THEORY AND METHODS

Life table methods for quantitative impact assessments in chronic mortality

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Quantitative health impact assessments of chronic mortality, where the impacts are expected to be observed over a number of years, are complicated by the link between death rates and surviving populations. A general calculation framework for quantitative impact assessment is presented, based on standard life table calculation methods, which permits consistent future projections of impacts on mortality from changes in death rates. Implemented as a series of linked spreadsheets, the framework offers complete flexibility in the sex specific, age specific, and year specific patterns of baseline mortality death rates; in the predicted impacts upon these; in the weights or values placed on gains in life; and in the summary measures of impact. Impacts can be differential by cause of death. Some examples are given of predictions of the impacts of reductions in chronic mortality in the populations of England and Wales and of Scotland.

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Impact assessment is a process whereby predictions are made about the future consequences or impacts of changes being made or considered. The concept is general, and the changes may be for example to people's environments or lifestyles, or to industrial processes, or to economic or political systems. Within a specific context, such as health effects, there may be a wide range of outcomes for which impacts could be assessed, such as death, death from a specific cause, hospitalisation, GP visits, awareness of symptoms, absence from work, and many more. Different contexts may emphasise different outcome measures, but the constant theme is future prediction, and in particular prediction of differences in outcome under different scenarios of change against the status quo. It may also be desired to attach monetary values to these outcomes, for example, as input to a cost-benefit analysis.

The work reported here was motivated principally by a need to make impact assessments with respect to the long term effects of particulate air pollution on mortality in the UK. Principal evidence of long term effects comes from two American cohort studies,[1 2] and recent reanalyses of their data[3] have largely confirmed the earlier observed associations and estimates of the size of the effects. If true and causal, these associations imply that future reductions in ambient air pollution could reduce mortality risks, and makers of policy need to balance the costs of interventions with the value (economic, social or other) of the benefits.

Interpretation of mortality rates and their projection into impact assessments present conceptual difficulties, primarily because each subject in a cohort can die only once, and eventually the number of deaths predicted for any cohort must equal the size of the cohort. Attempts to quantify impacts on mortality in terms of attributable deaths ("brought forward", or "extra")[4] can give approximate estimates for short periods of future prediction, but they can be misleading for long term predictions.[5] However, standard methods of life table calculation, which allow for the changes in future population shape that are induced by changes in risks, can be used as a basis for consistent impact assessments.

In this paper we demonstrate how life table calculations can be organised in a framework of multiple spreadsheets, which permits maximum flexibility in assumptions of changes to risk, in associated monetary or other valuation, and in summary measures of total impacts. The framework has already been used in research for the European Commission[6] and to provide updated estimates of impact for the UK Committee on the Medical Effects of Air Pollution (COMEAP).[7] However, it can be useful in any area of impact assessment that involves changes in long term mortality risks.

REPRESENTING MORTALITY RISKS

Age specific mortality risks over short periods can be characterised interchangeably by hazard or survival probabilities. The hazard, also known as the "force of mortality", is defined as the instantaneous probability of death at a particular time, conditional on having survived to that time.[8 9] The relation between this quantity and the probability of surviving a period of time is the basis of standard life table methods of describing mortality patterns. The exact form of this relation depends on how much detail is available on the exact timing of deaths.[10] Where timing is known only to within a calendar year, the usual ("actuarial") convention is that half the deaths in a year take place in each half of the year. The average hazard rate for each year is estimated from observed data as number of deaths d divided by the mid-year population m

$$h=d/m$$

If we represent the probability of surviving to the end of the year by s, then it is easy to see that

Table 1 Mid-year population and number of deaths in England and Wales, 1995, by sex and five year age groups

