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On the relationship between aging, medical progress and age-specific health care expenditures

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Abstract

This paper investigates the impact of population aging, driven by medical progress, upon age-specific expenditure on health care. In a model set up in discrete time, individuals at each age may catch a lethal disease which, upon receiving appropriate medical treatment, nevertheless involves a mortality risk such that length of life is stochastic. The incidence of lethal diseases, the associated survival probability conditional upon treatment, and health care expenditure conditional upon health status may all depend on an individual´s history. For a given age, the history of an individual contains information on her health status in the past.

Medical progress is taken to involve an increase in the survival probability of a specified lethal disease. On the one hand, this produces a direct effect on age-specific health care expenditure to the extent that progress affects the cost of treatment of the disease. On the other hand, indirect effects may also arise. These effects are caused by individuals who, having survived the disease at some prior age due to progress, change the structure of individuals alive at current age. Specifically, the “new survivors” may have an influence on age-specific expenditure either through changes in the incidence of lethal diseases or in the associated treatment cost. The sign of an indirect effect crucially depends on health care expenditure for “new survivors” *relative* to their peers.

The analysis yields a number of general results which are important for the discussion of the impact of medical progress on the age profile of health care expenditure. Compression of morbidity, to the extent that it involves a reduction in age-specific expenditure, is neither necessary nor sufficient for medical progress to produce a downward shift of the profile. A similar observation applies to an expansion of morbidity. Both concepts relate to “new survivors” and, thus, take into account only indirect effects of progress.

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1. Introduction

Aging of the population is a well-known phenomenon currently under way in most developed countries. A declining overall birth rate, coupled with reductions in age-specific mortality rates, has fuelled a process of double aging over the last decades which led to substantial changes in the age composition of the population. It seems safe to assume that this process will carry on in the future.[1] In particular, advances in medical technology are projected to reduce age-specific mortality further and particularly so in higher age classes.

What is the impact of an aging population on the demand for health care and on health care expenditure? A substantial body of research has evolved in the recent past in order to address these issues.[2] The answers are important not only for the future evolution of the health care system but also for the financing and, in particular, the sustainability of social health insurance.

The traditional approach to forecasting health care expenditures under conditions of demographic change is simple: A *given expenditure profile*, i.e., a vector of age-specific health care expenditure, preferably containing most recent data, is combined with the age structure of the population as projected for a future year.[3] Thus, one obtains health care expenditure in a future year, with the change to the current year being due to demographic change *by itself*.[4] More specifically, since cross-sectional data indicate that age-specific expenditure rises sharply with age, the approach implies aging of the population to produce an increase in per capita expenditure.

However, the traditional approach has come under attack for being naïve.[5] Essentially, the main criticism runs as follows: Aging of the population cannot occur by itself but must relate to a cause, e.g., medical progress, an increase in preventive activities through better lifestyles or some other reason. Now any factor which has an influence upon the age structure is also likely to produce changes in age-specific expenditure on health care, albeit in a less obvious manner.[6] If that is true, both the significance and the usefulness of the traditional approach may be questioned.

Medical progress provides a staple example. Advances in medical technology may lead to reductions in the mortality of patients from specific conditions, thus contributing to or even driving the process of population aging. This raises two issues which are relevant for the impact on age-specific health care expenditure. First, the change in treatment strategy may affect the cost of treatment.[7] Second, increases in longevity produce "new survivors" who may consume different amounts of health care in comparison with their peers.

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[1] For the OECD countries cf. Lafortune et al. (2007), S. 11ff. For Germany, cf. Federal Statistical Office (2006).
[2] Surveys are provided by Newhouse (1992), Technical Review Panel (2000) and Westerhout (2006).
[3] E.g., cf. Abel-Smith/Titmuss (1956) for an early application, as well as Dang et al. (2001).
[4] Cf. Reinhardt (2003: 30).
[5] Cf. Breyer/Felder (2006).
[6] This is certainly true of the two factors just mentioned. For a general analysis along these lines, cf. Richardson (2004).
[7] Cf. Technical Review Panel (2000: pp. 28-37).

For the second issue, the literature offers competing views with respect to the impact on the expenditure profile. According to Fries, the rise in length of life mainly provides an individual with additional healthy time. Thus, medical progress involves a *compression of morbidity* over the – extended – life-cycle such that a decline in age-specific morbidity comes about.[8] Taking the opposite stance, Gruenberg and Verbrugge suggested that increases in life expectancy primarily will be spent as sick time.[9] In their view, medical progress leads to an *expansion of morbidity*, producing a rise in age-specific morbidity.

As time elapses, the two views can be taken to imply shifts of the health care expenditure profile which occur in opposite direction. The available empirical evidence on this issue appears to be mixed. To some extent, improvements in age-specific health status seem to have taken place.[10] On the other hand, expenditure profiles usually have shifted upwards in the recent past.[11]

Another line of argument stresses the significance of time to death rather than age.[12] The "cost of dying" approach is based on the observation that, for each age, per capita expenditure on health care for decedents by far exceeds the corresponding expenditure for survivors.[13] As the population ages, the relative number of decedents at each age will decline. Hence, ceteris paribus population aging tends to reduce age-specific expenditure on health care. In recent years, several projections have taken this effect into account, yielding lower expenditure figures than the traditional approach.[14]

The main objective of the present paper is to investigate the impact of medical progress on age-specific health care expenditure by means of a theoretical model. More specifically, progress is taken to reduce mortality and, thus, to drive the process of population aging. In contrast to the bulk of the literature, however, health care expenditure is linked explicitly to health status. More precisely, the following analysis relies on the simple notion that the treatment decision can only depend on information which is available at the time a decision must be taken: An individual´s current health status and possibly his history of health status in prior periods as well. A similar statement applies to expenditure on health care.

Therefore, at any age, per capita expenditure on health care depends on the distribution of health status and the associated treatment cost. It follows that the model is able to capture both effects of medical progress on age-specific expenditure mentioned above. In particular, changes in the distribution of health status due to the presence of "new survivors" in later periods are taken into account.

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[8] Cf. Fries (1980), Fries (1983) and Fries (2000).
[9] Cf. Gruenberg (1977), Verbrugge (1984).
[10] Cf. Dinkel (1999), Cutler (2001), Busse et al. (2002).
[11] Cf. Technical Review Panel (2000), Reinhardt (2003), Buchner/Wasem (2006). In some contrast, Seshamani and Gray show that this has not been true for England and Wales, cf. Seshamani/Gray (2004).
[12] Cf. Fuchs (1984), Zweifel et al. (1999), Stearns/Norton (2004), Breyer/Felder (2006), Werblow et al. (2007).
[13] The only exception being very old age, i.e., ages above 85 or even 90 years.
[14] Cf. Stearns/Norton (2004), Breyer/Felder (2006).

The paper is organized as follows. Section 2 presents the theoretical model. In section 3, after a description of medical progress, I derive two kinds of effects on age-specific expenditure on health care. Section 4 gives a discussion of the results while the last section concludes.

2 The model

2.1 Building blocks

This section sets up a model which will serve later to analyze the impact of medical progress. The focus is on mortality, i.e. morbidity-related health outcomes will not be addressed explicitly. In each period of calendar time, members of a new generation are born who *may* live for a maximum number of Ω periods. Actual length of life is stochastic, however, because an individual faces a mortality risk in each period. This probability of dying is generated by two factors of influence: The probability of catching a lethal disease, i.e. a disease which involves a certain risk of dying, and the probability that the patient does not survive appropriate medical treatment.

A basic assumption is that the important variables of interest do not change over time. Hence, a long-term view is adopted which relates to a stationary state such that members belonging to different generations all face the same parameter values over their lifetime. It follows that, when referring to a member of a particular generation, it suffices to specify her age while it is not necessary to account for calendar time explicitly.

As explained in the introduction, the main objective is to model age-specific expenditures on health care. Therefore, it is not necessary to account for the number of births or the number of individuals within a cohort over time.

Each individual is born at the beginning of a period and will die either at the end of the first or some later period. As mentioned above, lifetime T of a member of a generation will be taken not to exceed an upper bound Ω:[15]

(1) $$1 \le T \le \Omega .$$

At each age, an individual may catch a lethal disease. In total, there are n such diseases. Moreover, it is also possible that no lethal disease occurs. Hence, an individual´s health status within a period t of her lifetime can be represented by a variable D_t which satisfies:

(2) $$D_t \in \{d_{1,t};...;d_{n,t};d_{n+1,t}\};\quad 1 \le t \le \Omega .$$

Specifically, $d_{j,t}$ denotes the event that health status d_j turns up at age t. More precisely, for $1 \le j \le n$ the index j is taken to indicate a lethal disease whereas d_{n+1} denotes the absence of such a disease. Note that the latter status may also involve a disease albeit one that never results in the death of the individual.

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[15] Ω can be interpreted as an upper bound upon length of life imposed by biological limitations, cf. Fries (1980), p. 130f.

