

Innovation-Driven Longevity and the Redesign of Health Insurance Contracts

Maria Carannante Valeria D'Amato Cinzia Di Palo Maria Sole Staffa

Link Campus University Sapienza University of Rome
University of Cassino and Southern Lazio European University of Rome

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Agenda

- ▶ Medical innovation, longevity and morbidity
- ▶ The vitagion-augmented Lee–Carter model: innovation indicator, identification and penalised estimation
- ▶ From survival to healthy longevity: the QALY framework
- ▶ Longevity convexity and survival-contingent liabilities
- ▶ Critical Illness under vitagion: multi-state valuation and innovation channels
- ▶ Numerical evidence: life expectancy, QALY and Critical Illness premiums
- ▶ Actuarial implications and conclusions

1. Vitagion-based mortality framework

Medical innovation is introduced into the Lee–Carter model through an external innovation indicator with an age-specific loading.

2. Mortality and healthy longevity

QALY is derived as a structural transformation of model-implied survival under the assumption of proportional health deterioration.

3. Longevity convexity

Innovation-driven survival improvements may generate a nonlinear response in survival-contingent liabilities, particularly when improvements affect the right tail of the lifetime distribution.

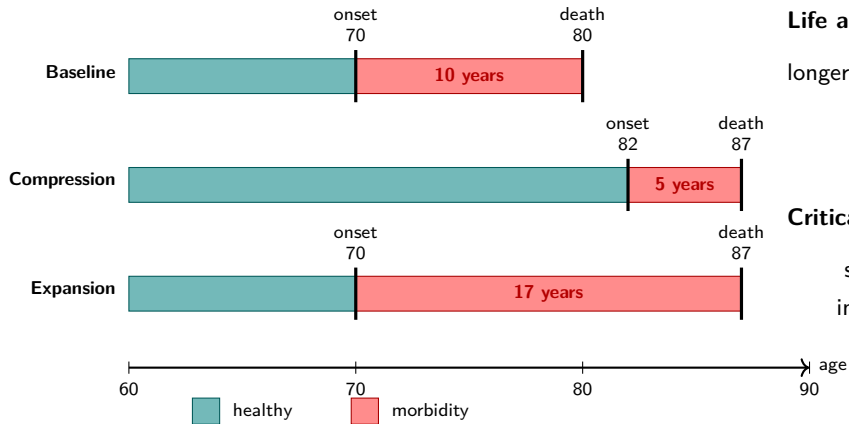
4. Product-specific valuation effects

For Critical Illness insurance, innovation acts through survival exposure, disease incidence and claim severity. The overall valuation effect is therefore not necessarily monotonic.

Medical progress: longer life, healthier life?

Medical innovation may extend life, but its effect on healthy lifetime is not predetermined.

Alternative morbidity scenarios



Insurance valuation

Life annuity

longer survival $\Rightarrow$ more exp. payments

$$EPV_{\text{annuity}} \uparrow$$

Critical Illness

survival exposure $\uparrow$,
incidence/severity may fall

$$EPV^{CI} ?$$

Gruenberg (1977); Fries (1980); Manton (1982).

A vitagion shock is not a standard improvement trend

Traditional mortality models generally represent extrapolations of historical experience.

A **vitagion** is instead an innovation-induced shift that may simultaneously affect mortality and health trajectories.

Unlike a standard mortality improvement, a vitagion shock may alter:

- ▶ the **age profile** of mortality improvements;
- ▶ the distribution of survival probability toward advanced ages;
- ▶ the quality profile of additional life years;
- ▶ the balance between **incidence, severity and exposure** in health products.

Vitagion is modelled as a structural source of longevity risk, not merely as an extrapolation of past mortality trends.

The vitagion-driven innovation indicator

Let $n_i(t)$ denote the number of therapies of type i approved in year t , and let

$$N_i = \sum_t n_i(t)$$

be the total number of approvals of type i over the observation period.

