Expert Views

Assessing Future Cancer Risk and Its Impact on Insurance

Footprint Scenario Analysis

SCOR
The Art & Science of Risk

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Executive Summary

Cancer is the leading cause of death worldwide, impacting many aspects of people's lives. Although the path to finding a cure may be long and complex, many scientists believe that accelerating advancement in preventive measures such as screening and cancer vaccines and improvement in cancer treatment will drastically relieve or even eliminate this dreadful disease someday. How would the outcome of these advancements affect the future of the insurance business? Is it possible to scientifically analyze and quantify the magnitude of the influence on mortality and morbidity for various possible future scenarios? SCOR's biometric risks modeling team has taken up this challenge and conducted an in-depth analysis. This report is a part of SCOR's footprint (= what if) scenario analysis, which aims to illustrate the impact of potential "real-life" events on insurers' portfolios, particularly the potential offsets or accumulations between lines of business in life insurance.

The article focuses on three technological advances for fighting cancer that materially impact the life and health insurance business:

- liquid biopsy
- cancer vaccines
- immunotherapy

These technologies could help to detect cancer at earlier stages, prevent cancer, and reduce cancer recurrence and mortality. Based on the outlook of these technologies, we have set up two cancer footprint scenarios that could potentially happen in the future:

Scenario 1 considers a leap in early cancer detection in the next 10 years, leading to better health outcomes and lower cancer mortality.

Scenario 2 considers a breakthrough in the understanding of cancer in the next 30 years: innovations in cancer detection, prevention, and treatment leading to complete recovery/avoidance of cancer for most individuals and slower progression to cancer death for others.

Both scenarios result in an extremely positive impact on the mortality portfolio and a negative impact on the longevity and long-term care portfolio. Impact on critical illness is negative for Scenario 1 and very positive for Scenario 2.

Introduction

Throughout the history of healthcare, technological developments have brought numerous innovative medical inventions - anesthetics, antibiotics, magnetic resonance imaging, and radiotherapy to name a few. Today, the impact of technological advancements on healthcare is reaching new heights. For example, smartwatches with advanced health and fitness monitoring functions can reduce the risk of cardiovascular disease. mRNA vaccines lower Covid-19 mortality risk substantially. How will these technological breakthroughs improve the insured population's mortality and morbidity in the near future? In this report, we highlight the emerging technologies that can impact (re) insurers' life portfolio and evaluate their potential impact on the main lines of business with long-term biometric risk.

During our analysis process, we have mapped out 10 emerging technologies. Among them, we have chosen three major technological advancements that are expected to have a high impact on L&H insurance – 1) liquid biopsy, 2) cancer vaccines, and 3) immunotherapy.

Our footprint scenario analysis focuses on cancer as it is heavily related to all three technological advancements with high impact. In addition, cancer is the leading cause of death and the number one cause of claims for critical illness insurance across the globe. According to Globocan,[1] there are an estimated 19.3 million newly diagnosed cancer cases worldwide and 10 million cancer deaths in 2020. Advancements in cancer prevention, diagnosis, and treatment therefore will reduce cancer incidence and mortality and bring positive results to L&H business.

Many scientists maintain a positive outlook on finding a cure for cancer in the future, backed by various new discoveries. For example, recent developments in liquid biopsy can potentially revolutionize cancer screening with the possibility of detecting multiple cancer types with one single drop of blood. If it could be applied at the general population level, a large part of late-stage cancers would be detected at earlier stages and significantly reduce cancer mortality. Finding a cure relies on whether we can obtain a complete understanding of how normal cells become cancerous and how cancer cells become metastatic. If future discoveries could reveal its mechanism, cancer could be prevented and cured.

Emerging Technologies

In Table 1, we have listed the 10 emerging technologies that may impact life insurers' business. We evaluated the future development of each technology and ranked its potential impact from low, medium to high.

Table 1: Emerging medical technologies and their potential impacts of L&H insurance.

Emerging Technologies	Key Focus	Potential Impact
Liquid biopsy	Multi-cancer early detection (MCED) test using a single blood sample. Early detection of cancer leading to better survival rate.	High
Immunotherapy including CRISPR gene editing	Immunotherapy including CRISPR to treat cancers	High
Preventive cancer vaccines	Use of vaccine technology to harness immune system to attack cancer cells for cancer prevention	High
Wearable tech	Preventing and monitoring cardiovascular diseases	Medium
Precision medicine	To target care more precisely to patients through individualized health care, better delivery of monitoring and drugs	Medium
Biomarkers for dementia diagnosis	Improving screening and diagnosis of dementia/ Alzheimer's Diseases	Medium
Advances in surgical techniques, including robotics & 3D printing	More effective removal of tumors and better implants, bypasses, etc.	Low
AI for cancer diagnostics, drug development and trials	Interpretation of digital images to detect cancer Improving drug development and speed of trials through AI	Low
Nanotechnology and stem cells	Nanotechnology and Stem Cell usage in treatment of cardiac disease. Nano-tech can also be used to detect diseases/cancers	Low
Improvements in radiotherapy	Further improvements in radiotherapy technology	Low

Below are the three technologies with potentially high impact on L&H insurance:

1. **Liquid biopsy** analyzes biomarkers in a single blood sample and can detect multiple cancers simultaneously without invasive procedures. There are several commercial test kits called multi-cancer early detection tests (e.g., Galleri, CancerSEEK, and PanSeer) available on the market. These tests are not approved for medical diagnosis yet due to their low accuracy in terms of sensitivity and specificity. In the near future, if these tests become sufficiently precise to catch a wide range of cancers at the early stage, cancer onset or progression could be slowed or even stopped using early intervention techniques, achieving a higher survival rate. However, this method has a limitation.

   Liquid biopsies may not be able to detect all types of cancer. For example, bone and brain cancers do not shed cells into the bloodstream and thus couldn't be detected in the blood sample. It could also cause over-diagnosis of indolent cancers like early-stage thyroid cancer.

