначенные проблемы модели Гроссмана. Её применение может стать основой для прогнозирования человеческого капитала и эмпирического изучения капитала здоровья.

Ключевые слова: человеческий капитал, капитал здоровья, модель Гроссмана, производство капитала здоровья, амортизация капитала здоровья, инвестиции в здоровье

1. Introduction

Health capital is a capital stock that produces health time output (Grossman, 1972). As one of the elements of human capital, health capital is the foundation of productivity and the guarantee of economic development. The health level of workers will directly affect labor supply and labor productivity, and indirectly affect technological progress and material capital accumulation (Zhao & Zhou, 2021). Understanding the production mechanism of health capital and correctly evaluating health capital are very important for the economic development of individuals and countries. At present, the health capital model proposed by Michael Grossman (MGM), which is widely referenced by the economics community, has problems such as time constraints and depreciation substitution (Bhattacharya et al., 2014). In addition, in empirical studies, MGM can only explain health needs in consumption, but not in investment (Volkova & Volkova,

2024). This makes MGM difficult to apply in practice. Since the assumption of MGM allows individuals to trade health capital across periods, it cannot predict future health stocks (Grossman, 1972). However, the formulation and feedback of health capital public policies require a reasonable health capital evaluation method. Therefore, the study of the production mechanism of health capital and its evaluation have become an important and urgent topic.

This article analyzes the hypothetical flaws of the MGM and proposes that health production is a restorative process without time constraints. This perspective helps explain several theoretical and empirical problems associated with the MGM. By constructing a health capital model based on non-intertemporal transactions, we develop a new theory of the health capital production mechanism and address the issue of future available health capital that the MGM fails to predict.

2. Literature Review

In 1961, Schultz first systematically developed the theory of human capital, arguing that human capital consists of an individual's physical strength, knowledge, skills, and health status, among other attributes, with health capital representing a core component of human capital (Schultz, 1961). He argued that improvements in physical and mental health generated through health investment could extend working life, reduce social medical costs, and enhance overall labor productivity. Building on this idea, Mushkin (1962) proposed that health capital should be regarded as a form of capitalized health and emphasized that it is an investment good capable of generating returns.

In economic theory, capital is generally defined as a productive input used to generate goods and services (Samuelson & Nordhaus, 2001). Earlier, Smith (1776) described capital as a stock that individuals expect to use to finance future income. Extending these ideas to health economics, Grossman (1972) conceptualized health as a durable capital stock that produces healthy time as its output. Individuals inherit an initial stock of health at birth, which depreciates with age but can be increased through health investment. Grossman further argued that the value of health capital lies in the lifetime income and utility it generates. The returns to health capital include both healthy days and utility derived from consumption and investment motivations.

Based on this framework, Grossman (1972) constructed the personal health demand model (MGM), which describes the complex trade-offs individuals face in managing health. MGM adopted Becker's household production function approach, which distinguishes between market goods purchased directly from the market and consumption commodities produced by households (Becker, 1964; Grossman, 1972). Under this framework, consumers combine market goods with their own time to produce commodities that generate utility. Consequently, the purpose of purchasing medical services is not the services themselves, but the production of health. Medical services therefore function as inputs into health production, making the demand for medical care a derived demand for health. Consumers seek to maximize utility subject to income and time constraints (Becker, 1964). MGM thus provides a theoretical explanation for how individuals allocate time and financial resources to health investment and remains a foundational framework for analyzing the production and management of health capital.

3. The Basic Principles and Defects of MGM

Grossman thought that health capital was different from other human capital in that it affected the total time available to earn income or produce consumer goods, rather

than the productivity of market or non-market activities (Grossman, 1972). In other words, the return on investment in health capital is to extend life or increase health time, rather than increase wages. The stock of health, or health capital, can be used as both a consumer product and an investment product. Since illness is non-utility, health capital, as a consumer product, is directly included in the utility function. MGM assumed that in any given time period *t*, an individual's utility is based on his or her health level and consumption of goods not used for health. The individual's utility in time period *t* is defined as (Bhattacharya et al., 2014):

$$U_t = U(H_t, Z_t), \tag{1}$$

U: Individual utility;
H: Health level;
Z: Consumption of goods not used for health.

According to Grossman's hypothesis, health itself is a consumer product, and the individual's health level directly affects the individual's utility. An individual's behavior may affect both *H* and *Z*. For example, drinking alcohol increases the production of *Z*, but may have a negative impact on *H*. Traveling may increase both *H* and *Z*.

Grossman argued that time constrained an individual's ability to obtain utility, so individuals had to weigh different actions that affect *H* and *Z*. MGM assumed that in any given period *t*, an individual's time unit Θ was allocated to four different activities and faced the following time constraints (Bhattacharya et al., 2014):

$$\Theta = T_t^W + T_t^Z + T_t^H + T_t^S, \tag{2}$$

T^W: Time spent on work. The income generated by work is used to buy goods that can improve *H* and *Z*;
T^Z: Time spent on entertainment. Entertainment can improve *Z*;
T^H: Time spent on health promotion. Health promotion can improve *H*;
T^S: Time spent on illness. Illness cannot improve *H* and *Z*, so it does not increase utility. Time spent on illness will generate opportunity costs, which is wasted time.