An important feature of the model is that previous lethal diseases may exert an impact on the individual as well as on health care expenditure at a later age. To be sure, this presupposes that medical treatment of those diseases has been successful. More specifically, the *history* of an individual contains information upon her health status at each prior age. For a later life period t, the set H_t of all histories of an individual who is *still alive* is given by:

(3a) $$H_t = D_1 \otimes D_2 \otimes ... \otimes D_{t-1}.$$

A specific history h_t is an element of the set H_t which can be represented by a vector of dimension t-1.[16] Its i-th component $h_{t,i}$ denotes health status at a prior age i. Furthermore, let $h_{t,-[i,t-1]}$ denote the first i-1 components of the vector h_t. Intuitively, the vector $h_{t,-[i,t-1]}$ represents that part of an individual´s history h_t which includes the first periods of her life up to period i-1:

(3b) $$h_{t,-[i,t-1]} = \left(h_{t,1}\ h_{t,2}\ ...\ h_{t,i-1}\right).$$

The next task is to define the incidences of lethal diseases as well as the corresponding survival probabilities. With respect to lifetime, observe that the first and the last period Ω represent special cases, albeit for different reasons. In the first period, by definition no history is available for an individual. On the other hand, lifetime cannot exceed Ω by assumption. Another assumption is that an individual always receives medical care as is appropriate for his health status. Specifically, in the case of lethal disease, the associated survival probability always reflects the prevailing state of medical knowledge.

In the first period, the incidences of lethal diseases satisfy:

(4a) $$0 \langle\ \rho\left(d_{k,1}\right) \langle\ 1; \quad 1 \le k \le n; \quad \sum_{k=1}^{n} \rho\left(d_{k,1}\right) \langle\ 1.$$

This implies for the probability of the absence of such a disease:

(4b) $$\rho\left(d_{n+1,1}\right) = 1 - \sum_{k=1}^{n} \rho\left(d_{k,1}\right) \rangle\ 0.$$

If a lethal disease strikes, there is a mortality risk whereas the complementary state $d_{n+1,1}$ involves no such risk:

(4c) $$\begin{array}{ll} 0 \langle\ e\left(d_{k,1}\right) \langle\ 1 & 1 \le k \le n \\ e\left(d_{k,1}\right) = 1 & k = n+1 \end{array}.$$

In every later period, survivors exhibit a history which may influence both the incidence of health status and the probabilities of survival in the case of a lethal disease. As long as the last period is not reached, it is again possible that no lethal disease turns up. For every history $h_t \in H_t$, the incidences of the lethal diseases are taken to satisfy:

(5a) $$0 \langle\ \rho\left(d_{k,t} \middle| h_t\right) \langle\ 1; \quad k = 1,...,n; \quad \sum_{k=1}^{n} \rho\left(d_{k,t} \middle| h_t\right) \langle\ 1; \quad 2 \le t \le \Omega - 1.$$

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[16] Observe that $2 \le t \le \Omega$ must hold because no history exists in the first period of life.

This implies for the probability of the absence of such a disease:

(5b) $$\rho\left(d_{n+1,t}\middle|h_t\right)=1-\sum_{k=1}^{n}\rho\left(d_{k,t}\middle|h_t\right)\rangle\ 0;\quad 2\le t\le\Omega-1\,.$$

Likewise, the survival probabilities now depend on the history of prior health status but otherwise are restricted in the same manner as in the first period:

(5c) $$\begin{matrix} 0\ \langle\ e\left(d_{k,t}\middle|h_t\right)\langle\ 1 \quad 1\le k\le n \\ e\left(d_{n+1,t}\middle|h_t\right)=1 \end{matrix};\quad 2\le t\le\Omega-1\,.$$

In the last period, the assumptions require some modification for reasons of consistency. More precisely, each individual will be taken to catch a lethal disease which she cannot survive. Thus, for every $h_\Omega\in H_\Omega$, the incidences of the lethal diseases satisfy:

(6a) $$0\ \langle\ \rho\left(d_{k,\Omega}\middle|h_\Omega\right)\langle\ 1;\quad k=1,\dots,n;\quad \sum_{k=1}^{n}\rho\left(d_{k,\Omega}\middle|h_\Omega\right)=1\,.$$

In addition, the restriction on the associated survival probabilities is given by:

(6b) $$e\left(d_{k,\Omega}\middle|h_\Omega\right)=0;\quad 1\le k\le n\,.$$

Taken together, the assumptions introduced up to now imply that Ω represents maximum length of life.[17]

For a description of the distribution of health status in a later period t, it is also necessary to take into account the conditional probabilities of the possible histories. More precisely, the condition is given by survival up to the period under consideration. Obviously, these probabilities can be calculated by means of the parameters introduced above. More specifically, one obtains for the probability of a history $h_t\in H_t$ (with $t\ge 2$):

(7a) $$P(h_t)=\rho\left(h_{t,1}\right)\cdot e\left(h_{t,1}\right)\cdot\prod_{i=2}^{t-1}\rho\left(h_{t,i}\middle|h_{t,-[i,t-1]}\right)\cdot e\left(h_{t,i}\middle|h_{t,-[i,t-1]}\right).$$

In all, there are $(n+1)^{t-1}$ histories relating to a period t. The probability of survival up to this period is given by:

(7b) $$P(T\ge t)=\sum_{h_t\in H_t}P(h_t).$$

Applying Bayes´ theorem, the conditional probability of a history is defined by:

(7c) $$P\left(h_t\middle|T\ge t\right)=\frac{P(h_t)}{P(T\ge t)}\,.$$

This is the probability that an individual who survives up to the present period t has the history h_t.

[17] The assumptions introduced so far imply constant age-specific mortality rates. If, in addition, age-specific birth rates are constant as well and no migration occurs, the population converges to a stable age structure in the long run, cf. Mueller (2000). For the analysis below, however, it is not necessary to impose further restrictions.

Observe that these conditional probabilities are very important for a description of the distribution of the relevant variables with respect to age. Consider the incidence of health status in a later period t. The probability of a history $h_t \in H_t$ and a health status d_k is given by:

(8a) $$P(d_{k,t}; h_t | T \geq t) = P(h_t | T \geq t) \cdot \rho(d_{k,t} | h_t).$$

This implies for the overall incidence at age t:

(8b) $$\rho(d_{k,t} | T \geq t) = \sum_{h_t \in H_t} P(d_{k,t}; h_t | T \geq t) = \sum_{h_t \in H_t} \rho(d_{k,t} | h_t) \cdot P(h_t | T \geq t).$$

The probabilities $\rho(d_{k,t} | T \geq t)$ are similar to the incidences $\rho(d_{k,1})$ for the first period. However, as (8b) shows, in a later period it is necessary to take into account the structure of individuals with respect to history.

In the first period, expenditure on health care only depends on current health status and is denoted by $L(d_{k,1})$. In a later period t, history may become relevant. Let $L(d_{k,t} | h_t)$ denote health care expenditure for an individual with health status d_k conditional upon history h_t.

2.2 Age-specific expenditure on health care

In general, the age profile of expenditure on health care in the present model is derived from expected expenditure in each period. For the first period, this is given by:[18]

(9a) $$E_1(L_1) = \sum_{k=1}^{n+1} \rho(d_{k,1}) \cdot L(d_{k,1}).$$

In every later period, the structure of individuals with respect to history needs to be taken into account as well. For expected health care expenditure, conditional upon a given history, one obtains:

(9b) $$E_t(L_t | h_t) = \sum_{k=1}^{n+1} \rho(d_{k,t} | h_t) \cdot L(d_{k,t} | h_t).$$

This implies for expected health care expenditure in a later period:

(9c) $$E_t(L_t | H_t) = \sum_{h_t \in H_t} P(h_t | T \geq t) \cdot E_t(L_t | h_t).$$

In order to prepare for the analysis of medical progress below, it is useful to consider several ways of decomposing expected health care expenditure for a later period t. This is done by adding further conditions, apart from survival up to that period. What does this imply for the incidence of health status and expected health care expenditure at the current age? Since the values of these variables, conditional upon history, are given by assumption, an influence may operate only through a change in the conditional probabilities of the histories themselves.

[18] The subscript „t“ is added to the expectation operator to indicate that expected value is taken at the beginning of period t, i.e., before current health status is revealed.

Suppose an individual of age t has survived the lethal disease m in a prior period j. This implies that her history satisfies $h_{t,j} = d_{m,j}$. The total probability that a history relating to the current age t satisfies this condition is given by:

(10a) $$P\left(h_{t,j} = d_{m,j} \middle| T \geq t\right) = \sum_{\substack{h_t \in H_t \\ h_{t,j} = d_{m,j}}} P\left(h_t \middle| T \geq t\right).$$

Applying Bayes´ theorem, one obtains for the conditional probability of a history which includes the lethal disease m in the prior period j:

(10b) $$P\left(h_t \middle| T \geq t; h_{t,j} = d_{m,j}\right) = \frac{P\left(h_t \middle| T \geq t\right)}{P\left(h_{t,j} = d_{m,j} \middle| T \geq t\right)}.$$

Any other history satisfies the complementary condition $h_{t,j} \neq d_{m,j}$ and, thus, cannot occur as long as one imposes $h_{t,j} = d_{m,j}$.