2. **Cancer vaccines** refer to preventive vaccines that can help the immune system attack cancer or pre-cancer cells to prevent cancer from developing among healthy individuals. Currently, there are several cancer vaccines undergoing early-stage clinical trials. However, there is only one FDA-approved cancer vaccine so far, Sipuleucel-T(Provenge)[2], and it is used for preventing recurring cancer. If a cancer vaccine is successfully developed to prevent multiple cancers with high efficacy, it can significantly reduce cancer incidence and mortality in the future.
3. **Immunotherapy** is a type of cancer treatment that can boost the immune system to fight against cancer cells. It includes monoclonal antibodies, T-cell transfer, treatment vaccines, etc. It is already in clinical use to treat certain types of cancer and has successfully increased lung cancer's two-year survival rate from 10% to 30%. The negative side of immunotherapy is that it is currently expensive, and the side effects could be severe. There is hope that the fast-developing CRISPR gene editing tool could improve its efficacy and reduce the cost in the future. If immunotherapy becomes a key tool in cancer treatments, we can expect a significant reduction in cancer mortality.

Our consultation with oncologists, cancer researchers and epidemiologists suggests that in the next 10 years, liquid biopsy is highly likely to achieve sufficient accuracy to be approved for cancer screening among healthy individuals. Cancer vaccines and immunotherapy may take a longer to develop, but once successful, their impact on cancer incidence and mortality would be substantial. There is a good possibility that we may see a major medical breakthrough in the next 30 years, and cancer will eventually become a preventable and curable disease.

Cancer Footprint Scenarios

Based on our perspective on the future development of emerging technologies and their impact on cancer diagnosis and treatment, we have set up the following two cancer footprint scenarios:

Scenario 1: Earlier detection of cancers leading to earlier treatment and lower mortality

The first scenario considers a leap in early cancer detection in the next 10 years driven by innovations in multi-cancer early detection tests (MCED), leading to a lower number of late-stage cancer and cancer deaths. This scenario will be a reality when MCED achieves high accuracy and becomes available at a low cost. If we can detect cancer at an earlier stage, the treatment would be less invasive and the survival rate would be higher, leading to a significant reduction in cancer mortality. Furthermore, if MCED can detect the risk at a pre-cancer stage, it can prevent the disease, leading to lower cancer incidence.

Blood-based MCED tests, also called liquid biopsy, are currently in development. They are showing promising results in detecting cancer at earlier stages[3] and reducing cancer deaths.[4] These tests could detect plasma cfDNA and identify the methylation patterns specific to cancer cells, allowing them to detect multiple cancers simultaneously with a single blood sample. Some tests could also predict the tissue of origin using a machine-learning algorithm.[5]

If these tests could reach high accuracy in detecting cancer at the population level, especially with higher specificity to avoid false negative results, they are expected to substantially reduce cancer-associated morbidity and mortality. When the tests become affordable, people can take a test every six months or every year to check if any cancer may present.

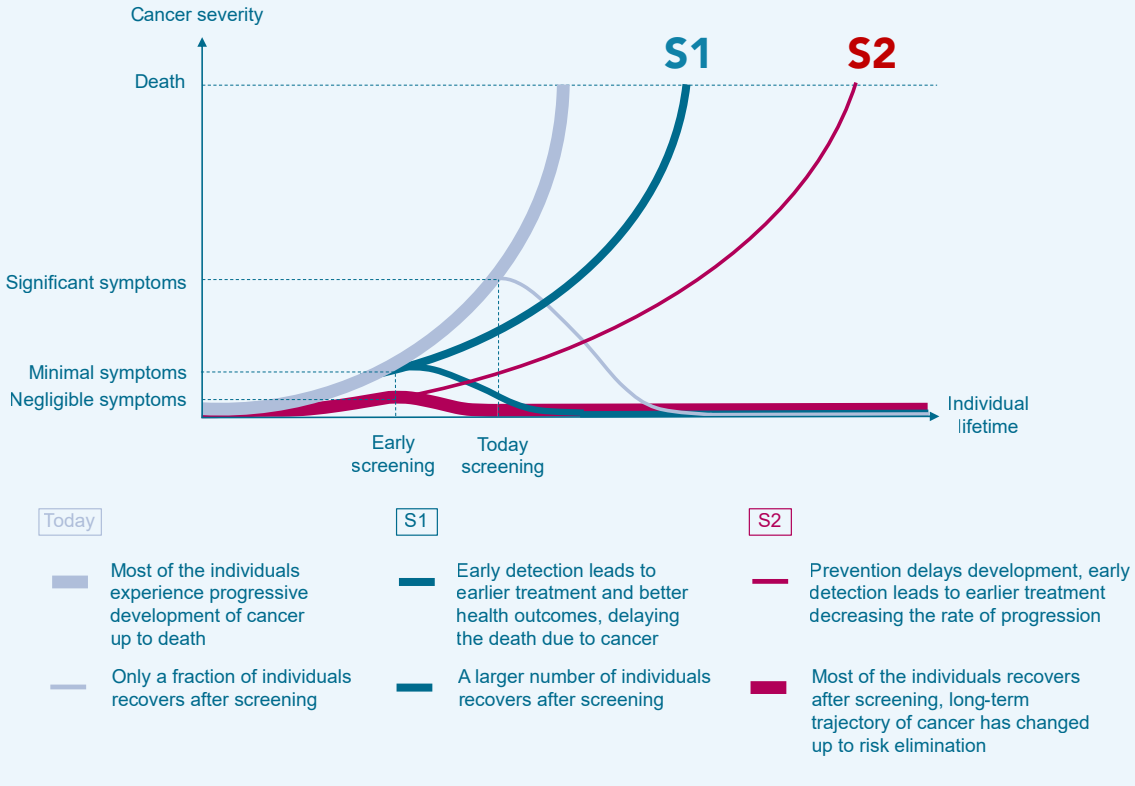
Scenario 2: Technology breakthroughs on the mechanisms of cancer leading to complete cure or prevention of cancer

The second scenario assumes a major breakthrough in cancer in the next 30 years, such as game-changing innovations in cancer detection, prevention, and treatment, leading to a complete cure or elimination of the disease for most of the population.