In MGM, T^S is completely determined by *H* and is not an activity that individuals actively choose. The healthier an individual is, the less sick time he or she has. This means that individuals have more productive time. Grossman defined productive time as all time outside of sick time; that is, the total time allocated to work, leisure, and health-promoting activities (Bhattacharya et al., 2014):

$$T_t^P \equiv \Theta - T_t^S = T_t^W + T_t^Z + T_t^H, \tag{3}$$

T^P: Time spent in labor. Labor time is in addition to sick time.

In MGM, the marginal return of health on productive time is diminishing (Figure 1) (Bhattacharya et al., 2014). If an individual is already healthy enough and rarely gets sick, then an extra unit of health will bring very little productive time. On the contrary, if an individual is very unhealthy, then even a small increase in health can increase productive time a lot. This explains the role of health capital as an investment good used to generate productive time.

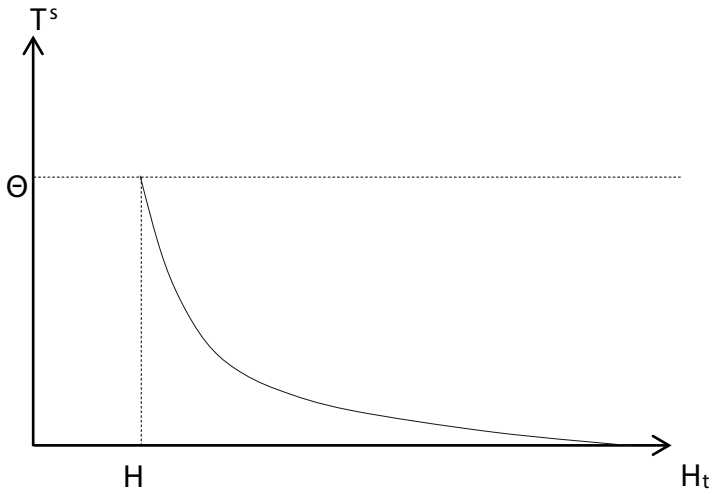


Fig. 1. *Disease avoidance in MGM*
Source: Bhattacharya et al., 2014

Grossman set a minimum health level (H_{min}). At this health level, $T^S = \Theta$. This implies that the entire period is consumed by sick time, leaving the individual with no time for work, leisure, or health-promoting activities. In other words, the individual has no productive time and therefore cannot generate additional health capital. When $H_t \leq H_{min}$, the individual will die. This is an economic definition of death provided by MGM.

According to MGM, the only way to reduce sick time is to improve health. Any input or time that improves health can generate additional productive time. The newly generated productive time can be used to continue investing in activities that promote health, or it can be used for work and entertainment. This means that the ultimate goal of reducing sick time is to have more time to produce *H* and *Z*.

On the other hand, MGM showed that the total productive time of an individual depended on his or her health level. An increase in *H* can lead to an increase in T^p, but the marginal benefits of health are decreasing (Figure 2) (Bhattacharya et al., 2014).

In addition to time constraints, MGM also takes into account the budget constraints of health capital production. Individuals weigh the choice of health investment under the conditions of time constraints and budget constraints. This makes it possible to analyze the production possibility frontier (PPF) of health capital (Bhattacharya et al., 2014).

Grossman proposed that there were two costs of health investment:

a) Opportunity cost. In order to invest in health, individuals give up the opportunity to invest resources in other market investment projects.

b) Depreciation cost. Depreciation caused by aging is another cost of health investment.

In order to ensure the rationality of health investment, the return on health investment must at least cover the opportunity cost and depreciation cost. The marginal efficiency of health capital determines that when the marginal cost of health investment is equal to the marginal benefit of health investment, the individual is at the optimal health level (Figure 3) (Bhattacharya et al., 2014).

MGM explains the utility of an individual throughout his life. The choices made by an individual in any given time period t will not only affect the utility of the current period, but also the utility of future periods. Therefore, MGM is a multi-period utility function.