Given the additional condition $h_{t,j} = d_{m,j}$, the incidence of health status in the current period is defined by:

(10c) $$\rho\left(d_{k,t} \middle| T \geq t; h_{t,j} = d_{m,j}\right) = \sum_{\substack{h_t \in H_t \\ h_{t,j} = d_{m,j}}} \rho\left(d_{k,t} \middle| h_t\right) \cdot P\left(h_t \middle| T \geq t; h_{t,j} = d_{m,j}\right), \quad 1 \leq k \leq n+1.$$

In turn, this implies for expected health care expenditure at age t:

(10d) $$E_t\left(L_t \middle| H_t; h_{t,j} = d_{m,j}\right) = \sum_{\substack{h_t \in H_t \\ h_{t,j} = d_{m,j}}} P\left(h_t \middle| T \geq t; h_{t,j} = d_{m,j}\right) \cdot E_t\left(L_t \middle| h_t\right).$$

Likewise, for an individual of age t who did not catch the lethal disease m in a prior period j, one obtains for the total probability of her history satisfying the condition that the lethal disease did not turn up in a prior period j:

(11a) $$P\left(h_{t,j} \neq d_{m,j} \middle| T \geq t\right) = \sum_{\substack{h_t \in H_t \\ h_{t,j} \neq d_{m,j}}} P\left(h_t \middle| T \geq t\right).$$

Then, Bayes´ theorem implies for the conditional probability of a history which does not include the lethal disease m in the prior period j:

(11b) $$P\left(h_t \middle| T \geq t; h_{t,j} \neq d_{m,j}\right) = \frac{P\left(h_t \middle| T \geq t\right)}{P\left(h_{t,j} \neq d_{m,j} \middle| T \geq t\right)}.$$

Any other history satisfies the complementary condition $h_{t,j} = d_{m,j}$ and, thus, cannot occur as long as one imposes $h_{t,j} \neq d_{m,j}$.

Given the additional condition $h_{t,j} \neq d_{m,j}$, the incidence of health status in the current period is defined by:

(11c) $$\rho\left(d_{k,t} \middle| T \geq t; h_{t,j} \neq d_{m,j}\right) = \sum_{\substack{h_t \in H_t \\ h_{t,j} \neq d_{m,j}}} \rho\left(d_{k,t} \middle| h_t\right) \cdot P\left(h_t \middle| T \geq t; h_{t,j} \neq d_{m,j}\right), \quad 1 \leq k \leq n+1.$$

In turn, this implies for expected health care expenditure at age t:

(11d) $$E_t\left(L_t \middle| H_t; h_{t,j} \neq d_{m,j}\right) = \sum_{\substack{h_t \in H_t \\ h_{t,j} \neq d_{m,j}}} P\left(h_t \middle| T \geq t; h_{t,j} \neq d_{m,j}\right) \cdot E_t\left(L_t \middle| h_t\right).$$

Consider an individual of age t. Clearly, her history either satisfies $h_{t,j} = d_{m,j}$ or the complementary condition $h_{t,j} \neq d_{m,j}$. Thus, expected health care expenditure for all individuals of that age, $E_t\left(L_t \middle| H_t\right)$, just represents the average of expected expenditure for those two groups. Indeed, relying on the definitions above, one obtains the following decomposition:

(12) $$E_t\left(L_t \middle| H_t\right)$$
$$= P\left(h_{t,j} = d_{m,j} \middle| T \geq t\right) \cdot E_t\left(L_t \middle| H_t; h_{t,j} = d_{m,j}\right) + P\left(h_{t,j} \neq d_{m,j} \middle| T \geq t\right) \cdot E_t\left(L_t \middle| H_t; h_{t,j} \neq d_{m,j}\right).$$

Alternatively, a particular health state in the current period may act as an additional condition. Applying Bayes′ theorem again, one obtains for the probability of a history $h_t \in H_t$ under the condition that current health status is given by $d_{k,t}$:

(13a) $$P\left(h_t \middle| T \geq t; d_{k,t}\right) = \frac{P\left(h_t \middle| T \geq t\right) \cdot \rho\left(d_{k,t} \middle| h_t\right)}{\rho\left(d_{k,t} \middle| T \geq t\right)}.$$

Thus, the corresponding expected expenditure on health care is defined by:

(13b) $$E_t\left(L_t \middle| H_t; d_{k,t}\right) = \sum_{h_t \in H_t} P\left(h_t \middle| T \geq t; d_{k,t}\right) \cdot L\left(d_{k,t} \middle| h_t\right).$$

For the special case k=n+1, one obtains $E_t\left(L_t \middle| H_t; d_{n+1,t}\right)$, i.e. expected health care expenditure for individuals who do not catch a lethal disease in the current period. In sum, (13b) leads to the following decomposition of expected expenditure on health care relating to age t:

(13c) $$E_t\left(L_t \middle| H_t\right) = \sum_{k=1}^{n+1} \rho\left(d_{k,t} \middle| T \geq t\right) \cdot E_t\left(L_t \middle| H_t; d_{k,t}\right).$$

In general, it is useful to take into account the incidence of a lethal disease m for which progress will be available later on. Moreover, it is also worthwhile to consider the composite event $\overline{d_{m,t}}$ explicitly. For the probability of this event which is complementary to $d_{m,t}$, one has:

(14a) $$\rho\left(\overline{d_{m,t}} \middle| T \geq t\right) = \sum_{\substack{k=1 \\ k \neq m}}^{n+1} \rho\left(d_{k,t} \middle| T \geq t\right) = 1 - \rho\left(d_{m,t} \middle| T \geq t\right).$$

This implies for the incidence of a health status other than $d_{m,t}$ in the current period under the additional condition $\overline{d_{m,t}}$:

(14b) $$\rho\left(d_{k,t}\middle|T\geq t;\overline{d_{m,t}}\right)=\frac{\rho\left(d_{k,t}\middle|T\geq t\right)}{\sum\limits_{\substack{k=1\\k\neq m}}^{n+1}\rho\left(d_{k,t}\middle|T\geq t\right)}=\frac{\rho\left(d_{k,t}\middle|T\geq t\right)}{\rho\left(\overline{d_{m,t}}\middle|T\geq t\right)};\quad 1\leq k\leq n+1;\quad k\neq m\,.$$

Combining these conditional incidences with expected expenditure on health care according to (13b), one obtains expected health care expenditure for individuals who do not catch the lethal disease m at current age:

(15a) $$E_t\left(L_t\middle|H_t;\overline{d_{m,t}}\right)=\sum_{\substack{k=1\\k\neq m}}^{n}\rho\left(d_{k,t}\middle|T\geq t;\overline{d_{m,t}}\right)\cdot E_t\left(L_t\middle|H_t;d_{k,t}\right).$$

This provides another decomposition of total expected health care expenditure:

(15b) $$E_t\left(L_t\middle|H_t\right)$$
$$=\rho\left(\overline{d_{m,t}}\middle|T\geq t\right)\cdot E_t\left(L_t\middle|H_t;\overline{d_{m,t}}\right)+\rho\left(d_{m,t}\middle|T\geq t\right)\cdot E_t\left(L_t\middle|H_t;d_{m,t}\right).$$

Finally, consider individuals who have survived the lethal disease m in the prior period and will experience a particular health state in the current period. Observe that this involves a combination of the two types of conditions investigated above. Again, Bayes´ theorem yields the probability of a history $h_t\in H_t$ relating to a later period t given that $h_{t,j}=d_{m,j}$ holds and current health status will be equal to $d_{k,t}$:[19]

(16a) $$P\left(h_t\middle|T\geq t;h_{t,j}=d_{m,j};d_{k,t}\right)=\frac{P\left(h_t\middle|T\geq t;h_{t,j}=d_{m,j}\right)\cdot\rho\left(d_{k,t}\middle|h_t\right)}{\rho\left(d_{k,t}\middle|T\geq t;h_{t,j}=d_{m,j}\right)}.$$

Under these conditions, expected expenditure on health care at age t is equal to:

(16b) $$E_t\left(L_t\middle|H_t;h_{t,j}=d_{m,j};d_{k,t}\right)=\sum_{\substack{h_t\in H_t\\h_{t,j}=d_{m,j}}}P\left(h_t\middle|T\geq t;h_{t,j}=d_{m,j};d_{k,t}\right)\cdot L\left(d_{k,t}\middle|h_t\right).$$

For k=n+1, one obtains $E_t\left(L_t\middle|H_t;h_{t,j}=d_{m,j};d_{n+1,t}\right)$, i.e. expected health care expenditure for individuals who survived the lethal disease m in the prior period j and do not catch a lethal disease in the current period. Taken together, (16b) leads to a further decomposition of expected expenditure on health care at age t:

(16c) $$E_t\left(L_t\middle|H_t;h_{t,j}=d_{m,j}\right)=\sum_{k=1}^{n+1}\rho\left(d_{k,t}\middle|T\geq t;h_{t,j}=d_{m,j}\right)\cdot E_t\left(L_t\middle|H_t;h_{t,j}=d_{m,j};d_{k,t}\right).$$

[19] Of course, this applies only to histories which satisfy $h_{t,j}=d_{m,j}$.

3. Long-term effects of medical progress on age-specific health care expenditure

3.1 Medical progress

In what follows, medical progress is taken to improve the ability to treat a lethal disease such that the associated survival probabilities increase in every period except for the final period Ω. As demonstrated below, this implies an increase in the probability of survival up to every later period. Hence, medical progress leads to an increase in life expectancy at birth but maximum length of life remains as before.

More specifically, the assumption is that progress occurs with respect to treatment of the lethal disease m. In the first period of life, it brings about a *relative* increase in the survival probability relating to that disease as stated by the following condition A_1:

$$(17a) \qquad A_1 : \quad \frac{d\left[e\left(d_{m,1}\right)\right]}{e\left(d_{m,1}\right)} = a_{m,1} \rangle\ 0 .$$

Additionally, in each later period t up to Ω-1, condition A_t implies the relative increase in the survival probability associated with the lethal disease m not to depend on an individual´s history:

$$(17b) \qquad A_t : \quad \frac{d\left[e\left(d_{m,t}|h_t\right)\right]}{e\left(d_{m,t}|h_t\right)} = a_{m,t} \rangle\ 0 \quad \forall h_t \in H_t; \quad 2 \le t \le \Omega - 1 .$$

All other exogenous probabilities of the model remain unchanged. Therefore, medical progress has no effect upon the incidence of lethal diseases conditional upon history. Similarly, the associated survival probabilities for every *other* lethal disease do not change.