Our current understanding of cancer is still limited. We don't know exactly how normal cells become cancerous and how cancer cells become metastatic. If technology development can help us fill this knowledge gap, we can design effective cancer vaccines to prevent cancer or develop new treatments to clear up cancer cells and stop metastasis. This will revolutionize cancer diagnosis and treatment and hopefully could lead to eliminating the risk from cancer death.

Figure 1 illustrates the estimated impact of Scenario 1 and 2 on cancer progression and survival. Today, most individuals diagnosed with cancer experience a progressive development of the disease up to death, and only a fraction recover from cancer after screening and treatment, as shown in the grey lines. In Scenario 1 (dark blue lines), a higher proportion of individuals recover thanks to early detection, since the survival rate for early-stage cancers is higher than those diagnosed in later stages. The improvement is even more drastic in Scenario 2 (dark red line), where most individuals recover after screening and treatment, significantly reducing cancer death.

Figure 1: The impact of future cancer scenarios on cancer progression and survival



Estimating the Impact on Insurance Portfolios

How would these future scenarios on cancer diagnosis and treatment impact life and health insurance? We used a data-driven approach, combined with evidence-based assumptions and advanced modeling techniques, to estimate the future impact on various lines of business.

Scenario 1 (early detection of cancer)

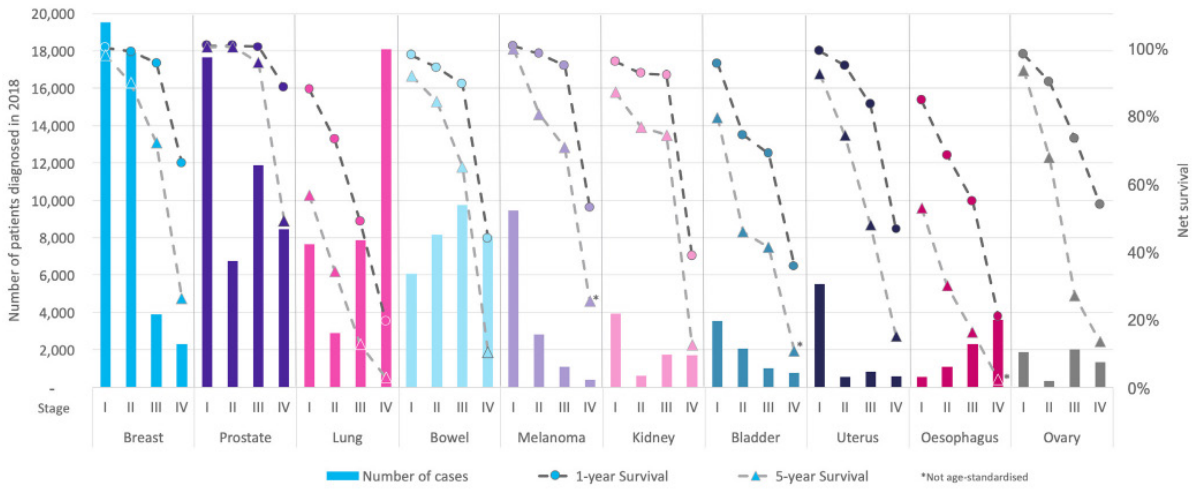
Early detection impacts both cancer incidence and mortality. For cancer mortality, substantial evidence shows that cancers diagnosed and treated at early stages have a higher survival rate. Figure 2 illustrates that five-year survival rates for major cancers based on data from England decrease significantly for cancers diagnosed at stages III and IV compared with stages I and II. Taking female breast cancer, for example, those diagnosed with stage I and II have more than a 90% survival rate after five years, while those diagnosed with stage IV is barely above 20%. If all the stage IV cancers can be detected at stage I and II, we would see significant improvement in cancer survival rate. However, not all cancers would benefit from early detection. Pancreatic cancer, which is not shown in the graph, has an extremely high mortality rate and is largely unchanged even when detected at an early stage.

For cancer incidence, early detection is most effective for certain pre-stage cancers such as breast, cervical, and colon cancer. If early detection methods can detect pre-cancer, it could be treated with existing medical interventions, like removing polys using colonoscopy, and prevent cancers from happening. For indolent cancers like thyroid and prostate cancer, large-scale population screening with MCED may lead to over-diagnosis of stage I cancers that are mostly asymptomatic and harmless if they remain undetected. These cancers could be highly prevalent, autopsy study has shown that 59% of men over age 79 have prostate cancer.

To estimate the impact of Scenario 1 on cancer incidence and mortality, we have set up the following assumptions:

i. Earlier detection will shift part of late-stage cancers (stages III & IV) to early stages (stages I & II). This reduces cancer mortality rates.
ii. Earlier detection during the pre-cancer stage shifts 50% of stage I & II cancers to pre-cancer. This reduces both cancer mortality and incidence

Figure 2: Incidence by stage (2018) with 1-year and 5-year age standardized net survival by stage in England[5]



iii. Earlier detection does not affect the mortality rate of thyroid, prostate, and pancreas cancers. It increases substantially the incidence rate of thyroid cancer.
iv. Earlier detection detects other undiagnosed indolent cancers and increases the overall cancer incidence rate by 10%.

The detailed assumptions on cancer incidence and mortality under Scenario 1 are described in Appendix 1 "Assumptions for cancer incidence and mortality under Scenario 1."

To transform the above assumptions into numbers for modeling, we used cancer survival data from England from 2013-2017, where cancer stage distribution and mortality rate by stage are available.[8] The time horizon of progress in early detection is set at 10 years. After this 10-year horizon of additional improvement, the age-specific incidence and mortality rates due to cancer are expected to revert to their pre-shock dynamic. The estimated changes in cancer mortality and incidence for insurance claims over 10 years are shown in Table 2.