	Mid-year populations			Deaths		
Age (y)	Men	Women	Total	Men	Women	Total
0–4	1736000	1651900	3387900	2702	2025	4727
5–9	1744900	1656400	3401300	274	198	472
10–14	1649300	1563000	3212300	344	213	557
15–19	1557000	1469100	3026100	929	394	1323
20–24	1791200	1703400	3494600	1559	516	2075
25–29	2092300	2001900	4094200	1881	765	2646
30–34	2160000	2074400	4234400	2226	1118	3344
35–39	1843900	1810600	3654500	2498	1440	3938
40–44	1678900	1669100	3348000	3436	2226	5662
45–49	1830400	1828200	3658600	5711	3863	9574
50–54	1474200	1478800	2953000	7806	5158	12964
55–59	1321600	1339100	2660700	11959	7386	19345
60–64	1204000	1254000	2458000	19044	11531	30575
65–69	1107300	1245800	2353100	30492	19867	50359
70–74	970300	1231100	2201400	44531	33143	77674
75–79	622100	933600	1555700	45003	40232	85235
80–84	409600	768900	1178500	47314	56955	104269
85–89	182800	468100	65090	31479	56976	88455
90–94	44180	196450	240630	12781	36973	49754
95–99	5520	40900	46420	2534	12324	14858
100+	350	4200	4550	264	2063	2327
Total	25425850	26388950	51814800	274767	295366	570133

$$s=(m-\tfrac{1}{2}d)/(m+\tfrac{1}{2}d)$$

that is, the ratio of the number alive at the end of a period to those alive at its start.

Then hazard rate h and survival probability s for survival over the year are related as

$$s=(2-h)/(2+h)$$

and

$$h=2(1-s)/(1+s)$$

Hazard rates increase markedly with age in adults. Table 1 shows mid-year population sizes by sex and age group (from census data), along with numbers of deaths at these ages (from the death registration systems), for England and Wales, 1995. Dividing deaths by mid-year populations produces age specific death rates.

Table 1 is a life table summarised in five year intervals, but the original data were available by individual year, and are shown in figure 1 for men and women. This figure also includes rates for Scotland. The hazard rates are a very good fit to a log-linear curve (which means that we can estimate, from the grouped data, rates for individual ages of 90 and above by log-linear extrapolation). The observed rates for Scotland (1996 data) show somewhat greater scatter, because of the smaller population size.

The probability of surviving over a number of one year periods is calculated by multiplying together the individual one year survival probabilities. Among other things, this permits the calculation of a complete survival curve from a set of hazards, such as in table 1. This table shows the mortality experienced in one year by separate birth cohorts. However, the life

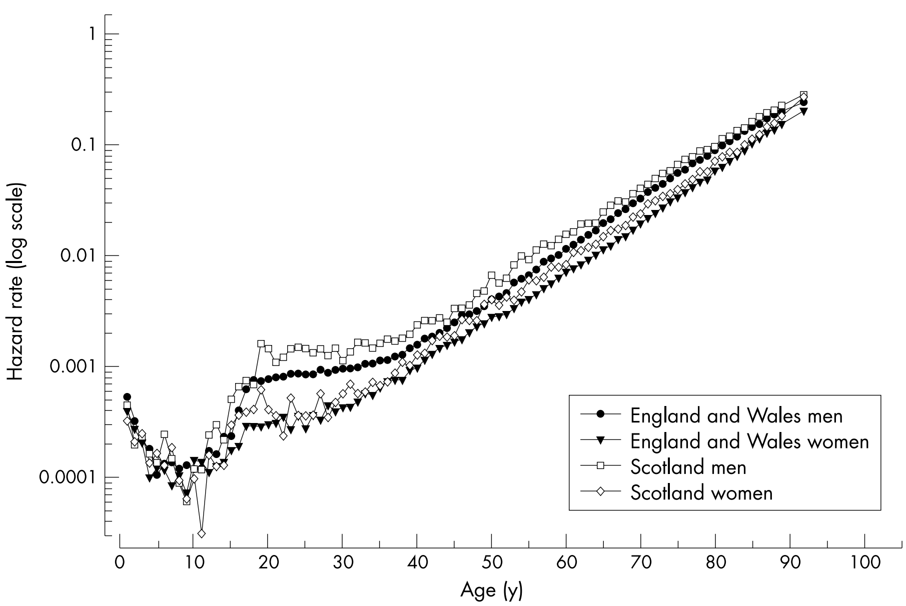

Figure 1 Hazard ratios by sex and one year age groups (a) England and Wales, 1995, (b) Scotland, 1996.