In comparison with the original stationary state, progress in the long term has an impact upon the structure of individuals with respect to history. First, for given probabilities of the histories, a reduction in age-specific mortality occurs in every period except for Ω. These changes reflect the *direct effects* of medical progress on mortality. As a result of a direct effect operating in a period t, more individuals will be alive in the following period and possibly in further periods as well. A characteristic of these “new survivors” is that their history contains the lethal disease m in some prior period. Hence, the structure of individuals with respect to history will also change due to medical progress. In turn, this gives rise to a second type of effects, i.e., *indirect effects* upon age-specific mortality which may turn up in every period t with $2 \le t \le \Omega$.

In general, the improvement in treatment capability brought about by progress will also affect the associated expenditure on health care in case of the lethal disease m. In what follows I assume a constant elasticity of health care expenditure for that disease with respect to the associated survival probability. Specifically, in the first period this elasticity will be denoted by a parameter $c_{m,1}$:[20]

[20] Intuitively, health care expenditure for any lethal disease will generally depend upon the outcome, i.e., the associated survival probability. In order to economize on notation and since these probabilities remain constant for any other lethal disease, this is not taken into account explicitly.

(18a) $$\frac{d\,\{L(d_{m,1})\}}{L(d_{m,1})} = c_{m,1} \cdot \frac{d\,[e(d_{m,1})]}{e(d_{m,1})} = c_{m,1} \cdot a_{m,1}\,.$$

Likewise, in every later period t with $2 \le t \le \Omega - 1$, one has for every history $h_t \in H_t$:

(18b) $$\frac{d\,[L(d_{m,t}|h_t)]}{L(d_{m,t}|h_t)} = c_{m,t} \cdot \frac{d\,[e(d_{m,t}|h_t)]}{e(d_{m,t}|h_t)} = c_{m,t} \cdot a_{m,t}\,.$$

In some contrast to the parameters $a_{m,t}$, it is not possible to indicate the sign of the cost parameters $c_{m,t}$ a priori. More specifically, the sign depends upon the type of technological change under consideration. On the one hand, an improvement in the outcome of treatment, as given by the higher survival probability, represents a product innovation. On the other hand, this may also involve a reduction in the cost of treatment which can be interpreted as a process innovation. In the special case $c_{m,t} = 0$, the higher quality of treatment is exactly matched by cost savings such that overall there is no effect on health care expenditure. However, for $c_{m,t} \langle 0$ cost savings dominate whereas for $c_{m,t} \rangle 0$, the higher quality represents the dominant or perhaps even the only factor.

What is the impact of medical progress upon age-specific expenditure on health care? As in the case of mortality, it is again useful to distinguish between two types of effects. For a given structure of individuals with respect to history, *direct effects* upon health care expenditure may occur in every period except for Ω. In addition, further changes in expected expenditure on health care may arise due to changes in the structure of individuals. As indicated above, these tend to increase the share of individuals with the lethal disease m in at least one prior period at the expense of individuals who did not catch that disease in the past. Hence, in later periods the "new survivors" may cause *indirect effects* on age-specific health care expenditure.

To be sure, after medical progress has taken place both direct and indirect effects on age-specific health care expenditure will occur together in the long run because conditions A_1 through to $A_{\Omega-1}$ hold simultaneously.[21] In particular, expenditure at age t will be affected by conditions A_1 up to A_t, with A_1 up to A_{t-1} governing the indirect effect and A_t producing the direct effect. Therefore, it should be kept in mind that the distinction between the two types of effects introduced above represents but a conceptual device. However, as the analysis below will reveal, this is useful in that it leads to a better understanding of how medical progress affects age-specific expenditure on health care.

[21] A similar statement applies to direct and indirect effects on age-specific mortality.

3.2 Direct effects

In the first period of life, the direct effect of progress on health care expenditure can be derived from (9a) and (18a). Specifically, one obtains:

(19a) $$d\left[E_1(L_1)\right]=\rho(d_{m,1})\cdot d\left[L(d_{m,1})\right]=c_{m,1}\cdot a_{m,1}\cdot \rho(d_{m,1})\cdot L(d_{m,1}).$$

With no history available for that period, there can be no indirect effect. Thus, (19a) also represents the total effect on expected health care expenditure in the first period.

For a later period, one needs to keep the structure of individuals with respect to history in order to be able to identify a direct effect. Thus, the probabilities of the histories conditional upon survival remain constant and a similar statement applies to the incidences of health states.

Making use of (13c), this implies for the direct effect of progress on health care expenditure:

(19b) $$d\left[E_t(L_t|H_t)\right]\Big|_{A_t}=\rho(d_{m,t}|T\geq t)\cdot d\left[E_t(L_t|H_t;d_{m,t})\right];\quad 2\leq t\leq \Omega-1.$$

Next, (13b) and (18b) yield for the change in expected expenditure on health care conditional upon the occurrence of the lethal disease m in the current period:

(19c) $$d\left[E_t(L_t|H_t;d_{m,t})\right]\Big|_{A_t}=c_{m,t}\cdot a_{m,t}\cdot E_t(L_t|H_t;d_{m,t}).$$

In sum, one obtains for the direct effect in a later period t:[22]

(19d) $$d\left[E_t(L_t|H_t)\right]\Big|_{A_t}=c_{m,t}\cdot a_{m,t}\cdot \rho(d_{m,t}|T\geq t)\cdot E_t(L_t|H_t;d_{m,t});\quad 2\leq t\leq \Omega-1.$$

Not surprisingly, the sign of the parameter $c_{m,t}$ governs the sign of a direct effect. For the size of this effect, the incidence of the lethal disease m in the original stationary state turns out to be important as well. Intuitively, this can be explained by the fact that a given change in expenditure $E(L_t|H_t;d_{m,t})$ ceteris paribus will have a greater impact on age-specific health care expenditure the higher the probability of the associated condition $d_{m,t}$.

[22] By construction, this is the change in expected health care expenditure $E_t(L_t|H_t)$ given that the conditional probabilities $P(h_t|T\geq t)$ remain constant.

3.3 Indirect effects

At higher ages, indirect effects upon health care expenditure can turn up because medical progress influences the probabilities of histories conditional upon survival. As explained above, these changes are due to the increase in conditional survival probabilities associated with treatment of the lethal disease m in prior periods. Hence, in a later period t in general it is necessary to take into account t-1 indirect effects each relating to a prior period j with $1 \le j \le t-1$.

In order to be ready to cope with the potential multiplicity of indirect effects, define a set $I_t(h_t)$ for a history $h_t \in H_t$ which includes those prior periods in which the lethal disease of interest has occurred:

(20) $$I_t(h_t) = \{ j \in Z \mid 1 \le j \le t-1; h_{t,j} = d_{m,j} \}.$$

If the history does not contain the event d_m, the individual under consideration has not experienced the lethal disease m up to now. Hence, the set $I_t(h_t)$ will be empty.

With these definitions, it is possible to describe the change in the structure of individuals with respect to history at every later age. First, one has for the increase in the unconditional probability of a history:

(21a) $$d\left[P(h_t)\right] = \sum_{j \in I_t(h_t)} a_{m,j} \cdot P(h_t).$$

In turn, this implies for the associated relative increase in this probability:

(21b) $$\frac{d\left[P(h_t)\right]}{P(h_t)} = \sum_{j \in I_t(h_t)} a_{m,j} .$$

Ceteris paribus, the relative increase becomes bigger the more often the lethal disease m is included in a history.

Lemma: For the set H_t of histories relating to a later period t, one has:

(22) $$\sum_{h_t \in H_t} \sum_{j \in I_t(h_t)} a_{m,j} \cdot P(h_t) = \sum_{j=1}^{t-1} \sum_{\substack{h_t \in H_t \\ h_{t,j} = d_{m,j}}} a_{m,j} \cdot P(h_t).$$

Consider an arbitrary history $h_t' \in H_t$ which contains the lethal disease m in a prior period j′, i.e., with $j' \in I_t\left(h_t'\right)$. Then, for j=j′, the history h_t' belongs to the set $\{ h_t \in H_t \mid h_{t,j'} = d_{m,j'} \}$. This shows that each term on the left hand side also appears on the right hand side. Conversely, consider an arbitrary prior period j′′ and a history h_t'' belonging to the set $\{ h_t \in H_t \mid h_{t,j''} = d_{m,j''} \}$. Clearly, for $h_t'' \in H_t$ this implies $j'' \in I_t\left(h_t''\right)$. Thus, each term of the right hand side is also included in the sum on the left hand side.