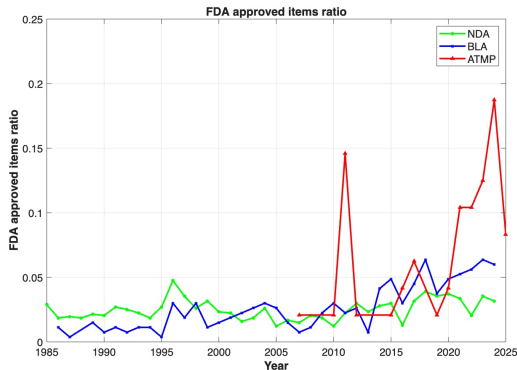
The type-specific innovation indicator is

$$I_i(t) = \frac{n_i(t)}{N_i}, \quad \sum_t I_i(t) = 1,$$

whenever $N_i > 0$.

An aggregate indicator $I(t)$ is obtained by combining the type-specific shares using economically or clinically meaningful weights.

In the numerical application, FDA approvals are summarised through a weighted average of the New Drug Applications (NDAs), Biologics License Applications (BLAs), and Advanced Therapy Medicinal Products (ATMPs).



FDA-approved items by type: NDA, BLA and ATMP.
NDAs, BLAs, and ATMPs exhibit distinct diffusion regimes.

$$\log \mu(x, t) = \alpha(x) + \beta(x)\kappa(t) + \theta(x)I(t) + \varepsilon(x, t).$$

- ▶ $\alpha(x)$: average level of mortality at age x ;
- ▶ $\beta(x)\kappa(t)$: age-specific sensitivity to the temporal mortality trend;
- ▶ $\theta(x)I(t)$: age-specific sensitivity to pharmaceutical innovation;
- ▶ $\varepsilon(x, t)$: error term at age x and time t .

The innovation term separates the age-specific association with medical innovation from the general temporal evolution of mortality.

Identifiability constraints

The introduction of the innovation covariate creates an identifiability problem because the period factor $\kappa(t)$ and the innovation process $I(t)$ may capture overlapping temporal variation.

In addition to the standard Lee–Carter normalisations,

$$\sum_t \kappa(t) = 0, \quad \sum_x \beta(x) = 1,$$

the paper imposes

$$\text{cov}(\kappa(t), I(t)) = 0, \quad \boldsymbol{\kappa} = (\kappa(1), \dots, \kappa(T)) \neq \mathbf{0}.$$

These constraints prevent the period factor from absorbing the explanatory contribution of the innovation process and allow the two temporal components to be separately identified.

The temporal relation between $\kappa(t)$ and $I(t)$ can be estimated through a time-series regression.

Penalised estimation

The age-specific profiles $\beta(x)$ and $\theta(x)$ are estimated by minimising the penalised least-squares objective

$$Q(\alpha, \beta, \kappa, \theta) = \sum_{x=x_{\min}}^{x_{\max}} \sum_{t=t_{\min}}^{t_{\max}} \left[\log \mu(x, t) - \alpha(x) - \beta(x)\kappa(t) - \theta(x)I(t) \right]^2 \\ + \pi_{\beta} \sum_x [\Delta^2 \beta(x)]^2 + \pi_{\theta} \sum_x [\Delta^2 \theta(x)]^2.$$

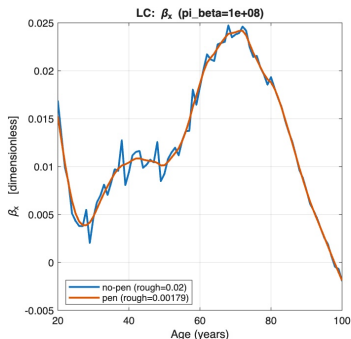
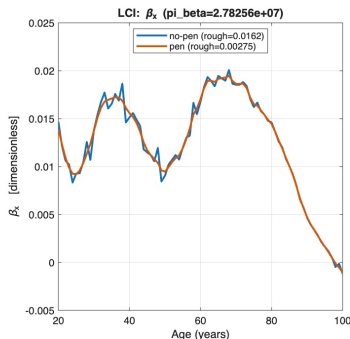
The second-order differences are

$$\Delta^2 \beta(x) = \beta(x+2) - 2\beta(x+1) + \beta(x),$$

$$\Delta^2 \theta(x) = \theta(x+2) - 2\theta(x+1) + \theta(x).$$

- ▶ Larger values of π_{β} and π_{θ} produce smoother age profiles.
- ▶ Joint penalisation controls irregularities in both the mortality sensitivity $\beta(x)$ and the innovation sensitivity $\theta(x)$.
- ▶ The smoothing parameters can be selected by cross-validation on prediction errors.