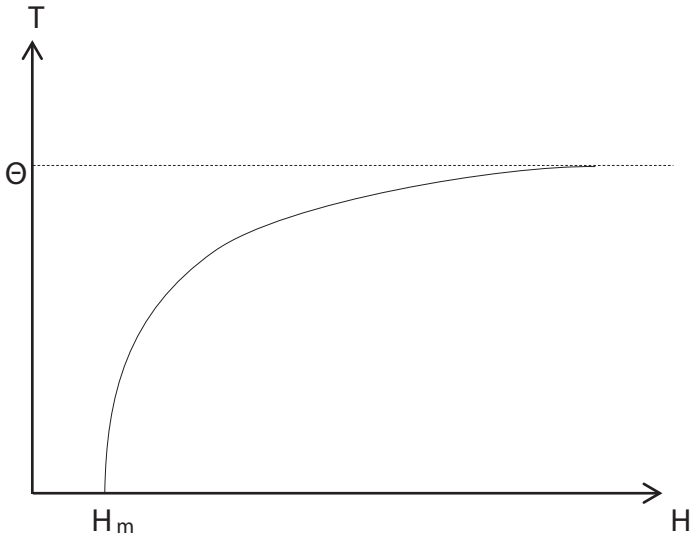


Fig. 2. *Grossman's Marginal Gains of Health*
Source: Bhattacharya et al., 2014

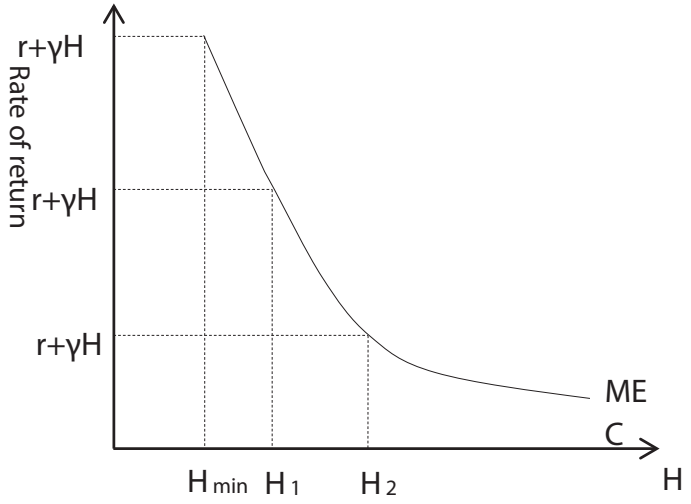


Fig. 3. *The Return on Health Investment in MGM*
MEC: Marginal Efficiency of Capital
r: The Opportunity Cost of Forgone Market Investment Opportunities
γ: Depreciation of Health
Source: Bhattacharya et al., 2014

The sum of the utility flow generated by the individual's decision in each period is the utility stock of his life (Bhattacharya et al., 2014):

$$U = \sum_{t=0}^{\Omega} \delta^t U(H_t, Z_t), \quad (4)$$

$\delta \in (0, 1)$: individual discount factor.

As a multi-period model, Grossman needs to take into account the value of health investments in previous periods, which will also depreciate due to depreciation. Therefore, in any given time period t and the previous time period $t–1$, Grossman's health production function can be expressed as (Bhattacharya et al., 2014):

$$H_t = H((1-\gamma)H_{t-1}, T_t^H, M_t), \quad (5)$$

M: Inputs used to produce health.

As an important theory to explain the production mechanism of health capital, MGM has been repeatedly used and tested by scholars over the past half century since its publication (Volkova & Volkova, 2024; Abdul-Rahman, 2008; Kara, 2024; Bishai et al., 2015; Jacobson, 2000; Jones et al., 2019; Ried, 1998; Mehlhop, 2021; Eze, 2018; Hartwig & Sturm, 2018).

Since its introduction, the MGM has been widely extended in both theoretical and empirical research. A first strand of literature focuses on model extensions and theoretical refinement. Bishai et al. (2015) modified the MGM to analyze investment in the public health sector and to estimate the value of individual health capital using mortality measures. At the household level, Jacobson (2000) developed a family health demand model based on the MGM and showed that health investment decisions are determined by the condition that the marginal consumption rate equals the marginal net effective cost rate of health capital, rather than a simple marginal benefit–cost trade-off at the individual level. Jones et al. (2019) further integrated the MGM with the Becker–Murphy theory of rational addiction, proposing a dynamic framework for estimating the human capital cycle using long-panel data.

A second strand of literature applies the MGM empirically across different contexts. Abdul-Rahman (2008) used the model to predict health demand for physical exercise among the elderly population in the United States, while Kara (2024) applied it to examine the effects of human capital components on individual health status in Turkey. Ried (1998) employed comparative dynamics to study the effects of changes in the depreciation rate of health capital. Mehlhop (2021) applied the MGM to myocardial infarction and found support for the effects of education and age on health demand, but no significant evidence for wages or medical care. Similarly, Volkova & Volkova (2024) confirmed the dual nature of health capital as both a consumption and investment good, although income effects were found to operate primarily through consumption rather than investment.

At the same time, a substantial body of literature has identified important theoretical and empirical limitations of the MGM. Eze (2018) argued that the model fails to distinguish between preventive care and curative care: preventive care should be treated as health investment, whereas curative care functions more appropriately as a consumption good. Hartwig and Sturm (2018), using macroeconomic panel data to test the determinants of health expenditure proposed by the MGM, found that only real wages received consistent empirical support.

Several scholars have also attempted to explain why the empirical performance of the MGM has often been inconsistent with its theoretical predictions. Nocera and Zweifel (1998) argued that previous empirical tests relied excessively on cross-sectional data, despite the MGM being inherently dynamic in nature. After incorporating single time-series information for multiple variables into the empirical analysis, they found stronger support for the model. Similarly, Wagstaff (1993) suggested that discrepancies between

the MGM and empirical findings arose from inappropriate assumptions introduced when translating the theoretical model into empirical specifications. In particular, he argued that adjustments to health capital are non-instantaneous and that the model's linear assumptions should therefore be relaxed. Empirical evidence has also challenged one of the MGM's central predictions regarding the relationship between health and medical care demand. Galama and Van Kippersluis (2013) noted that individuals in poorer health typically demand more health care services than healthier individuals, while Wagstaff (1986) similarly found a negative relationship between health status and health care demand. To address this inconsistency, Galama and Kapteyn (2011) proposed incorporating a health threshold into the MGM, such that individuals above the threshold would not require additional health care. By relaxing some of the model's restrictive assumptions, they argued that the contradiction between the MGM's predictions and empirical evidence could be resolved.