Scenario 2 (complete cure or prevention of cancer)

In February 2022, U.S. President Joseph Biden announced a reignition of the 'Cancer Moonshot' program to reduce cancer deaths in the US by at least 50% over the next 25 years.[9] As part of this project, unprecedented funding into research is expected, hoping to produce a comprehensive mapping of human tumors and to improve prevention, early detection, and treatments.[10]

Scenario 2 assumes that 'Operation Moonshot' exceeds expectations, making unexpected further breakthroughs, leading to a 75% reduction in both cancer incidence and mortality over the next 30 years. Preventive cancer vaccines could be a main contributor to achieving this goal if they can stimulate the immune system to erase all cancer cells emerging in healthy individuals. Since it can prevent cancer from happening, cancer incidence would decrease as well as cancer mortality.

We also expect to see rapid progress in immunotherapy and other innovative cancer treatments in the next 30 years, leading to highly effective personalized targeted cancer treatment with little or no side effects. Last but not least, early detection would be more accurate and widely used, further contributing to a reduction in cancer incidence and mortality.

Based on expert judgment, we evaluate that Scenario 1 is very likely to happen and Scenario 2 is likely to happen. Both scenarios are very positive views of possible future outcomes with respect to health impact, particularly with Scenario 2. Scenario 1 is more likely than Scenario 2, as considerable scientific progress has already been made. It relies on improvements in testing capability and assumes treatment does not improve significantly in timescales that materially affect insurers' portfolios.

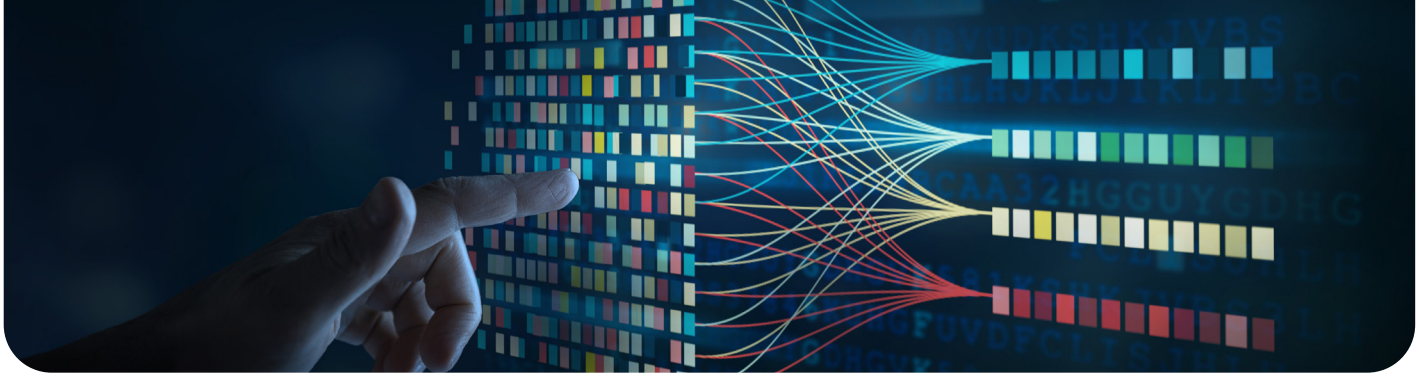
Table 2: Changes in cancer mortality and incidence over the next 10 years under Scenario 1.

Cancer Incidence

Pre-cancer		Indolent cancers		Late to early stages	
• Cervix:	-74%	• Thyroid:	+1400%	• Lung:	+10%
• Breast:	-32%	• Prostate (excluding stage 1):	+5%	• Pancreas:	+10%
• Bladder:	-25%			• Others:	+10%
• Colon:	-12%				

Cancer Mortality

Pre-cancer		No Change		Late to early stages	
• Cervix:	-64%	• Thyroid:	0%	• Lung:	-19%
• Breast:	-51%	• Prostate:	0%	• Others:	-23%
• Bladder:	-23%	• Pancreas:	0%		
• Colon:	-43%				



Application of the Scenarios

This section summarizes our modeling process and the application of the two scenarios. More detailed technical aspects of the modeling are found in the appendix.

Data

The mortality and longevity scenario modeling used in this analysis is based on data from the U.S. and U.K. We analyzed mortality dynamics by cause of death linked to the highest educational attainment levels and highest deciles of the index of multiple deprivation to derive insured U.S. and U.K. population proxy data.

The morbidity scenarios for the Long Term Care (LTC) model incidence rates and termination rates were based on a high-level estimation using key distributions in France. It was built on the assumption that the mortality reduction caused by a better understanding of cancer occurs at a gradual speed. Therefore, current in-force policyholders with cancer will not benefit from the mortality reduction. As a result, mortality reduction is only applied to autonomous individuals who are not currently holding LTC and may develop cancer in the future.

The morbidity scenarios for Critical Illness (CI) model incidence rates are based on data from China.

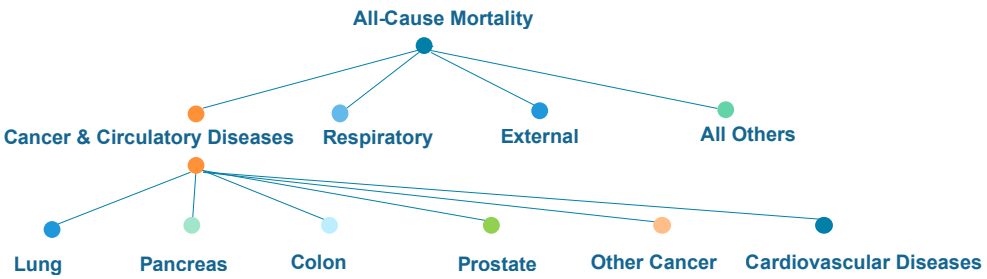
To classify causes of death used for mortality statistics, we used the International Classification of Diseases (ICD), which provides a system of diagnostic codes. For the illustration of our scenarios, only five cancers are assessed separately, and the remaining causes of death are grouped into four broad categories: diseases of the circulatory system, respiratory diseases, external causes, and a category "all other," regrouping all deaths not included in the previous categories.