Corollary 1: For the set H_t of histories relating to a later period t, one has:

(23)
$$\sum_{h_t \in H_t} \sum_{\substack{1 \le j \le t-1 \\ j \notin I_t(h_t)}} a_{m,j} \cdot P(h_t) = \sum_{j=1}^{t-1} \sum_{\substack{h_t \in H_t \\ h_{t,j} \neq d_{m,j}}} a_{m,j} \cdot P(h_t).$$

The proof of corollary 1 relies on the above lemma. First, note the following equivalence:

(24a)
$$\sum_{h_t \in H_t} \left[\sum_{j \in I_t(h_t)} a_{m,j} \cdot P(h_t) + \sum_{\substack{1 \le j \le t-1 \\ j \notin I_t(h_t)}} a_{m,j} \cdot P(h_t) \right] = \sum_{h_t \in H_t} \sum_{j=1}^{t-1} a_{m,j} \cdot P(h_t).$$

Similarly, one has:

(24b)
$$\sum_{j=1}^{t-1} \left[\sum_{\substack{h_t \in H_t \\ h_{t,j} = d_{m,j}}} a_{m,j} \cdot P(h_t) + \sum_{\substack{h_t \in H_t \\ h_{t,j} \neq d_{m,j}}} a_{m,j} \cdot P(h_t) \right] = \sum_{j=1}^{t-1} \sum_{h_t \in H_t} a_{m,j} \cdot P(h_t) = \sum_{h_t \in H_t} \sum_{j=1}^{t-1} a_{m,j} \cdot P(h_t),$$

with the last equivalence due to the fact that the double sum contains only a finite number of terms.

Combining (24a) with (24b) and applying (22), one obtains (23). Corollary 1 will be useful in providing another representation of indirect effects on age-specific health care expenditure.

Making use of (22), one obtains for the increase in the probability of surviving for at least t periods:

(25a)
$$d\left[P(T \ge t)\right] = d\left[\sum_{h_t \in H_t} P(h_t)\right] = \sum_{j=1}^{t-1} \sum_{\substack{h_t \in H_t \\ h_{t,j} = d_{m,j}}} a_{m,j} \cdot P(h_t)$$
$$= \sum_{j=1}^{t-1} a_{m,j} \cdot \sum_{\substack{h_t \in H_t \\ h_{t,j} = d_{m,j}}} P(h_t) = \sum_{j=1}^{t-1} a_{m,j} \cdot P(h_{t,j} = d_{m,j}).$$

This is equivalent to:

(25b)
$$\frac{d\left[P(T \ge t)\right]}{P(T \ge t)} = \frac{\sum_{h_t \in H_t} \sum_{j \in I_t(h_t)} a_{m,j} \cdot P(h_t)}{P(T \ge t)} = \sum_{j=1}^{t-1} a_{m,j} \cdot P(h_{t,j} = d_{m,j} | T \ge t).$$

The impact of medical progress, operating through a prior period j, is due to two factors: Apart from the relative increase in the survival probability captured by the parameter $a_{m,j}$, the size of the effect also depends on the relative frequency of the lethal disease m in the prior period j, as evaluated from the perspective of the current period t. The latter factor is represented by the probability $P(h_{t,j} = d_{m,j} | T \ge t)$. The product of both factors expresses how the “new survivors” of period j contribute to the increase in the probability of survival up to the current period t.

Relying on (21b) and (25b), the relative change in the conditional probability of a history is given by:

(26a) $$\frac{d\left[P(h_t|T \geq t)\right]}{P(h_t|T \geq t)} = \frac{d\left[P(h_t)\right]}{P(h_t)} - \frac{d\left[P(T \geq t)\right]}{P(P(T \geq t))} = \sum_{j \in I_t(h_t)} a_{m,j} - \sum_{j=1}^{t-1} a_{m,j} \cdot P(h_{t,j} = d_{m,j}|T \geq t)$$

$$= \sum_{j \in I_t(h_t)} a_{m,j} \cdot \left[1 - P(h_{t,j} = d_{m,j}|T \geq t)\right] - \sum_{\substack{1 \leq j \leq t-1 \\ j \notin I_t(h_t)}} a_{m,j} \cdot P(h_{t,j} = d_{m,j}|T \geq t).$$

If the history does not include the lethal disease m at all, the conditional probability of a history must decline. On the other hand, the conditional probability of the history which contains the lethal disease in each prior period necessarily increases. For any other history, it is not possible to establish the sign of the relative change in its conditional probability in general. Ceteris paribus, survival of the lethal disease m in a prior period acts to increase the conditional probability of a history, whereas the occurrence of some other health state in a prior period works in the opposite direction.[23]

For the change in the conditional probability of a history, one obtains:

(26b) $$d\left[P(h_t|T \geq t)\right] = \left[\sum_{j \in I_t(h_t)} a_{m,j} - \sum_{j=1}^{t-1} a_{m,j} \cdot P(h_{t,j} = d_{m,j}|T \geq t)\right] \cdot P(h_t|T \geq t).$$

Now it is possible to describe the overall indirect effect on health care expenditure due to medical progress in a concise manner.

Proposition 1: Medical progress, as given by (17a), (17b), (18a) and (18b), exerts a total indirect effect on expected health care expenditure in a later period which is equal to:[24]

(27) $$d\left[E_t(L_t|H_t)\right]\Big|_{A_1 \wedge \ldots \wedge A_{t-1}}$$

$$= \sum_{j=1}^{t-1} a_{m,j} \cdot P(h_{t,j} = d_{m,j}|T \geq t) \cdot \left[E_t(L_t|H_t; h_{t,j} = d_{m,j}) - E_t(L_t|H_t)\right].$$

Using (26b), one obtains from the definition (9c) of expected health care expenditure for a later period t:[25]

[23] Observe that each term, taken by itself, on the right hand side of the last equivalence in (26a), is positive.

[24] By construction, this is the change in expected health care expenditure $E_t(L_t|H_t)$ given that the survival probabilities in the current period remain constant.

[25] Since the focus in on indirect effects, the terms $E_t(L_t|h_t)$ remain unaffected.

(28a)
$$d\left[E_t\left(L_t \middle| H_t\right)\right]\Big|_{A_1 \wedge \ldots \wedge A_{t-1}}$$

$$= \sum_{h_t \in H_t} \left[\sum_{j \in I_t(h_t)} a_{m,j} - \sum_{j=1}^{t-1} a_{m,j} \cdot P\left(h_{t,j} = d_{m,j} \middle| T \geq t\right) \right] \cdot P\left(h_t \middle| T \geq t\right) \cdot E_t\left(L_t \middle| h_t\right)$$

$$= \sum_{h_t \in H_t} \sum_{j \in I_t(h_t)} a_{m,j} \cdot P\left(h_t \middle| T \geq t\right) \cdot E_t\left(L_t \middle| h_t\right) - \sum_{j=1}^{t-1} a_{m,j} \cdot P\left(h_{t,j} = d_{m,j} \middle| T \geq t\right) \cdot E_t\left(L_t \middle| H_t\right).$$

Making use of (11b), (18) and the lemma, it is possible to transform the first sum as follows:

(28b)
$$\sum_{h_t \in H_t} \sum_{j \in I_t(h_t)} a_{m,j} \cdot P\left(h_t \middle| T \geq t\right) \cdot E_t\left(L_t \middle| h_t\right) = \sum_{j=1}^{t-1} \sum_{\substack{h_t \in H_t \\ h_{t,j} = d_{m,j}}} a_{m,j} \cdot P\left(h_t \middle| T \geq t\right) \cdot E_t\left(L_t \middle| h_t\right)$$

$$= \sum_{j=1}^{t-1} a_{m,j} \cdot P\left(h_{t,j} = d_{m,j} \middle| T \geq t\right) \cdot \sum_{\substack{h_t \in H_t \\ h_{t,j} = d_{m,j}}} \frac{P\left(h_t \middle| T \geq t\right)}{P\left(h_{t,j} = d_{m,j} \middle| T \geq t\right)} \cdot E_t\left(L_t \middle| h_t\right)$$

$$= \sum_{j=1}^{t-1} a_{m,j} \cdot P\left(h_{t,j} = d_{m,j} \middle| T \geq t\right) \cdot E_t\left(L_t \middle| H_t ; h_{t,j} = d_{m,j}\right).$$

This establishes (27).

For the purpose of interpretation, it is useful to start by looking at the right hand side of (27). Each term in brackets corresponds to an indirect effect relating to a prior period. On the one hand, its size is influenced by $a_{m,j} \cdot P\left(h_{t,j} = d_{m,j} \middle| T \geq t\right)$ and, hence, by the "new survivors" of period j, to the extent that they survive up to the current period. On the other hand, the difference between expected health care expenditures $E_t\left(L_t \middle| H_t ; h_{t,j} = d_{m,j}\right)$ and $E_t\left(L_t \middle| H_t\right)$ plays an important role as well. In particular, it drives the sign of an indirect effect. More specifically, the difference is positive if, for a "new survivor" of a prior period j, expected expenditure is higher in the current period than for her peers. Likewise, one obtains a negative indirect effect if "new survivors" of a prior period j on average consume less health care in the current period than individuals of the same age in general.

The intuition for this result on the sign of an indirect effect is straightforward. First, observe that medical progress which has taken place at an earlier age j affects the composition of individuals who survive for at least t periods. Clearly, the rise in survival probabilities associated with the lethal disease m at age j produces "new survivors" with respect to age j+1. Some of these will not catch a lethal disease at that age and of those who do, some will survive by virtue of assumption (5c). A similar observation applies to each later period up to Ω-1. Thus, there will be "new survivors" with respect to every later age including the maximum age Ω. In other words, the probabilities $P\left(h_{t,j} = d_{m,j} \middle| T \geq t\right)$ will be positive for $1 \leq j \langle t \leq \Omega$.

Second, medical progress relating to a prior age j will affect average expenditure on health care at some later age t if and only if it produces "new survivors" with respect to age t who, on average, consume a different amount of health care than their peers. Relying on the appropriate expenditure concepts, this is true if and only if $E_t\left(L_t \middle| H_t; h_{t,j} = d_{m,j}\right)$ differs from $E_t\left(L_t \middle| H_t\right)$.