Although the MGM has made important contributions to understanding health demand and the production of health capital, it has also been widely criticized for several theoretical limitations (Sepehri, 2015; Zweifel, 2012; Galama & Van Kippersluis, 2013; Hren, 2012).

A first group of criticisms concerns uncertainty, irreversibility, and lifecycle dynamics of health capital. Sepehri (2015) argues that the MGM overstates individuals' control over health by insufficiently accounting for uncertainty in health status. Non-preventive health care demand is inherently uncertain, and information asymmetries between patients and physicians, together with uncertainty about treatment effectiveness, further complicate both health consumption and investment decisions. He also emphasizes that health deterioration is often irreversible, as some diseases prevent full recovery. This contradicts the MGM assumption of full restoration of health and implies unrealistic long-term implications, including the theoretical possibility of complete and repeated health restoration. Zweifel (2012) similarly highlights the model's inability to account for abrupt and irreversible losses in health capital, such as those associated with suicide or abortion. In addition, Galama and Van Kippersluis (2013) argue that the MGM fails to incorporate the long-term effects of early-life health investments on adult health outcomes, suggesting the need to explicitly model childhood health as a determinant of later health capital.

A second line of criticism focuses on risk and insurance mechanisms. Hren (2012) argues that future medical expenditures are uncertain, and that for risk-averse individuals, health insurance and health investment decisions are jointly determined by this uncertainty. However, the standard MGM framework does not adequately capture the role of health insurance in shaping individual health investment behavior.

4. Health Capital Production from a Medical Perspective

Clinically, health production is a continuous process throughout the life course. Bed rest for patients with non-physical injuries and rest for healthy individuals (or subclinical patients) represent different stages of physiological recovery during decompensation and compensation processes (Jones, 2003). Disease arises when internal homeostasis is disrupted (Wang & Qin, 2022), and individuals rely on self-regulatory recovery mechanisms to restore stability in response to environmental stressors and pathogenic factors (López-Otín & Kroemer, 2021). This self-regulatory capacity can be interpreted as health resilience. When this capacity is insufficient to maintain homeostasis, disease

occurs. In this sense, both healthy individuals and subclinical individuals continuously engage in recovery processes, although at different levels of efficiency and intensity.

From this perspective, sick time and health production time are not distinct categories but different expressions of the same underlying recovery process. For example, fatigue after normal work is resolved through rest and represents routine physiological compensation. In contrast, excessive workload may lead to prolonged fatigue and reduced functional capacity without reaching a clinical disease state, reflecting a subclinical compensation phase. Severe overload leads to clinically defined disease, where self-regulation remains active but is insufficient to fully restore homeostasis. Thus, living organisms are continuously engaged in health production, and disease occurs when health production cannot compensate for the depletion of health stock within a given period.

A key illustration of this mechanism is self-limiting disease, where recovery occurs without medical intervention (Blanco & Matute, 2020), such as influenza, chickenpox, hepatitis A, and viral respiratory infections (Zhu & Zhu, 2021; Peters et al., 2011). In these cases, the "sick period" is simultaneously a period of health production, during which the body actively restores homeostasis. From a medical perspective, therefore, sick time can be interpreted as a form of health recovery time at different intensity levels, rather than a pure loss of health production.

However, the MGM conceptualizes health capital primarily as a stock generating lifetime utility and income, implying that sick time does not contribute to utility or investment returns and is therefore effectively "wasted time." This creates a tension between the model and biological evidence suggesting that recovery processes during illness can generate long-term protective effects. This is particularly evident in immunological processes. Infection not only reduces productivity in the short run but also generates adaptive immune memory, which improves resistance to future infections (Netea et al., 2019). The strength and duration of immune memory depend on the intensity of the initial immune response (Lam et al., 2024). Thus, illness can generate a long-term protective stock that reduces future health risks, implying that sick time has intertemporal productive value.

A similar logic applies to vaccination, which induces immune memory through active immunity. While vaccination typically does not involve sick time, it also generates long-term protection by enhancing immune response. To distinguish these mechanisms, we conceptualize health capital as consisting of two components: available capital (current health status) and regulatory capital (immune capacity for risk control). During illness, part of regulatory capital is mobilized to restore available capital, and upon recovery, regulatory capacity is gradually rebuilt, reflecting the formation and stabilization of immune memory. Vaccination, in contrast, directly strengthens regulatory capital with minimal depletion of available capital.

Therefore, both infection-induced immunity and vaccination involve interconversion between available and regulatory capital, but differ in their cost structure. Importantly, excessive stimulation of the immune system may lead to immune exhaustion, increasing vulnerability to other diseases (Boretti, 2024), indicating that regulation itself is a constrained form of capital allocation.