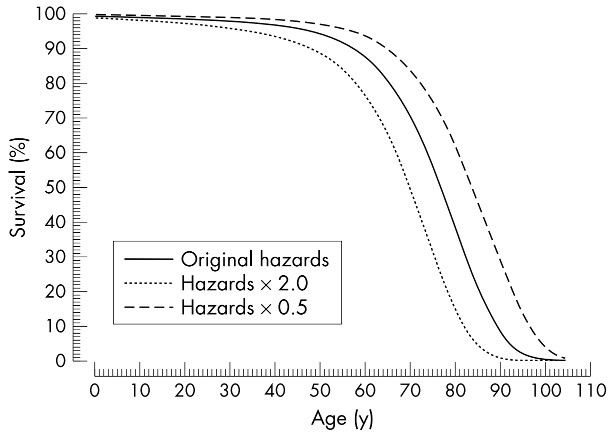

Figure 2 Cumulative survival for men, based on England and Wales, 1995 (solid line). Broken lines show survival curves for hazards doubled or halved throughout.

table constructed from these rates is relevant to a theoretical birth cohort that will experience these rates as its surviving members age. Figure 2 (solid line) shows the estimated survival curve for males based on the hazard rates in England and Wales, 1995.

We can summarise mortality experience, and compare across cohorts, in units of the life year (or person year). An individual who is alive at the start of a year and survives to the end lives exactly one whole life year, while one who dies during the year provides only a fraction of a life year. If we do not have exact dates of death, we can continue with the actuarial assumption that half have occurred by mid-year. (Then the total life years for a given age group and year equals the size of the mid-year population.)

The survival curve for a birth cohort predicts the temporal pattern of deaths in the cohort. Expected (average) length of life from birth can be calculated easily by summing the life years over all periods and dividing by the size of the starting population. Conditional life expectancy, having reached a particular age, can also be calculated by summing the years of life at that age and later, and dividing by the number achieving that age. Some example results for England and Wales and for Scotland are shown in table 2, which also shows that the results may be summarised as the percentage reaching a stated age. All the indices show the somewhat lower life expectancy in the Scottish population than in England and Wales, plus the usual sex difference in life expectancy. These mirror the differences in the hazard rates in figure 1.

QUANTIFYING DIFFERENCES BETWEEN SURVIVAL CURVES

We may treat the solid line in figure 2 as a reference group. This figure also shows the survival curves generated by two other sets of hazard rates. The longer dashes in the graph trace out the survival for a hypothetical male group whose annual hazards are half those of the reference group, while the shorter dashes are for another group whose hazards are twice those of the reference group. We note that even twofold differences in hazards produce quite similar looking curves.

There are a number of ways to characterise the difference between two survival curves, and the choice may be driven by the context in which the question is asked. We may compare the difference in the average life expectancy (which is equivalent to comparing the area under the two curves); or we may compare the position of specific points on the curve, for example, what proportion survive to a particular age. Table 2 shows predictions from the baseline hazards for men and women, of three measures of life expectancy (expected length of remaining life, conditional % expected to survive to ages 65 and 75), conditional on achieving a range of ages. Table 3 shows examples of the impact on these three measures of a 1% reduction in hazard rates at all ages 30 and above, in a single birth cohort. It is interesting to note that, despite the difference in

Table 2 Life expectancy, by age and sex. Estimated from baseline hazards for England and Wales, 1995 and Scotland, 1996