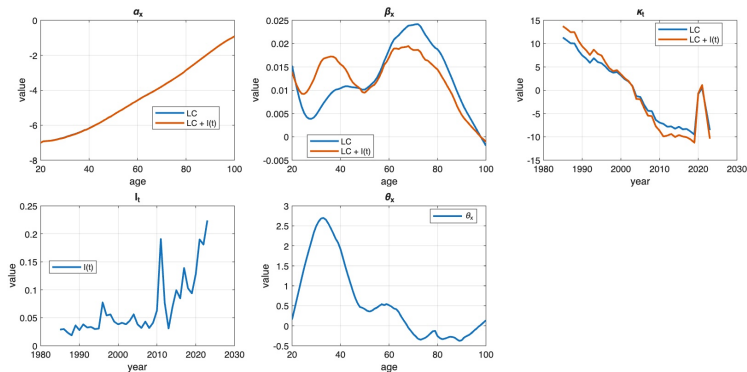
Effect of penalisation on age sensitivity



Penalised $\beta(x)$ under the LC and LCI models.

- ▶ In the LC model, $\beta(x)$ displays a pronounced peak around ages 70–75.
- ▶ In the LCI model, the inclusion of $I(t)$ redistributes the age-specific sensitivity.
- ▶ A higher sensitivity emerges among young adults, particularly between ages 30 and 45.

LC versus LCI: parameter decomposition



Baseline LC model and innovation-augmented LCI specification.

- ▶ The estimated $\alpha(x)$ profiles remain similar across the two specifications.
- ▶ The largest differences in $\beta(x)$ emerge between ages 30 and 45.
- ▶ Both $\kappa(t)$ trajectories capture the general mortality decline and the 2020 pandemic shock.
- ▶ In the LCI model, $\kappa(t)$ shows a more marked post-2010 decline.
- ▶ The estimated loading $\theta(x)$ reaches its maximum among adult ages.

From annual to continuous survival

Projected central mortality rates define annual death and survival probabilities:

$$q_{x+j,t_0+j} = 1 - \exp(-m_{x+j,t_0+j}), \quad p_{x+j,t_0+j} = 1 - q_{x+j,t_0+j}.$$

The prospective probability of surviving t years is

$${}_t p_{x,t_0} = \prod_{j=0}^{t-1} p_{x+j,t_0+j}.$$

Under piecewise-constant annual mortality hazards,

$$p_{x+j,t_0+j} = \exp(-m_{x+j,t_0+j}),$$

so the discrete survival product has the equivalent continuous-time representation

$$S_{x,t_0}(t) = \exp \left\{ - \int_0^t \mu(x+s, t_0+s) ds \right\}.$$

From survival to healthy longevity

Given the prospective survival function, the expected quality-adjusted lifetime is defined as

$$\text{QALY}_{x,t_0} = \int_0^\infty S_{x,t_0}(t) u_{x,t_0}(t) dt,$$

where $u_{x,t_0}(t)$ is the health-utility weight associated with survival at time t .

The paper assumes that the instantaneous rate of health deterioration is proportional to the mortality hazard:

$$\gamma(x+s, t_0+s) = \kappa \mu(x+s, t_0+s), \quad \kappa \geq 0.$$

Therefore,

$$u_{x,t_0}(t) = \exp \left\{ - \int_0^t \gamma(x+s, t_0+s) ds \right\} = S_{x,t_0}(t)^\kappa,$$

and

$$\boxed{\text{QALY}_{x,t_0} = \int_0^\infty S_{x,t_0}(t)^{1+\kappa} dt}.$$

A unified hazard interpretation

Define the health-adjusted survival process as

$$H_{x,t_0}(t) = S_{x,t_0}(t) u_{x,t_0}(t).$$

Using the structural relation between mortality and health deterioration,

$$H_{x,t_0}(t) = \exp \left\{ - \int_0^t [\mu(x+s, t_0+s) + \gamma(x+s, t_0+s)] ds \right\}.$$