At a broader level, immune memory exhibits intergenerational and collective effects. Adaptive immunity can be partially transmitted across generations (Boraschi & Italiani, 2018), and at the population level, widespread immune memory generates herd immunity, protecting non-infected individuals (McDermott, 2021). These mechanisms imply that individual sick time can reduce future disease probability both for oneself

and for others, contradicting the MGM assumption that only improvements in health stock reduce illness time.

In the MGM framework, sickness is treated as a non-utility state, and the model introduces a minimum health threshold (H_{min}) to prevent health stock from falling below zero. However, this assumption implies discontinuities in the health trajectory and fails to capture the productive role of the interval between Hmin and full recovery. By contrast, if health production is understood as a continuous, time-unconstrained physiological process, sick time can be reinterpreted as an active component of health capital formation rather than a period of zero production.

In medicine, no activity can be unconditionally classified as either "healthy" or "unhealthy," because the effects of health-related behaviors depend on context, intensity, and underlying physiological conditions. Health production activities generally improve health only within an optimal range. In practice, however, individuals may over-invest in health. For instance, athletes may engage in prolonged overtraining to enhance performance, which can ultimately lead to injuries. Similar nonlinear effects are observed in pharmacology: between the minimum effective dose and the minimum toxic dose, drugs improve health outcomes, but excessive intake may cross toxic or lethal thresholds and become harmful.

This trade-off is formalized in pharmacology through the concept of a "safety margin," defined as the ratio between the dose that is lethal to 1 % of the population and the dose effective for 99 % of the population (Saganuwan, 2020). In clinical terms, this reflects the gap between therapeutic efficacy and the onset of serious adverse effects. A wider safety margin indicates higher tolerance to dosing variation, while a narrow margin increases the risk of adverse outcomes. By extension, most health production activities also exhibit a safety margin, although typically much larger than that of prescription drugs. Excessive engagement in health production is therefore not necessarily beneficial and may reflect underlying psychological or social dysfunctions. For example, compulsive overtraining or over-medication may indicate anxiety-related behavior or poor adherence to medical guidance, resulting in negative marginal returns where additional health investment reduces overall well-being by crowding out psychological or social health.

In the MGM framework, health investment yields diminishing marginal returns, and once marginal returns reach zero, individuals are expected to stop investing in health. However, the model does not explicitly account for the possibility of negative returns from continued health production beyond this point.

A related limitation arises in Grossman's treatment of health investment returns and depreciation. Grossman argues that returns to health investment are sufficient to offset both opportunity costs and depreciation costs, raising the question of whether sustained investment could imply indefinite survival or reversal of aging. To resolve this, he assumes that health depreciation accelerates sharply at advanced ages, approaching an effectively infinite rate prior to death. However, this "late-life collapse" assumption is inconsistent with observed gradual aging processes. Moreover, it generates internal tension within the model: while health investment becomes theoretically inefficient at older ages due to rapid depreciation, the production possibility frontier implies that health investment is most productive when health levels are low (Bhattacharya et al., 2014), which would instead suggest stronger incentives for investment among the elderly.

These inconsistencies stem from the MGM's implicit assumption that health production is a growth-oriented process, in which health capital accumulates over time. In contrast, we argue that health production is fundamentally restorative rather than

purely accumulative. In any given period, the upper bound of health gains is constrained by the physiological maximum achievable health stock, conditional on depreciation dynamics. As a result, health production cannot permanently offset cumulative past depreciation, although it may influence future depreciation trajectories.

To further clarify this mechanism, we introduce the concept of health elasticity, defined as the body's capacity to maintain or restore internal homeostasis in response to external stress. Consider physical exercise as an illustration. An individual who exercises moderately (e.g., 2 hours per session, three times per month) accumulates health production time, yet may experience no lasting change in health capital if the physiological stimulus remains within existing adaptive capacity. By contrast, frequent and sustained exercise (e.g., daily sessions over several weeks) may exceed adaptive thresholds, inducing a new homeostatic state and thereby increasing health capital. However, once the activity ceases, the system may gradually revert toward its previous state, indicating that the persistence of health gains depends on continued reinforcement and the stability of the induced physiological state.

This implies that health capital gains are not simply cumulative but conditional on surpassing physiological thresholds and maintaining adaptive states over time. Consequently, MGM's interpretation of health outcomes as a monotonic accumulation of lifetime health investment is incomplete. Instead, health production should be understood as a threshold-dependent and reversible process, where gains are tied to dynamic homeostatic regulation rather than permanent stock accumulation.

Finally, this perspective also helps explain why empirical evidence often supports MGM more strongly in the context of health consumption (e.g., curative care) than health investment. Curative care is more consistent with restorative production processes, whereas preventive care is more closely associated with growth-oriented assumptions embedded in the MGM. This distinction further supports the view that health capital production is fundamentally restorative in nature.

5. Evaluation of Health Capital

The MGM describes the flow, stock, and production mechanisms of health capital, but its underlying assumptions are problematic. In response, we revise these assumptions and propose a more appropriate framework for evaluating health capital.