It is important to note that an indirect effect on age-specific health care expenditure crucially depends on average expenditure for "new survivors" *relative* to average expenditure for all individuals of age t. Therefore, the *absolute* amount of health care consumed by "new survivors" is not really relevant for the sign of an indirect effect relating to a prior age j. In particular, if either the incidence of lethal diseases or the associated consumption of health care is high for the "new survivors" at age t, average health care expenditure at that age may nevertheless decline. Conversely, age-specific expenditure may rise even though health care consumption by "new survivors", taken by itself, is low.

It is also possible to provide a slightly different representation of the indirect effects due to medical progress. As (12) shows, $E_t\left(L_t \middle| H_t\right)$ is the expected value of average health care expenditure for individuals of age t whose history satisfies $h_{t,j} = d_{m,j}$ and those with $h_{t,j} \neq d_{m,j}$. Hence, $E_t\left(L_t \middle| H_t; h_{t,j} = d_{m,j}\right)$ will be higher than $E_t\left(L_t \middle| H_t\right)$ if $E_t\left(L_t \middle| H_t; h_{t,j} = d_{m,j}\right)$ is higher than $E_t\left(L_t \middle| H_t; h_{t,j} \neq d_{m,j}\right)$ and vice versa.

Drawing on (26b) and noting that $P\left(h_{t,j} = d_{m,j} \middle| T \geq t\right) + P\left(h_{t,j} \neq d_{m,j} \middle| T \geq t\right) = 1$ must hold, one obtains for the relative change in the conditional probability of a history:

(29a)
$$\frac{d\left[P\left(h_t \middle| T \geq t\right)\right]}{P\left(h_t \middle| T \geq t\right)} = \sum_{j \in I_t(h_t)} a_{m,j} \cdot P\left(h_{t,j} \neq d_{m,j} \middle| T \geq t\right) - \sum_{\substack{1 \leq j \leq t-1 \\ j \notin I_t(h_t)}} a_{m,j} \cdot P\left(h_{t,j} = d_{m,j} \middle| T \geq t\right).$$

This is equivalent to:

(29b)
$$d\left[P\left(h_t \middle| T \geq t\right)\right]$$
$$= \left[\sum_{j \in I_t(h_t)} a_{m,j} \cdot P\left(h_{t,j} \neq d_{m,j} \middle| T \geq t\right) - \sum_{\substack{1 \leq j \leq t-1 \\ j \notin I_t(h_t)}} a_{m,j} \cdot P\left(h_{t,j} = d_{m,j} \middle| T \geq t\right)\right] \cdot P\left(h_t \middle| T \geq t\right).$$

Corollary 2: The total indirect effect on expected health care expenditure in a later period due to medical progress, as given by (17a), (17b), (18a) and (18b), is equal to:

(30)
$$d\left[E_t\left(L_t \middle| H_t\right)\right]\Big|_{A_1 \wedge \ldots \wedge A_{t-1}}$$
$$= \sum_{j=1}^{t-1} a_{m,j} \cdot P\left(h_{t,j} \neq d_{m,j} \middle| T \geq t\right) \cdot P\left(h_{t,j} = d_{m,j} \middle| T \geq t\right) \cdot$$
$$\left[E_t\left(L_t \middle| H_t; h_{t,j} = d_{m,j}\right) - E_t\left(L_t \middle| H_t; h_{t,j} \neq d_{m,j}\right)\right].$$

Using (29b), one obtains from (9c):

(31a)
$$d\left[E_t\left(L_t|H_t\right)\right]\Big|_{A_1\wedge\ldots\wedge A_{t-1}}$$

$$=\sum_{h_t\in H_t}\left[\sum_{j\in I_t(h_t)}a_{m,j}\cdot P\left(h_{t,j}\neq d_{m,j}|T\geq t\right)-\sum_{\substack{1\leq j\leq t-1\\ j\notin I_t(h_t)}}a_{m,j}\cdot P\left(h_{t,j}=d_{m,j}|T\geq t\right)\right]\cdot P\left(h_t|T\geq t\right)\cdot E_t\left(L_t|h_t\right)$$

$$=\sum_{h_t\in H_t}\sum_{j\in I_t(h_t)}a_{m,j}\cdot P\left(h_{t,j}\neq d_{m,j}|T\geq t\right)\cdot P\left(h_t|T\geq t\right)\cdot E_t\left(L_t|h_t\right)$$

$$-\sum_{h_t\in H_t}\sum_{\substack{1\leq j\leq t-1\\ j\notin I_t(h_t)}}a_{m,j}\cdot P\left(h_{t,j}=d_{m,j}|T\geq t\right)\cdot P\left(h_t|T\geq t\right)\cdot E_t\left(L_t|h_t\right)$$

$$=\sum_{j=1}^{t-1}\sum_{\substack{h_t\in H_t\\ h_{t,j}=d_{m,j}}}a_{m,j}\cdot P\left(h_{t,j}\neq d_{m,j}|T\geq t\right)\cdot P\left(h_t|T\geq t\right)\cdot E_t\left(L_t|h_t\right)$$

$$-\sum_{j=1}^{t-1}\sum_{\substack{h_t\in H_t\\ h_{t,j}\neq d_{m,j}}}a_{m,j}\cdot P\left(h_{t,j}=d_{m,j}|T\geq t\right)\cdot P\left(h_t|T\geq t\right)\cdot E_t\left(L_t|h_t\right).$$

For the last transformation, both the lemma and corollary 1 have been used. Next, invoke (10b) and (11b) to arrive at:

(31b)
$$d\left[E_t\left(L_t|H_t\right)\right]\Big|_{A_1\wedge\ldots\wedge A_{t-1}}$$

$$=\sum_{j=1}^{t-1}a_{m,j}\cdot P\left(h_{t,j}\neq d_{m,j}|T\geq t\right)\cdot P\left(h_{t,j}=d_{m,j}|T\geq t\right)\cdot$$

$$\left[\sum_{\substack{h_t\in H_t\\ h_{t,j}=d_{m,j}}}\frac{P\left(h_t|T\geq t\right)}{P\left(h_{t,j}=d_{m,j}|T\geq t\right)}\cdot E_t\left(L_t|h_t\right)-\sum_{\substack{h_t\in H_t\\ h_{t,j}\neq d_{m,j}}}\frac{P\left(h_t|T\geq t\right)}{P\left(h_{t,j}\neq d_{m,j}|T\geq t\right)}\cdot E_t\left(L_t|h_t\right)\right].$$

Applying (10d) and (11d), one obtains (30).

Thus, an alternative way to determine the indirect effect relating to a prior period j is to compare $E_t\left(L_t|H_t;h_{t,j}=d_{m,j}\right)$ with $E_t\left(L_t|H_t;h_{t,j}\neq d_{m,j}\right)$.

Returning to the representation by (27), the *total* indirect effect on age-specific health care expenditure at some age t is given by a weighted sum of the indirect effects relating to each prior age. More specifically, the weights are determined by the impact which "new survivors" of a prior age exert on the relative increase of the probability of surviving through to age t. Hence, in (27) a given difference in brackets contributes more to the total indirect effect if it relates to a prior period in which medical progress produces a greater number of "new survivors" up to the age under consideration. This may happen either because progress yields a high relative increase in survival probabilities or due to a high probability of the event $h_{t,j}=d_{m,j}$ at the outset.

It follows that for the total indirect effect the same qualitative statements apply, mutatis mutandis, as for an individual indirect effect relating to a single prior period. In particular, the sign of the total effect is not determined by expected health care expenditure for “new survivors” at the current age either. Rather, the decisive factor is again average expenditure for this group relative to all individuals of the same age. E.g., the total indirect effect on age-specific health care expenditure at age t may be negative even though “new survivors” at that age, in comparison with younger ages, face a high incidence of a lethal disease and require a large amount of health care in such a case. However, as (27) shows, this will be true only if the corresponding values for all individuals of age t, on average, turn out to be even higher.

As explained above, an indirect effect is solely due to a change in the structure which individuals of age t exhibit with respect to history. However, this change is but a necessary condition. In order for an indirect effect on age-specific health care expenditure to actually come about, history must have an influence on either the incidence of health status or the associated expenditure on health care. To see this more clearly, it is helpful to consider three special cases.

Take a single indirect effect relating to a prior age j. As pointed out above, the difference between $E_t\left(L_t \middle| H_t; h_{t,j} = d_{m,j}\right)$ and $E_t\left(L_t \middle| H_t\right)$ determines the sign of this effect while also affecting its size. Relying on (13c) and (16c) and rearranging terms, one obtains the following representation:

(32)
$$\begin{aligned} & E_t\left(L_t \middle| H_t; h_{t,j} = d_{m,j}\right) - E_t\left(L_t \middle| H_t\right) \\ &= \sum_{k=1}^{n+1} \rho\left(d_{k,t} \middle| T \geq t; h_{t,j} = d_{m,j}\right) \cdot \left[E_t\left(L_t \middle| H_t; h_{t,j} = d_{m,j}; d_{k,t}\right) - E_t\left(L_t \middle| H_t; d_{k,t}\right)\right] \\ &\quad + \sum_{k=1}^{n+1} E_t\left(L_t \middle| H_t; d_{k,t}\right) \cdot \left[\rho\left(d_{k,t} \middle| T \geq t; h_{t,j} = d_{m,j}\right) - \rho\left(d_{k,t} \middle| T \geq t\right)\right]. \end{aligned}$$

Thus, the difference is the sum of two effects, with each effect arising from a comparison of “new survivors” of the prior age j with all individuals of age t. First, a *treatment expenditure effect* which will be positive if and only if health care expenditure conditional upon health status, on average, is higher for individuals who survived the lethal disease at age j. Second, an *incidence effect* which will be positive if and only if “new survivors” tend to be in those health states more often that require a high expenditure on health care as measured by $E_t\left(L_t \middle| H_t; d_{k,t}\right)$.