The effective hazard governing healthy longevity is therefore

$$\lambda(x+s, t_0+s) = \mu(x+s, t_0+s) + \gamma(x+s, t_0+s),$$

and, since $\gamma = \kappa\mu$,

$$\lambda(x+s, t_0+s) = (1+\kappa)\mu(x+s, t_0+s).$$

Hence, QALY can be interpreted as the expected lifetime under an effective hazard combining mortality and health deterioration.

Longevity convexity as a benchmark mechanism

Consider a generic life-contingent liability with actuarial value

$$AV = \sum_{t=0}^{\infty} B_t v^t {}_t p_x,$$

where B_t is the benefit payable at time t , v^t is the discount factor and ${}_t p_x$ is the survival probability.

A vitagion shock produces a change $\Delta {}_t p_x$ in survival probabilities, so that

$$\Delta AV \approx \sum_t B_t v^t \Delta {}_t p_x.$$

Although this expression is formally linear, its economic implications need not be linear:

- ▶ innovation-driven improvements may be concentrated at advanced ages;
- ▶ baseline survival probabilities are low in the right tail;
- ▶ small absolute survival changes may therefore produce large relative changes in outstanding payments.

Longevity convexity is the nonlinear sensitivity of actuarial liabilities to survival improvements concentrated in the right tail of the lifetime distribution.

Critical Illness: a continuous-time multi-state framework

Consider an individual aged x at contract inception, with t denoting time elapsed since inception.

The transition intensities are:

$\mu_{01}(t)$: healthy-to-CI diagnosis,

$\mu_{02}(t)$: healthy-to-death,

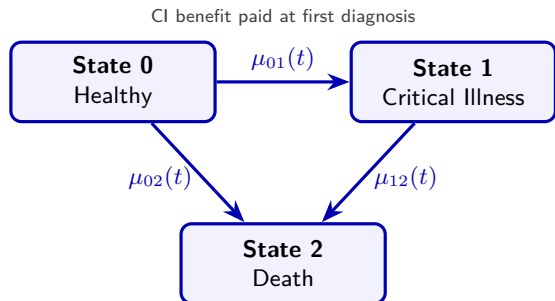
$\mu_{12}(t)$: death after diagnosis.

Before diagnosis, the total exit intensity from the healthy state is

$$\lambda_0(t) = \mu_{01}(t) + \mu_{02}(t).$$

Hence, the probability of remaining in the healthy state up to time t is

$$S_0(t) = \exp \left\{ - \int_0^t [\mu_{01}(s) + \mu_{02}(s)] ds \right\}.$$



Actuarial value of the Critical Illness benefit

For an individual aged x at contract inception, consider a lump sum $B(t)$ payable upon first diagnosis.

The first-diagnosis sub-density is $f_{01}(t) = S_0(t)\mu_{01}(t)$. Hence,

$$S_0(t)\mu_{01}(t) dt$$

is the probability of remaining alive and diagnosis-free up to time t and being diagnosed during $[t, t + dt)$. Therefore, the actuarial value is

$$AV^{CI}(x) = \int_0^{\infty} v(t) B(t) S_0(t) \mu_{01}(t) dt .$$

Innovation may affect both diagnosis-free exposure and diagnosis intensity.

Innovation channels in Critical Illness valuation

Let the benefit amount depend on the innovation index I : $B(t; I) = B_0 b(t; I)$.