Modeling approach and methodology

"What-if" type of scenarios for biometric risk translate into the need for hypothetical scenarios for one or more causes of death. Consequently, they require modeling at a granular cause-specific level, which is subject to the competing risk framework to consider the dependence between the causes.

Using the framework of Archimedean copula developed by Li and Lu (2019), projections of the mortality intensities by cause of death are obtained by allowing dependence among competing risks within cohorts. For mortality and longevity impact assessment, a two-level structure hierarchical Archimedean copula with nine causes of death is applied (see Figure 3). Five cancer sites (lung, pancreas, colon, and prostate for males and breasts for females and a category regrouping all other cancers) are modeled in the lower-level cluster together with the cardiovascular diseases. The higher level is composed of the cluster regrouping the cancer sites and the cardiovascular diseases, and of the respiratory diseases, external causes, and a category combining all the other causes that have not been accounted for. The technical details of this approach are discussed in Appendix 2.

Figure 3: The hierarchical structure of HAC for mortality and longevity impact assessment.

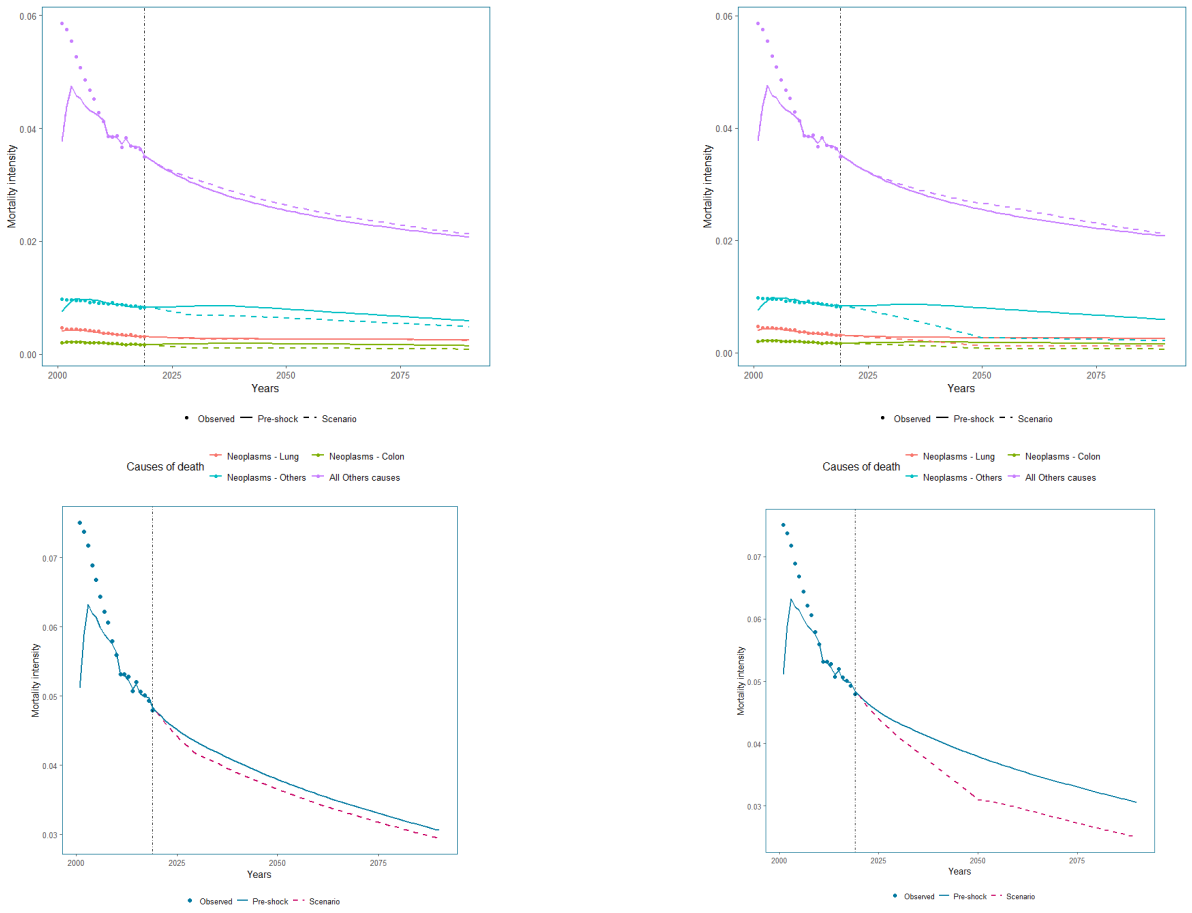


Based on the estimated stochastic mortality model, pre-shock marginal mortality intensities for each cause and cohort are projected. Scenarios 1 and 2 are applied to marginal cancer-specific mortality intensities, i.e., lung, colon, breast (for females), and other neoplasms. Scenario 1 models the impact of early multiple cancer detection, assuming cancer pre-shock mortality reduction after a 10-year horizon of 19% for lung, 43% for colon, 51% for breast, and 23% for other cancers, while pancreas and prostate cancer survival remain unchanged. Scenario 2 assumes a reduction of 75% of cancer mortality within the next 30 years.

Lastly, the resulting post-shock mortality intensities for each cause and cohort are obtained. The aggregate future mortality improvements (separately for mortality and longevity businesses, by age and gender) resulting from scenarios 1 and 2 are deduced. These improvements are used to compute the financial impact on the PV claims of both scenarios.

Figure 4 illustrates the pre- and post-shock mortality intensities by each cause (top panel) and in aggregate (bottom panel) for the mortality of insured U.K. male population (age 80) for scenarios 1 and 2, respectively. As dependence among competing risks is accounted for, gains in life expectancy resulting from the reduction or elimination of cancer-specific mortality are dampened by the increase of mortality from the other causes of death.

Figure 4: Mortality intensities by cause (top) and on aggregate (bottom) for U.K. insured male population proxy age 80, for scenario 1 (left) and scenario 2 (right).