Consider next the following two sets of conditions:

(33a)
$$\rho\left(d_{k,t} \middle| h_t\right) = \rho\left(d_{k,t}\right); \quad \forall h_t \in H_t; \ k = 1,\ldots,n; \ 2 \leq t \leq \Omega,$$

(33b)
$$L\left(d_{k,t} \middle| h_t\right) = L\left(d_{k,t}\right); \quad \forall h_t \in H_t; \ k = 1,\ldots,n+1; \ 2 \leq t \leq \Omega.$$

While (33a) implies that an individual´s history fails to affect the incidence of health status at the current age t, (33b) states that history has no influence on health care expenditure conditional upon current health status. These conditions give rise to three important special cases.

Clearly, (33a) and (33b) imply expected health care expenditure at a later age not to depend on history:

(34a) $$E_t(L_t|h_t)=\sum_{k=1}^{n+1}\rho(d_{k,t})\cdot L(d_{k,t})=E_t(L_t);\quad \forall h_t\in H_t;\ 2\le t\le\Omega.$$

This implies average expenditure at age t to be the same for “new survivors” of a prior age j and for all individuals:

(34b) $$E_t(L_t|H_t;h_{t,j}=d_{m,j})=E_t(L_t|H_t)=E_t(L_t);\quad 2\le t\le\Omega;\ 1\le j\le t-1.$$

Thus, each difference in (27) is equal to zero. Therefore, medical progress at prior ages has no influence at all upon average health care expenditure at age t.

Next, suppose that only (33b) holds. Then, health care expenditure at each age depends upon current health status but not on history. Making use of (13b) and (16b), one obtains:

(35a) $$E_t(L_t|H_t;h_{t,j}=d_{m,j};d_{k,t})=E_t(L_t|H_t;d_{k,t})=L(d_{k,t});$$
$$1\le j\le t-1;\ k=1,...,n+1;\ 2\le t\le\Omega.$$

Furthermore, (13c) and (16c) imply for the indirect effect relating to the prior age j:

(35b) $$E_t(L_t|H_t;h_{t,j}=d_{m,j})-E_t(L_t|H_t)$$
$$=\sum_{k=1}^{n+1}\left[\rho(d_{k,t}|T\ge t;h_{t,j}=d_{m,j})-\rho(d_{k,t}|T\ge t)\right]\cdot L(d_{k,t});\quad 1\le j\le t-1;\ 2\le t\le\Omega.$$

Hence, the sign of an indirect effect will be determined by the incidence effect alone, i.e., it depends on the way in which survival of the lethal disease at the prior age j affects the incidence of health status at the current age. More precisely, the difference is positive if and only if, in comparison with their peers, “new survivors” exhibit a higher incidence of those health states requiring a high consumption of medical care.

Finally, consider the implications of conditions (33a). From (8b) and (10c), one obtains:

(36a) $$\rho(d_{k,t}|T\ge t;h_{t,j}=d_{m,j})=\rho(d_{k,t}|T\ge t)=\rho(d_{k,t});$$

This implies:

(36b) $$E_t(L_t|H_t;h_{t,j}=d_{m,j})-E_t(L_t|H_t)$$
$$=\sum_{k=1}^{n+1}\rho(d_{k,t})\cdot\left[E_t(L_t|H_t;h_{t,j}=d_{m,j};d_{k,t})-E_t(L_t|H_t;d_{k,t})\right];\quad 1\le j\le t-1;\ 2\le t\le\Omega.$$

In this case, the sign of an indirect effect relating to a prior age j only depends on the impact which the condition $h_{t,j}=d_{m,j}$ exerts, on average, upon expected expenditure conditional on health status at current age. More precisely, the effect is positive if and only if, on average, survival of the lethal disease m at the prior age j implies an increase in expected health care expenditure which is necessary for the appropriate medical treatment of current health status.

Proposition 2 summarizes the results obtained for the three cases by looking at the total indirect effect upon age-specific health care expenditure.

Proposition 2: (i) If (33a) and (33b) hold, the indirect effect on age-specific health care expenditure due to medical progress is equal to zero:

(37a)
$$d\left[E_t\left(L_t \middle| H_t\right)\right]\Big|_{A_1 \wedge \ldots \wedge A_{t-1}} = 0; \quad 2 \le t \le \Omega .$$

(ii) If (33b) holds, the indirect effect on age-specific health care expenditure due to medical progress is determined solely by incidence effects:

(37b)
$$d\left[E_t\left(L_t \middle| H_t\right)\right]\Big|_{A_1 \wedge \ldots \wedge A_{t-1}} = \sum_{j=1}^{t-1} a_{m,j} \cdot P\left(h_{t,j} = d_{m,j} \middle| T \ge t\right) \cdot$$
$$\left\{\sum_{k=1}^{n+1}\left[\rho\left(d_{k,t} \middle| T \ge t; h_{t,j} = d_{m,j}\right) - \rho\left(d_{k,t} \middle| T \ge t\right)\right] \cdot L\left(d_{k,t}\right)\right\}; \quad 2 \le t \le \Omega .$$

(iii) If (33a) holds, the indirect effect on age-specific health care expenditure due to medical progress is determined solely by treatment expenditure effects:

(37c)
$$d\left[E_t\left(L_t \middle| H_t\right)\right]\Big|_{A_1 \wedge \ldots \wedge A_{t-1}} = \sum_{j=1}^{t-1} a_{m,j} \cdot P\left(h_{t,j} = d_{m,j} \middle| T \ge t\right) \cdot$$
$$\left\{\sum_{k=1}^{n+1} \rho\left(d_{k,t}\right) \cdot \left[E_t\left(L_t \middle| H_t; h_{t,j} = d_{m,j}; d_{k,t}\right) - E_t\left(L_t \middle| H_t; d_{k,t}\right)\right]\right\}; \quad 2 \le t \le \Omega .$$

4. Discussion

With the distinction between direct and indirect effects, the analysis has identified two types of effects due to medical progress which will usually affect age-specific expenditure on health care simultaneously.[26] More specifically, it is perfectly possible for these effects to differ in sign such that no general conclusions with respect to their relative size are available. Thus, a positive direct effect is neither necessary nor sufficient for an increase in age-specific health care expenditure. Conversely, a negative indirect effect does not imply a reduction in age-specific expenditure or vice versa.

In addition, the analysis provides sufficient conditions for the change in age-specific expenditure on health care to exhibit a definite sign. E.g., suppose that the improvement in the treatment of a lethal disease at current age involves a higher cost and that "new survivors" of prior ages on average consume more health care than their peers. Then, there must be an increase in age-specific expenditure on health care at current age.

[26] The exceptions being the first period (no indirect effect) and the maximum period (no direct effect).

With respect to other cases, the model highlights those variables which are significant for an assessment of the sign and the size of direct and indirect effects, respectively. Clearly, this is important for the evaluation of the change in age-specific health care expenditure. In addition, it leads to a better understanding of the impact of "new survivors" upon which a substantial part of the literature has focussed: The age profile of per capita health care expenditure may shift upward even though "new survivors", on average, involve lower expenditure than their peers.

E.g., this may happen when the following conditions are met: Suppose that "new survivors" constitute only a small part of all individuals in each age group. As demonstrated above, this implies the probabilities $P(h_{t,j} = d_{m,j} | T \geq t)$ to be low in each case. In addition, take the lethal disease to involve a high incidence $\rho(d_{m,t} | T \geq t)$ at each age. Based on these assumptions, one obtains the following description of the lethal disease: At any given age, a sizeable part of all individuals catches the disease. However, only a small number survives the disease.[27]

Similarly, it is also conceivable that medical progress leads to a downward shift of the age profile for health care expenditure even though "new survivors", on average, consume a higher amount of resources than their peers at each age. Given that indirect effects on age-specific expenditure now are positive by assumption, this can only happen if the change in treatment of the lethal disease involves a reduction in cost such that direct effects are sufficiently negative. Again, this scenario appears to be more likely for lethal diseases with a high incidence and a low survival probability at each age.

These considerations can also be used to argue that there is no necessary link between either compression of morbidity or expansion of morbidity and the change in age-specific expenditure on health care. If aging of the population is driven by medical progress, any change in age-specific morbidity must be due to the influence of "new survivors". Thus, both compression and expansion of morbidity will produce indirect effects, albeit of different sign, on the age profile of health care expenditure.[28] However, due to the presence of direct effects, the sign of the total effect will remain ambiguous in general. It follows that a downward shift of the age profile may occur even though an expansion of morbidity takes place. Similarly, compression of morbidity is not sufficient to prevent an upward shift in age-specific consumption of health care.

At any given age, direct effects on age-specific health care expenditure are caused by individuals who suffer from the lethal disease. On the other hand, indirect effects are associated with individuals who have survived the same disease at some prior age. Upon closer inspection, there is another important distinction between the two types of effects. By definition, medical progress creates new knowledge, but its contents as well as its price are unknown a priori. Hence, the sign of a direct effect can only be determined after progress has taken place. In contrast, it is usually possible to evaluate the sign of an indirect effect beforehand. More

[27] Conversely, with no change in the sign of either a direct or an indirect effect, the total effect may also turn out to be negative. More precisely, this could happen if progress would relate to a lethal disease with low age-specific incidence and high survival probabilities at each age.