The actuarial value is

$$AV^{CI}(x; I) = \int_0^{\infty} v(t) B_0 b(t; I) S_0(t; I) \mu_{01}(t; I) dt,$$

where

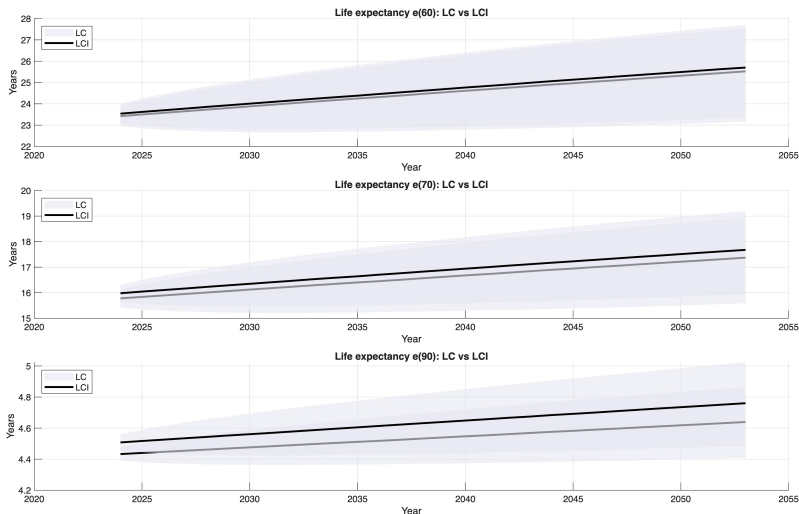
$$S_0(t; I) = \exp \left\{ - \int_0^t [\mu_{01}(s; I) + \mu_{02}(s; I)] ds \right\}.$$

Differentiating with respect to innovation gives

$$\frac{\partial AV^{CI}(x; I)}{\partial I} = \int_0^{\infty} v(t) B_0 \left[\underbrace{\frac{\partial b(t; I)}{\partial I} S_0(t; I) \mu_{01}(t; I)}_{\text{severity channel}} + \underbrace{b(t; I) S_0(t; I) \frac{\partial \mu_{01}(t; I)}{\partial I}}_{\text{incidence channel}} + \underbrace{b(t; I) \mu_{01}(t; I) \frac{\partial S_0(t; I)}{\partial I}}_{\text{survival exposure channel}} \right] dt. \quad (8)$$

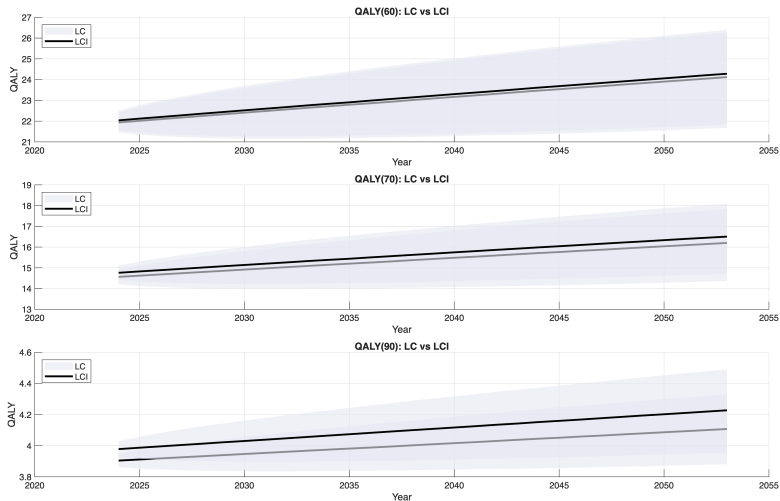
The overall innovation effect is generally sign-indeterminate.

Numerical evidence: life expectancy



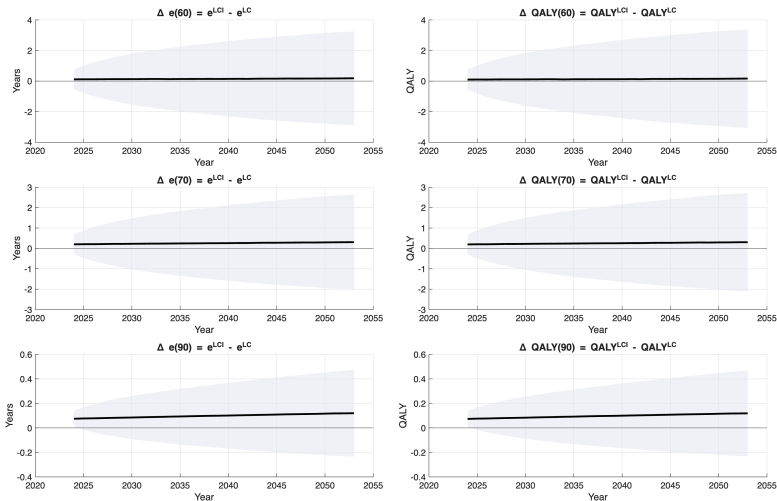
LC versus LCI for entry ages 60, 70 and 90. The innovation effect is positive but small relative to projection uncertainty.