According to Grossman's theory, health stock is viewed as the accumulation of health flows from previous periods. In the MGM framework, the utility flow of health capital is incorporated into the depreciation parameter δ, which implies intertemporal substitutability and allows future health utility to be discounted and transformed into present utility (Bhattacharya et al., 2014). However, this relies on the assumption that health capital can be transferred across time in a meaningful way. Yet, as the famous saying goes, one cannot step into the same river twice, because it is not the same river, and one is not the same person. In a similar sense, while H_{t-1} may influence H_t, the health outcome in period t is not the direct accumulation or consumption of H_{t-1}. H_t is H produced entirely in time period t, and the utility of H_t is independent. Thus, the utility generated in period $t-1$ belongs exclusively to that period, while the utility generated in period t belongs only to period t. For this reason, health capital cannot be meaningfully traded or shifted across time periods.

In order to solve the immortality problem in MGM, Laporte (2015) proposed to define a maximum possible lifespan and allow people to choose their own lifespan until the

upper limit is reached. Under the condition that health capital cannot be traded across periods, Laporte's idea is feasible. The setting of the maximum health stock can not only explain the restorative production of health capital, but also intuitively describe the endogenous depreciation of health capital of individuals in different periods.

Fu et al. (2016) proposed that the endogenous depreciation of health capital in MGM was certain, and the uncertainty of health capital depreciation came from the exogenous depreciation of health capital. She proposed that health investment can directly produce health capital through the assumption of capital accumulation in MGM, and can also indirectly produce health capital by reducing the exogenous depreciation rate. Therefore, under the condition that health capital cannot be traded across periods, the effect of H_{t-1} on H_t can only be achieved by affecting the depreciation rate of H_t.

Since the depreciation costs incurred in past time periods cannot be offset by health production, we propose that health production does not directly generate benefits from health capital, but rather produces more available health capital in any given time period *t* by reducing the depreciation rate of health capital increased by external environmental pressure (Figure 4).

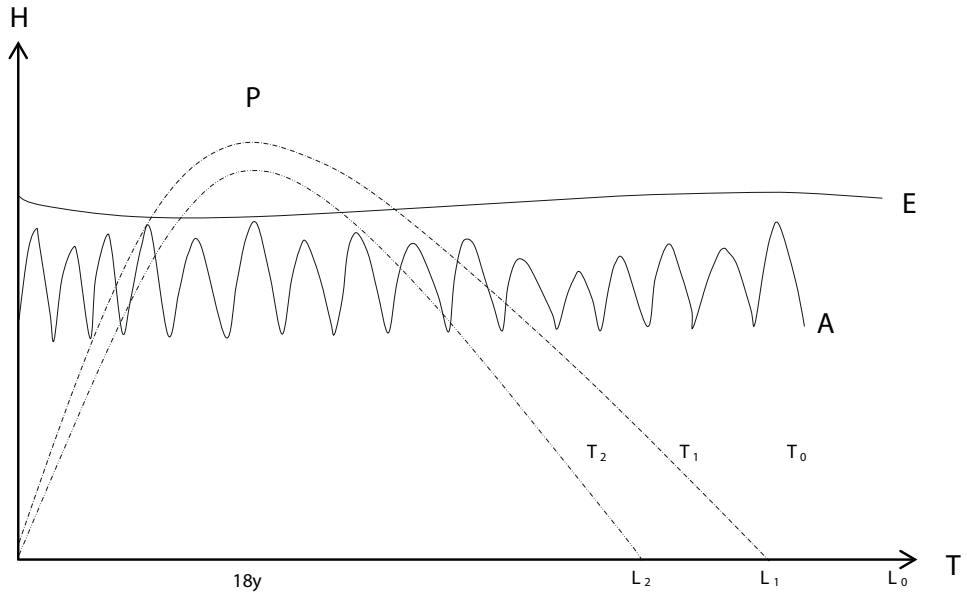


Fig. 4. *Health Production Mechanism Proposed in This Study*
T: Time
H: Health Level
T_0: Theoretical Maximum Health Stock Curve
T_1: Health Stock Curve after the First Depreciation Rate Increase
T_2: Health Stock Curve after the Second Depreciation Rate Increase
L_0: Theoretical Maximum Lifespan
L_1: Lifespan after the First Depreciation Rate Increase
L_2: Lifespan after the Second Depreciation Rate Increase
A: Activity Curve Affecting Health Capital
E: Traction Curve of Environmental Load (Living Environment and Living Habits) on the Body's Internal Homeostasis Level
P: Maximum Health Level
Source: authors

We assume that each individual possesses a theoretical maximum health stock at birth, defined as the highest attainable level of physical, psychological, and social functioning determined by genetic endowment in the absence of any external stressors. This theoretical maximum is unobservable in practice, as no individual can fully develop all health-related functions to their potential upper bound over the life course. Throughout life, health stock is continuously reduced by health-related events occurring at different times.

Within a given period *t*, reductions in health that fall within the body's homeostatic regulation capacity can be restored through health production activities. However, losses that exceed this regulatory capacity cannot be fully recovered. Moreover, even when partial recovery is achieved, the resulting health trajectory is altered: once a health shock occurs, subsequent restoration can only return the individual to a lower post-shock baseline rather than the pre-shock health trajectory. As a result, the health stock curve shifts irreversibly over time, and cumulative health events permanently reduce lifetime health stock.