[28] More generally, as the analysis undertaken above shows, the sign of an indirect effect on health care expenditure depends on a number of factors. Ceteris paribus, a rise (a decline) in age-specific incidence of lethal diseases can safely be taken to imply a negative (a positive) indirect effect.

precisely, this is true whenever at the outset at least some individuals already survive the lethal disease under consideration.[29] For a later age, a simple comparison of per capita expenditure on health care expenditure between "new survivors" and their peers supplies the required information.

Observe that it is not possible to infer the sign of an indirect effect from the evolution of age-specific expenditure on health care for "new survivors" alone. Essentially, the reason is that individuals who survived a given lethal disease in a prior period constitute but part of all individuals who are alive at a later age. For the sake of illustration, consider two successive ages j+1 and j+2. In addition, suppose that age-specific health care expenditure rises with age, i.e., $E_{j+2}\left(L_{j+2}\middle|H_{j+2}\right) \rangle\, E_{j+1}\left(L_{j+1}\middle|H_{j+1}\right)$. Turning to "new survivors" of the lethal disease m at age j, average expenditure is given by $E_{j+1}\left(L_{j+1}\middle|H_{j+1};h_{j+1,j}=d_{m,j}\right)$ and $E_{j+2}\left(L_{j+2}\middle|H_{j+2};h_{j+2,j}=d_{m,j}\right)$, respectively. Specifically, assume $E_{j+1}\left(L_{j+1}\middle|H_{j+1};h_{j+1,j}=d_{m,j}\right) \langle\, E_{j+2}\left(L_{j+2}\middle|H_{j+2};h_{j+2,j}=d_{m,j}\right)$, i.e., average expenditure on health care for "new survivors" is taken to rise with age as well. Under these conditions, it is perfectly possible that the indirect effects on age-specific health care expenditure turn out to be negative, i.e., that the two inequalities $E_{j+i}\left(L_{j+i}\middle|H_{j+i};h_{j+i,j}=d_{m,j}\right) \langle\, E_{j+i}\left(L_{j+i}\middle|H_{j+i}\right)$ are satisfied for i=1,2. More precisely, this will be the case whenever individuals who did not suffer from the lethal disease at age j on average consume a higher amount of health care at later ages than "new survivors".

Furthermore, changes in the incidence of lethal diseases within the population provide no reliable guide to the change in age-specific health care expenditure. To be specific, suppose that the incidence of each lethal disease rises with age. Thus, for two successive ages i and i+1 as well as an arbitrary lethal disease k one has $\rho\left(d_{k,i+1}\middle|T \geq i+1\right) \rangle\, \rho\left(d_{k,i}\middle|T \geq i\right)$. In addition, assume that the incidence of each lethal disease among "new survivors" of a lethal disease m at some prior age j is just equal to the average incidence for all individuals. Thus, for a later age t and an arbitrary lethal disease, one obtains $\rho\left(d_{k,t}\middle|T \geq t;h_{t,j}=d_{m,j}\right) = \rho\left(d_{k,t}\middle|T \geq t\right)$.

Given these assumptions, there is no incidence effect of medical progress. However, due to aging, the incidence of each lethal disease within the population at large has risen. For the sign of an indirect effect on age-specific health care expenditure, the impact of surviving the lethal disease at some prior age on the expected cost of treatment now turns out to be decisive.[30] More specifically, a negative treatment effect implies the indirect effect on age-specific health care expenditure to be negative.[31] With a direct effect that is sufficiently small, one obtains a negative total effect on age-specific expenditure. Therefore, medical progress may imply a downward shift of the age profile of health care expenditure even though the incidence of lethal diseases within the population has increased.[32]

[29] However, as (22) indicates, in order to be able to determine the size of an indirect effect on health care expenditure, knowledge of the (relative) increase in survival probabilities is an essential prerequisite. For obvious reasons, this will be available only ex post, i.e., after medical progress has taken effect.
[30] Cf. (26b).
[31] Clearly, the opposite conclusion holds for a positive impact.
[32] Empirical research is needed in order to determine the relevance of such a case. The argument only shows that there is no necessary link between a change in the incidence of a lethal disease within the population and the change in the age profile for health care expenditure.

The model of the present paper can also be used to evaluate the traditional approach to forecasting health care expenditure. As a first result, note that medical progress may drive aging of the population without any change in the age profile of health care expenditure. E.g., this will be the case if both direct and indirect effects are equal to zero, respectively, at every age. Thus, the traditional approach does not necessarily exclude the impact of medical progress. Rather, it can be taken to incorporate – albeit implicitly – a specific hypothesis with respect to the relationship between a reduction in age-specific mortality and the associated total effect upon health care expenditure.

Second, if only the direct effects of medical progress are equal to zero, it is still possible to employ the traditional approach in a useful manner. However, in this case the approach only indicates the change in health care expenditure due to "first round" effects while it fails to take into account those "second round" effects relating to the impact of "new survivors". Hence, in order to obtain the overall change in future health care expenditure, it is necessary to supplement the traditional approach by an evaluation of the change in the age profile due to the indirect effects of medical progress. More specifically, as explained in section 3.3, this requires a comparison of average health care expenditure for "new survivors" and their peers.

In any other case, it does not make sense to rely on the traditional approach when assessing the impact of medical progress on health care expenditure. Essentially, this holds true because it is not clear which part of the total effect is already taken into account by the approach. In particular, the traditional approach fails to provide a lower bound on the evolution of future health care expenditure since it excludes the possibility of a downward shift of the profile of age-specific expenditure on health care.

The analysis undertaken in the present paper also sheds light on the hypotheses mentioned in the introduction. More precisely, it is possible to identify conditions such that the change in age-specific health care expenditure associated with each hypothesis is brought about by medical progress. For the compression of morbidity and the expansion of morbidity, this has already been demonstrated above. In addition, aging of the population may go along with a steepening of the age profile of health care expenditure. For the sake of illustration, suppose that the increase in survival probabilities relating to the lethal disease m fails to produce any indirect effect. Furthermore, take average expenditure associated with treatment of that disease to increase with age, i.e., assume $\rho(d_{m,t}|T \geq t) \cdot E_t(L_t|H_t; d_{m,t})$ to be an increasing function of t. Next, let the parameters $c_{m,t}$ relating to medical progress be positive such that $a_{m,t} \cdot c_{m,t}$ is non-decreasing with respect to age t. Under these conditions, (19d) implies a rate of growth for age-specific health care expenditure which increases with age, i.e., a steepening of the age profile.

Finally, the model lends considerable support to a critical view of the costs of dying approach. It is true that medical progress leads to a reduction in age-specific mortality. However, taken by itself, this will not imply substantial reductions in age-specific health care expenditure as hypothesized by the approach. The reason is simple: Expenditure on health care relates to treatment of diseases in the first place, and not to the outcome of treatment. Thus, for every homogenous group of individuals who die at the end of a given period, there will be a similar group of survivors – albeit usually of different size – with the same amount of per capita expenditure on health care.[33] As long as medical progress has an influence on the outcome of treatment but not on the incidence of a lethal disease, any hope for a reduction in age-specific health care expenditure due to the reduction in age-specific mortality seems ill-founded.

5. Conclusion

Although the analysis undertaken above is purely theoretical, it may also serve as a guide to empirical investigations of the impact of medical progress on age-specific health care expenditure. It is true by definition that progress creates new knowledge which cannot be known in advance. This could be taken to imply that there is no way today of assessing the influence of progress which occurs tomorrow on future health care expenditure.

However, as the model presented in this paper clearly demonstrates, such a claim would be unnecessarily negative. More specifically, consumption of health care by individuals who survive a lethal disease today provides valuable information on the indirect effects of future medical progress on age-specific health care expenditure. In this sense, empirical data on "old survivors" are available today and can be used to assess at least part of the impact of progress which may take place in the future. In particular, the model suggests that empirical research should focus on the incidence of lethal diseases and the treatment costs for "old survivors" in relation to their peers.

Like any other theoretical analysis, the model excludes a number of potentially important aspects. While this is the price to pay in order to be able to derive precise results, it is important to bear these limitations in mind. E.g., the model certainly implements a somewhat restricted version of medical progress. More precisely, progress may also improve the quality of life of individuals not suffering from a lethal disease. Next, and potentially more important, the analysis offers a mechanical view of the way in which progress affects age-specific expenditure on health care: Progress just happens and there is no explicit consideration of decisions taken by individuals, insurers or other parties.

While the last observation is true, I do not think that it has substantial implications for the analysis undertaken in this paper. To see this, suppose that medical progress is made available for individuals according to some decision process. In this more general setting, the economy in the long run presumably will again tend to reach some kind of equilibrium such that the age profile of health care expenditure remains constant. Hence, adding economic substance by including decisions on the type of medical progress, certainly will have implications on both population aging and the evolution of health care expenditure. However, in order to assess the impact of progress on age-specific health care expenditure, it is nonetheless necessary to proceed precisely in the manner outlined above. Or, to put it slightly differently: While the model set up in this paper does not provide an explanation of medical progress, it is designed to capture all relevant effects on the age profile of health care expenditure. Therefore, its value should be judged according to this more moderate goal.

[33] More precisely, apart from the outcome of treatment of the same lethal disease, the survivors are identical to the decedents. Hence, the statement is true as long as the survival probability of a lethal disease is positive.

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