No behavioral change, such as lapses and adverse selection in the mortality or critical illness book, was included in the analysis. We believe it is unlikely that many policyholders would lapse their policies due to the lowered cancer risk, as it is only one of the possible causes of death or critical illness. There may be some additional lapses of short-duration policies with policyholders who, especially at younger ages, might be able to buy a cheaper new policy. This suggests that there is a possibility that the scenario impacts might be slightly overestimated.

Business Impact

Based on the results from the model described in the previous section, we have computed the financial impact on the present value (PV) of claims under the two footprint cancer scenarios. The impact varies among different lines of business for life and health insurance. Table 3 summarizes how each line of business would be impacted.

Table 3: Potential impact of Scenario 1 and 2 on main lines of business

Line of Business	Scenario 1	Scenario 2
Mortality	+++ Large Positive Impact	+++ Large Positive Impact
Longevity	- - - Large Negative Impact	- - - Large Negative Impact
Long Term Care	- Small Negative Impact	- - - Large Negative Impact
Critical Illness*	- Small Negative Impact	+++ Large Positive Impact

** For CI markets covering stage I thyroid cancer as major condition.*

Both Scenario 1 and 2 would result in a gain in life expectancy, leading to a substantial positive impact on the mortality business. Cancer is the leading cause of premature death. Eliminating these deaths has a significant impact in terms of years of life saved, and thus a longer premium payment and a significant claims impact on term insurance products. The impact of Scenario 2 is much stronger than Scenario 1.

On the contrary, longevity business will be negatively impacted due to the longer lifespan of the insured. Compared with the mortality business, however, the impact on the longevity business is lower because the average age of the longevity portfolio is higher. When cancer mortality is reduced or prevented, people at high ages are more likely to die from other causes of death. The number of years of life gained is smaller, leading to an overall lower impact on longevity.

For critical illness business, the impact of Scenario 1 varies significantly among the markets, depending on the coverage of early-stage thyroid cancer. For markets covering stage I thyroid cancer under major conditions, the overall impact is slightly negative since the over-diagnosis of thyroid cancer outweighs the reduction from pre-cancers. For other markets, detection of pre-cancer leads to lower cancer incidence and, thus, a positive impact on CI. Scenario 2 has a large favorable financial impact on CI since the cancer incidence rate will be reduced by 75% over the next 30 years.

For long-term care (LTC) business, both scenarios would impact the incidence and termination rates, i.e., the onset of loss of autonomy and the mortality of individuals with cancer in LTC. In Scenario 1, the incidence rate for cancer claims decreases by more than 20%, which results in a lower proportion of cancer claims among all LTC claims. Cancer claims have a much higher termination rate compared with other pathology. When cancer claims are replaced by claims from other pathology, there will be more claims with longer duration. The overall termination rate

becomes lower, leading to a negative impact on LTC business. In Scenario 2, both the incidence rate for cancer claims and the mortality rate for people with cancer were reduced by half. The joint impact of lower cancer incidence and mortality increases liabilities in LTC.

Closing Remarks

The pandemic has positively impacted some medical innovations. It has not only accelerated funding for innovators but also has brought unprecedented collaboration among pharmaceutical companies in developing a COVID-19 vaccine and rapidly bringing it to market. In addition, regulatory processes have been streamlined to make it easier to get diagnostic tests and therapies to market more quickly. As a result, new preventive and curative advances may emerge at an exponential pace in the near future.

Biopharmaceutical companies will continue to develop new ways to prevent, detect, monitor, treat, and possibly cure a range of cancers through vaccines and advancements in cell and gene therapies. At the same time, actionable health insights driven by radically interoperable data and smart artificial intelligence could help clinicians and consumers identify cancerous cells much earlier than today.

Our exploratory research demonstrated the power of robust new technological development available in the healthcare industry. It is crucial for (re)insurers to closely monitor these developments and integrate them into their enterprise and risk management. SCOR plans to continuously develop further scenarios that provide real insight into how insurers' in-force portfolio behaves in a range of possible future outcomes.

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Appendix 1. Assumptions for cancer incidence and mortality under Scenario 1

The impact of Scenario 1 on cancer mortality and incidence rate is calculated based on the following assumptions:

i. Earlier detection will shift late-stage cancers (stage 3 & 4) to early stages (stage 1 & 2).
   - Stage 3: 30% shift to stage 1, 30% to stage 2, 40% remain as stage 3
   - Stage 4: 20% shift to stage 2, 30% to stage 3, 50% remain as stage 4

This assumption reduces cancer mortality rates but does not affect cancer incidence rates.

ii. For cancers at pre-cancer stage, earlier detection shifts 50% of stage 1 and 2 cancers to pre- cancer stage.
   - Selected cancer sites: breast, cervix, colon, prostate (excluding stage 1), bladder
   - Once detected, pre-cancers would be treated and would not progress to cancer.
   - Mortality rate for pre-cancers is set at zero

This assumption reduces both cancer mortality rates and incidence rates.

iii. Earlier detection does not affect the mortality rate of thyroid, prostate, and pancreas cancers.

iv. Earlier detection increases the overall cancer incidence rate by 10%, to include in the people with undiagnosed indolent cancer. Prostate and thyroid are not part of this assumption. Separate analysis is performed for thyroid cancer,

v. The progress in risk detection over the next 10 years leads to incidence and mortality reduction. After this 10-year horizon of improvement, the age-specific incidence and mortality rates due to cancer are expected to keep their pre-shock estimated dynamic.

vi. To estimate the impact of thyroid cancer, we have set the assumptions as follows:

   A. Ultimate level of thyroid cancer: It is estimated to be 15 times the peak incidence level of thyroid cancer in Korea, under the assumption that the test is highly sensitive and could detect over 90% of indolent thyroid cancer in the population.

   B. Business mix: coverage on thyroid cancer differs by country and keeps on evolving over-time. The calculation is based on SCOR's CI portfolio and may not be applicable to other companies.

Appendix 2. Modeling cause-of-death mortality using Archimedean copula

This section introduces the necessary notations, assumptions and the competing risks model based on Archimedean copula from Li and Lu (2019).