Numerical evidence: quality-adjusted life years



Projected QALY under LC and LCI for entry ages $x \in \{60, 70, 90\}$.

Numerical evidence: innovation effect



Innovation effect on longevity and healthy longevity: $\Delta e_{x,t_0}$ and $\Delta QALY_{x,t_0}$.

Critical Illness contract configurations

We consider a Critical Illness contract paying a single lump-sum benefit of EUR 50,000 upon the first diagnosis of a specified severe illness.

- ▶ The benefit is paid once upon diagnosis.
- ▶ The contract terminates immediately after payment.
- ▶ If no diagnosis occurs during the coverage period, the contract expires without residual value.

Configuration	Entry age x	Duration n	Deferment
Config 1	60	20 years	None
Config 2	60	35 years	None
Config 3	60	20 years	10 years
Config 4	70	20 years	None

The configurations isolate the effects of entry age, coverage duration and deferment.

Critical Illness: actuarially fair premiums

The four contract configurations are valued under the LC, LCI, Q^{LC} and Q^{LCI} specifications.

Config.	Fair premium				Relative difference		
	LC	LCI	Q^{LC}	Q^{LCI}	ΔP_{LCI}	$\Delta P_{Q^{LC}}$	$\Delta P_{Q^{LCI}}$
Config 1	4455.25	4452.32	4306.76	4303.15	−0.07%	−3.33%	−3.41%
Config 2	6879.44	6916.94	6389.28	6425.13	+0.55%	−7.13%	−6.61%
Config 3	5018.84	5045.81	4628.52	4656.22	+0.54%	−7.78%	−7.23%
Config 4	7190.71	7251.10	6797.71	6863.09	+0.84%	−5.47%	−4.56%

- ▶ The LC–LCI effect ranges from −0.07% to +0.84%.
- ▶ The Q -adjustment produces substantially larger premium reductions.
- ▶ Contract duration, entry age and deferment affect the relative magnitude of the valuation response.

Integrated modelling

Mortality, morbidity and health quality should not be treated as independent dimensions when innovation dynamics are explicitly considered.

Product response

Innovation produces different valuation responses across survival- and health-contingent insurance products. The response of CI liabilities is not necessarily monotonic.

Risk allocation

Vitagion does not uniformly increase insurance liabilities. It reallocates actuarial risk across ages, health states and product lines.

Innovation reshapes not only survival levels but the distribution of actuarial risk.

Conclusions

- 1 Vitagion extends the Lee–Carter framework to represent **innovation-driven mortality dynamics**.
- 2 Identification, orthogonalisation and smoothing are essential for interpreting the age-specific innovation loading θ_x .
- 3 QALY provides a **structural link between stochastic survival and health-adjusted lifetime**.
- 4 Longevity convexity captures the nonlinear valuation response of survival-contingent liabilities.
- 5 Critical Illness valuation operates through **severity, incidence and survival-exposure channels**; the overall response is not necessarily monotonic.

**Innovation does not always increase liabilities;
it reallocates actuarial risk across ages, health states and products.**

The paper suggests some main extensions:

- ▶ allowing innovation intensity and its effects to vary over time;
- ▶ incorporating disease-specific transition processes;
- ▶ modelling endogenous behavioural responses to medical advances;
- ▶ extending the analysis to portfolio-level interactions across life- and health-contingent insurance products.

A multi-line framework could investigate whether offsetting valuation effects generate partial natural hedging within diversified insurance portfolios.

Thank you

Questions and discussion

Cinzia Di Palo

University of Cassino and Southern Lazio

c.dipalo@unicas.it

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