Consider the expression of disease-related genes as an illustration. Suppose gene B is associated with disease A. When gene B is expressed, disease A occurs. The timing of gene expression is probabilistic and varies across the life course. In an idealized case, the theoretical maximum health stock would require gene B to be expressed at the very end of life (e.g., at age 60). However, in reality, environmental conditions, behaviors, and stochastic health shocks alter the timing of gene expression, making early activation far more likely than this theoretical endpoint. Earlier expression implies an earlier onset of disease and therefore a larger cumulative loss of health stock over the life course.

Even in cases where the probability of gene expression is very low over most of the lifespan, rare but high-impact exposures (e.g., carcinogens) can substantially increase the likelihood of early activation. Thus, the estimation of theoretical maximum health stock must account for such low-probability but high-impact health events. Cancer provides a typical example, where long-term exposure to carcinogenic factors significantly increases the likelihood of disease gene activation.

In this framework, health stock is path-dependent and subject to irreversible shocks. Consequently, the curvature of the health stock trajectory can be interpreted as the depreciation rate of health capital. Under the mechanism of health elasticity, an individual's capacity to maintain homeostasis moderates the impact of health shocks, while long-term environmental conditions and lifestyle factors continuously shape baseline physiological regulation, further influencing the evolution of health stock over time.

The proposed health capital model aims to explain the following main points:

a) Health production is a restorative production, and its output cannot possibly exceed the theoretical maximum health level in any given time period *t*;

b) The theoretical maximum health level in any given time period *t* is not fixed, but changes according to the change of the health capital depreciation rate;

c) In the individual life cycle, the depreciation of health capital is irreversible, and its depreciation rate will only increase and not decrease. The individual's lifelong health capital and life expectancy also continue to decrease with the depreciation rate;

d) The production of health capital is achieved by reducing the exogenous depreciation rate;

e) Health is elastic, which is an ability to regulate the internal homeostasis of the body. It shows that only health production that breaks through health elasticity can improve health levels, while health production that cannot break through health elasticity will not improve health levels;

f) Health levels are influenced by the long-term effect of environmental loads on the body's internal homeostatic regulation, which drives the health equilibrium toward adaptation to prevailing environmental conditions in any given period *t*. This mechanism implies that any gains in health production that exceed the bounds of health elasticity can only be sustained through continuous investment in health production.

Under the influence of environmental load, health production can be divided into active and passive health production. The maintenance of active health production gains requires individuals to deliberately create a higher level of environmental load than the current baseline through intentional health investment. By contrast, passive health production does not require additional individual investment and instead arises directly from health production incentives embedded in the existing environmental load. As a result, the cost of active health production is higher than that of passive health production.

The model also explains heterogeneous responses to health events across different life stages. Both restorative health production and health-depleting events exert persistent effects on health status over the life course. Because the health stock curve is typically lower at both early and late stages of life, individuals are more likely to experience health shocks (*A*) that exceed the bounds of health elasticity during these periods. In old age, the body's capacity to regulate internal homeostasis declines, leading to a progressive loss of health elasticity. As a result, any realization of *A* directly translates into a decline in health status. Given the model's structure of health depreciation, elderly individuals experience a continuously declining health stock, with limited capacity for recovery. Consequently, the upper bound of restorative health production diminishes over time, and even small health investments yield low marginal returns. At the same time, reduced elasticity makes the elderly more vulnerable to the direct negative effects of *A*, which explains their higher susceptibility to disease.

In contrast, in childhood, health elasticity is also limited, making individuals more sensitive to environmental shocks. However, as individuals age into adulthood, increasing physiological resilience makes it more difficult for *A* to generate lasting effects on the health stock curve. These results are consistent with empirical evidence showing that children are particularly vulnerable to health shocks in real life (Bleakley, 2010).

According to the assumptions of the above health capital model, an individual has a theoretical maximum health stock determined by the genetic coefficient h. The endogenous depreciation rate of individual health capital is determined and exhibits different trajectory characteristics in childhood and adulthood. We denote the depreciation coefficients that determine the trajectory characteristics of health capital in childhood and the depreciation coefficients that determine the trajectory characteristics of health capital in adulthood by $\gamma 1$ and $\gamma 2$, respectively. The health capital formula based on the linear–exponential loss function is given as follows:

$$H = -h \cdot e^{-\gamma 1 \cdot t} - \gamma 2 \cdot t + h, \tag{6}$$

H: health level;

t: time;

h: genetic coefficient. The higher the genetic coefficient, the more theoretical maximum health capital determined by genes.

$\gamma 1$: depreciation coefficient of the growth period. The larger $\gamma 1$ is, the shorter the growth period is.

$\gamma 2$: depreciation coefficient of the aging period. The larger $\gamma 2$ is, the faster the aging is.