Mortality intensities and joint survival times

The concepts of crude and net mortality are introduced hereafter followed by the assumptions regarding the dependence structure between the survival variables.

Each individual in a population is assumed to be exposed to m causes of death and may deceased from any single one of these causes. The total lifetime of an individual, T, is given by the minimum of the m cause-specific lifetimes as:

$$T=\min(T_1,...,Tm).$$

In the competing risk framework, the observed cause of death is then the one corresponding to the minimum of the m stochastic lifetimes associated with the causes of death.

The all-causes (aggregate) mortality intensity is the instantaneous probability of death before time $t+u$ for an individual who already lived t years for small interval u:

$$\mu(t) = \lim_{u\to 0} \frac{\mathbb{P}(T \le t+u | T > t)}{u}.$$

For a specific cause, the **crude mortality intensity** $\mu_j(t)$ is the instantaneous probability of death if only one cause j exists, given the individual survives t years:

$$\mu_j(t) = \lim_{u\to 0} \frac{\mathbb{P}(T \le t+u, J=j | T > t)}{u}.$$

The crude cause-specific mortality intensities $\mu_j(t), j=1,...,m$, sum up to the aggregate mortality intensity:

$$\mu_1(t) + \cdots + \mu_m(t) = \mu(t).$$

And the observed (crude) survival function is given by the sum of the cause-specific mortality intensities:

$$S(t) = \exp\left(-\int_0^t \mu(s)ds\right) = \exp\left(-\int_0^t \sum_{i=1}^m \mu_i(s)\,ds\right).$$

The **net survival** function of cause T_j is the survival if the risks of death other than the cause j were removed,

$$S_j(t) = \mathbb{P}[T_1 > 0, \dots, T_j > t, \dots, T_m > 0] = \exp\left(-\int_0^t \lambda_j(s)ds\right),$$

where $\lambda_j(t)$ is the net cause-specific intensities of T_j. When studying a hypothetical scenario on a cause of death j, the net cause-specific intensities $\lambda_j(t)$ can be modified to reflect the excess or deficit mortality resulting from adverse events or future medical innovations affecting this specific cause. It is defined by

$$\lambda_j(t) = \lim_{u\to 0} \frac{\mathbb{P}(T_j \le t+u | T_j > t)}{u} = -\frac{\mathrm{d}}{\mathrm{d}t}\log S_j(t).$$

However, the cause-specific $P(T_j \le t+u \mid T_j > t)$ cannot be, in general, estimated from data as only $P(T \le t+u, J=j \mid T>t)$ is observed. In estimating the net mortality intensity, the **joint distribution of the survival times** $(T_1,...,T_m)$ denoted by $S(t_1,...,t_m)$ should then be considered:

$$S(t_1, \dots, t_m) = \mathbb{P}[T_1 > t_1, \dots, T_m > t_m].$$

The joint distribution of the survival times is related to the crude cause-specific mortality intensities:

$$\mu_j(t) = -\frac{\vartheta}{\vartheta t_j}\log \mathbb{P}[T_1 > t_1, \dots, T_m > t_m]\,|_{t_1=\cdots=t_m=t}.$$

(1)

However, due to the presence of the competing risks, it is impossible to identify the exact dependency structure between the survival times $T_1,...,T_m$ and additional assumptions must be made, see Tsiatis (1975).

Chiang (1968) proposed to consider the causes being independent, greatly simplifying the modeling which turns out to be very popular, see Prentice et al. (1978), Wilmoth (1995), Putter et al. (2007) and Boumezoued et al. (2018, 2019) among others. Under the assumption that the survival times are independent, net and crude cause-specific mortality intensities are equal but this *"may have no resemblance to reality"* as quoted by Tsiatis (1975).

To coherently assess the expected mortality patterns in hypothetical conditions when some causes of death are modified or eliminated, other modeling must be used. One popular approach is to model dependence with survivor copula. In the following of this study, cause-specific mortality is modelled with **Archimedean survivor copula** as suggested by Li and Lu (2019).

Modeling mortality scenarios using Archimedean survivor copula

The approach assumes that the survival times $(T_1,...,T_m)$ have a joint Archimedean survivor copula. The joint distribution writes:

$$\mathbb{P}[T_1 > t_1, \dots, T_m > t_m] = \psi\left(\psi^{-1} \circ S_1(t_1) + \cdots + \psi^{-1} \circ S_m(t_m)\right), \quad \forall t_1, \dots, t_m > 0,$$

where the symbol ○ represents the composition of functions and ψ the generator function. In the numerical applications, the Clayton copula is used. Li and Lu (2019) also provide illustrations with the Frank copula.

The Clayton copula is obtained by assuming $\psi(t)=(1+t)^{-1/\theta}$ where θ is a parameter that captures the dependence. The higher the value of θ, the stronger positive dependence between the survival times. When θ approaches 0, the copula reduces to the independent copula.

In a Clayton copula, the joint distribution of the survival times is

$$S(t_1, \dots, t_m) = \left[S_1(t_1)^{-\theta} + \cdots + S_m(t_m)^{-\theta} - m + 1\right]^{-1/\theta}.$$

(2)

If the joint survivor copula is Archimedean with generator ψ, Li and Lu (2019) have shown that the net survival function can be determined by the copula and the crude cause-specific mortality intensities:

$$S_j(t) = \psi\left[-\int_0^t \frac{\exp\left(-\int_0^t \sum_{i=1}^m \mu_i(u)\,\mathrm{d}u\right)}{\psi' \circ \psi^{-1} \circ \exp\left(-\int_0^t \sum_{i=1}^m \mu_i(u)\,\mathrm{d}u\right)} \mu_j(s)\mathrm{d}s\right], \quad \forall j = 1, \dots, m.$$

(3)

The assumption of symmetric dependence among the causes of death may be too restrictive and can be relaxed with the introduction of hierarchical Archimedean copula (HAC). For mortality and longevity impact assessment, a two-level structure HAC with 9 causes of death is applied. 5 cancer sites (lung, pancreas, colon, prostate for males and breasts for females and a category regrouping all other cancers) are model in the lower-level cluster together with the cardiovascular diseases. The higher level is composed of the cluster regrouping the cancer sites and the cardiovascular diseases, and of the respiratory diseases, external causes and a category combining all the others causes that have not been accounted for.