In biology, *γ1* and *γ2* are related. In most cases, organisms with faster development speed also have shorter lifespans (Yuan et al., 2023). This means that the larger *γ1* is, the larger *γ2* will be. *γ1* and *γ2* jointly determine the depreciation rate of health capital. When an individual's *γ1* increases due to health events, *γ2* will also increase. This means that the theoretical maximum stock of health capital in adult life that the individual has not yet experienced will also decrease, which explains the huge impact of early childhood health on adult health and the reason why it affects an individual's lifetime income to a greater extent (Bleakley, 2010). However, it is also an important issue that MGM has not yet solved. Galama and Van Kippersluis 2013 proposed that MGM needs to be expanded in the future to explain this feature of health capital in childhood. But the fact is that this is difficult to achieve under the assumption that MGM allows inter-temporal trading of health capital because individuals can rent adult health capital during childhood and return this capital after adulthood. Assuming inter-temporal trading of health capital is rejected, health capital in period *t-1* cannot utilize health capital that has not yet been produced in period t, nor can it be accumulated in period t. Health capital in period *t-1* can only influence the production of health capital in period t. It is the effect of health capital in period *t-1* on the exogenous depreciation rate of health capital in period *t*. The influence of early childhood health capital on the trajectory of individual health capital occurs at an early stage and therefore has a relatively large impact on health outcomes in subsequent periods. In contrast, *γ1* can affect *γ2*, but *γ2* cannot retroactively influence *γ1*. This time-directional asymmetry is naturally accommodated in the health capital model with non-intertemporal transactions, thereby resolving the issue within the proposed framework.

Since our health capital model is non-intertemporal, the *H* produced in time period *t* is not the balance of H_{t-1} in time period *t-1*, but the completely re-produced *H*. Therefore, it is feasible to evaluate the theoretical maximum health capital that has not been produced in the future time period. Health capital is defined as the area under the health stock curve, from which the corresponding calculation formula for health capital is derived:

$$K^H = \frac{h}{\gamma 1 \cdot (e^{-\gamma 1 \cdot l} - 1)} - \frac{\gamma 2 \cdot l^2}{2} + h \cdot l, \tag{7}$$

K^H: Individual lifelong health capital;

l: Individual life expectancy.

From the above formula, we can find that any A and E that affect health capital and life span can only be achieved by changing *γ1* and *γ2*, because h is a constant value inherited by an individual. This provides a mathematical validation of the theory proposed in this study: that health production is achieved by increasing available health capital through the reduction of the effective depreciation rate of health capital.

Based on the above formula, this study further deduced the calculation formula of personal residual health capital:

$$K_{t1}^H = \frac{h}{\gamma 1 \cdot (e^{-\gamma 1 \cdot l} - e^{-\gamma 1 \cdot t1})} - \frac{\gamma 2}{2 \cdot (l^2 - t1^2)} + h \cdot (l - t1), \tag{8}$$

K_{t1}^H: The individual remaining health capital after a given time point *t1*.

The evaluation of an individual's remaining health capital is an important contribution of this study. In the MGM framework, the utility flow of health capital is introduced with a discount factor, allowing intertemporal trade in health capital and representing health utility in period *t* as part of a dynamic flow process. Grossman assumes that future health capital depends on individuals' current decisions regarding health investment, which implies that future, yet-to-be-produced health capital can be optimally allocated from present resources.

However, this intertemporal structure also implies that MGM primarily captures the accumulation of past health flows rather than reliably predicting future health stock, and it raises the conceptual issue of potentially unbounded or "infinite" life under certain conditions. For this reason, MGM is often better suited to retrospective analysis of health demand in empirical applications.

In contrast, our model addresses the evaluation of future available health capital by rejecting intertemporal trade in health stock. In our framework, the health capital utility flow in period t is static: it is determined within the period and does not vary with current investment decisions or with the accumulation of health capital in period *t–1*. This static formulation ensures that each period's utility flow is independently defined.

As a result, the model treats health capital as a non-transferable production factor across time, which resolves the indeterminacy associated with future health stock in MGM. It also provides a more stable basis for empirical analysis, making the framework particularly suitable for cross-sectional studies.

6. Conclusion

The production of health capital is not a discrete activity but a continuous process throughout an individual's life course. Health investment generates benefits only under certain conditions, and excessive investment may lead to negative returns. Due to health elasticity, improvements in health status are conditional and can only be sustained through continuous investment in health production. In the presence of environmental load, active health production is more costly than passive health production. Moreover, because health production is fundamentally restorative, its benefits cannot fully offset cumulative depreciation costs.

Health capital cannot be traded across periods, and H_t is not the direct result of H_{t-1}. Instead, the production mechanism operates by increasing available health capital in period *t* through reducing the depreciation rate induced by external environmental pressures. In this sense, health production modifies the dynamics of depreciation rather than generating purely additive stock accumulation.

This study provides a new explanation for why the MGM is often rejected by empirical evidence, while also addressing several of its theoretical limitations. By constructing an exponential functional form, we analyze the production mechanism and evaluation method of health capital and show that health events influence individual health capital primarily by altering depreciation coefficients across developmental and aging periods.

Overall, this study develops a new theoretical model of health capital and proposes a method for evaluating remaining health capital. It offers a theoretical foundation for predicting human capital dynamics and for future empirical research on health capital.

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