In this model, the joint distribution of $(T_1,T_2,T_3,T_4,T_5,T_6,T_7,T_8,T_9)$; where 1 = Lung cancer, 2 = Pancreas cancer, 3 = Colon cancer, 4 = Prostate cancer, 5 = Other cancers, 6 = Circulatory, 7 = Respiratory, 8 = External and 9 = All others, satisfies

$$\begin{aligned}\mathbb{P}[T_1 > t_1, \dots, T_9 > t_9] &= \psi_{1:9}\left(\psi_{1:9}^{-1} \circ \mathbf{S}_{1,2,3,4,5,6}(S_1(t_1), \dots, S_6(t_6)) + \psi_{1:9}^{-1} \circ S_7(t_7) + \psi_{1:9}^{-1} \circ S_8(t_8)\right. \\ &\quad \left. + \psi_{1:9}^{-1} \circ S_9(t_9)\right)\end{aligned}$$

where the function $\mathbf{S}_{1,2,3,4,5,6}$ is given by

$$\mathbf{S}_{1,2,3,4,5,6}(u_1, \dots, u_6) = \psi_{1,2,3,4,5,6}\left(\psi_{1,2,3,4,5,6}^{-1}(u_1) + \cdots + \psi_{1,2,3,4,5,6}^{-1}(u_6)\right)$$

At the lower level, the joint distribution of $(T_1,T_2,T_3,T_4,T_5,T_6)$, the times at deaths of the cancer sites and cardiovascular diseases have an Archimedean copula with generator $\psi_{1,2,3,4,5,6}$ whereas at the higher level, the dependence between the clusters $(T_1,T_2,T_3,T_4,T_5,T_6)$ and T_7,T_8,T_9 is captured by another generator $\psi_{(1:9)}$.

Under the HAC model described above, the net survival function $S_j(t)$ for each j is uniquely determined by

$$S_j(t) = \psi_{1:9}\left[-\int_0^t \frac{\exp\left(-\int_0^t \sum_{i=1}^9 \mu_i(u)\,\mathrm{d}u\right)}{\psi'_{1:9} \circ \psi_{1:9}^{-1} \circ \exp\left(-\int_0^t \sum_{i=1}^9 \mu_i(u)\,\mathrm{d}u\right)} \mu_j(s)\mathrm{d}s\right], \quad \forall j = 7,8,9.$$

$$S_j(t) = \psi_{1,2,3,4,5,6}\left[-\int_0^t \frac{\mathbb{S}_{1,2,3,4,5,6}(s)}{\psi'_{1,2,3,4,5,6} \circ \psi_{1,2,3,4,5,6}^{-1} \circ \mathbb{S}_{1,2,3,4,5,6}(s)} \mu_j(s)\mathrm{d}s\right], \quad \forall j = 1, \dots, 6.$$

where

$$\mathbb{S}_{1,2,3,4,5,6}(t) = \psi_{1,2,3,4,5,6}\left[-\int_0^t \frac{\exp\left(-\int_0^t \sum_{i=1}^6 \mu_i(u)\mathrm{d}u\right)}{\psi'_{1,2,3,4,5,6} \circ \psi_{1,2,3,4,5,6}^{-1} \circ \exp\left(-\int_0^t \sum_{i=1}^6 \mu_i(u)\mathrm{d}u\right)} \sum_{i=1}^6 \mu_i(s)\,\mathrm{d}s\right].$$

Using this last result, the procedure of estimating the net mortality intensities and forecasting the mortality is described below.

First, the crude mortality intensities $\mu_{(j,c,t)}$ for each cause of death j, cohort c and calendar year t are obtained by

$$\mu_{j,c,t} = \frac{D_{j,c,t}}{E_{j,c,t}}, \quad \forall j = 1, \dots, m,$$

where $D_{(j,c,t)}$ and $E_{(j,c,t)}$ are the corresponding number of death and exposure, respectively.

Second, the marginal intensities are derived from the net survival functions $S_{(j,c)}(t)$:

$$\lambda_{j,c,t} = -\log \frac{S_{j,c}(t)}{S_{j,c}(t-1)},$$

where the marginal survival function $S_{(j,c)}(t)$ are obtain from the crude intensity of each.

Third, the Lee and Carter (1992) model is used to forecast the pre-shock marginal intensities for each cause of death separately.

Fourth, scenarios 1 and 2 are applied on the marginal specific cancer sites mortality intensity.

Fifth, after projecting the net intensities and applied a shock of the net cancer sites mortality intensity, the reverse reasoning is applied to recover the corresponding post-shock crude intensities. The latter are then used to obtain the aggregate future mortality improvements resulting from the scenario. These improvements are used to compute the financial impact on the PV claims.

Factors influencing the outcome

The magnitude of the shock on cancer-specific mortality and its horizon is set by expert judgement. These scenario assumptions are not the only factors to influence the resulting post-shock aggregate future mortality improvements.

The within-cohort dependence among the causes of death in the copula framework is another parameter set by expert judgement. The current modeling assumes a strong dependency between cancers and cardiovascular diseases and a weaker dependency on respiratory, external (non-medical) and other causes of death.

The pre-shock cancer specific mortality forecast is also influencing the outcome. In a general manner, the smaller the improvement is, the larger the number of deaths saved from dying of cancer, and the larger the potential impact of an improvement scenario.

The pre-shock mortality projection of the other causes at high ages also affects the result. To the extent other causes, such as cardiovascular or Alzheimer's and dementia diseases, have a high mortality, the impact of a shock on cancer mortality would be relatively small. Individuals would die of cardiovascular or Alzheimer's and dementia diseases shortly after being saved from cancer.

Finally, the shape of the mortality at very high ages, i.e., the completion assumption of the mortality table, is influencing the outcome as it defines the survival time of individuals saved from dying of cancer.

Appendix 2 References

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