		Male			Female		
Age at start of follow-up	Country	Expected life remaining (years)	Expected survival to age 65 (%)	Expected survival to age 75 (%)	Expected life remaining (years)	Expected survival to age 65 (%)	Expected survival to age 75 (%)
0	Eng & Wales	74.18	81.00	56.02	79.43	88.01	71.03
	Scotland	71.99	75.63	49.09	77.74	85.24	66.17
10	Eng & Wales	64.82	81.72	56.52	69.98	88.63	71.53
	Scotland	62.61	76.30	49.51	68.29	85.87	66.65
20	Eng & Wales	55.06	82.06	56.75	60.11	88.81	71.68
	Scotland	52.92	76.74	49.68	58.43	86.07	66.80
30	Eng & Wales	45.51	82.79	57.26	50.29	89.11	71.92
	Scotland	43.53	77.69	50.29	48.66	86.43	67.09
40	Eng & Wales	35.98	83.77	57.93	40.59	89.71	72.40
	Scotland	34.15	78.95	51.04	39.00	87.12	97.62
50	Eng & Wales	26.77	85.96	59.45	31.20	91.27	73.67
	Scotland	25.12	81.65	52.50	29.73	89.02	69.10
60	Eng & Wales	18.34	92.39	63.90	22.38	95.50	77.08
	Scotland	17.17	90.29	56.94	21.17	94.37	73.25
70	Eng & Wales	11.41	100.00	79.42	14.61	100.00	87.43
	Scotland	10.71	100.00	70.89	13.77	100.00	85.62
80	Eng & Wales	6.46	100.00	100.00	8.47	100.00	100.00
	Scotland	6.07	100.00	100.00	7.95	100.00	100.00

Table 3 Average expectation from birth of length of life and attainment of ages 65 and 75: comparing baseline hazard rates (England and Wales 1995, Scotland 1996) and the impact of a 1% reduction in hazard rates in subjects 30 years and over

		Male			Female		
Parameter	Country	Baseline hazards	Impacted hazards	Gain	Baseline hazards	Impacted hazards	Gain
Expected length of life (y)	Eng & Wales	74.18	74.27	0.09	79.43	79.53	0.10
	Scotland	71.99	72.09	0.10	77.74	77.83	0.09
% reaching age 65	Eng & Wales	81.00	81.15	0.15	88.01	88.11	0.10
	Scotland	75.63	75.82	0.19	85.24	85.37	0.13
% reaching age 75	Eng & Wales	56.02	56.33	0.31	71.03	71.27	0.24
	Scotland	49.09	49.42	0.34	66.17	66.43	0.26

Table 4 Schematic layout showing organisation of data, and life-table calculations for prediction of mortality effects

		Year												
		1995	1996	- - -	1999	2000	2001	2002	- - -	j	- - -	2103	2104	2105
Age	Entry popn	Births	b_1	- - -	b_5	b_6	b_7	b_8	- - -	b_i	- - -	b_{108}	b_{109}	b_{110}
0	e_0	h_0	h_0		h_0	$\mathbf{h_0}$	h_0	h_0		h_0		h_0	h_0	h_0
1	e_1	h_1	h_1		h_1	h_1	$\mathbf{h_1}$	h_1		h_1		h_1	h_1	h_1
2	e_2	h_2	h_2		h_2	h_2	h_2	$\mathbf{h_2}$		h_2		h_2	h_2	h_2
↓														
i	e_i	h_i	h_i		h_i	h_i	h_i	h_i		$\mathbf{h_{i,j}}$		h_i	h_i	h_i
↓														
103	e_{103}	h_{103}	h_{103}		h_{103}	h_{103}	h_{103}	h_{103}		h_{103}		$\mathbf{h_{103}}$	h_{103}	h_{103}
104	e_{104}	h_{104}	h_{104}		h_{104}	h_{104}	h_{104}	h_{104}		h_{104}		h_{104}	$\mathbf{h_{104}}$	h_{104}
105	e_{105}	h_{105}	h_{105}		h_{105}	h_{105}	h_{105}	h_{105}		h_{105}		h_{105}	h_{105}	$\mathbf{h_{105}}$

e, entry population; b, births; h, hazard rate.

Table 5 Schematic layout showing pattern of predicted output from mortality simulations

	Year												
Age	1995	1996	- - - -	1999	2000	2001	2002	- - - -	j	- - - -	2103	2104	2105
0	d y	d y		d y	**d y**	d y	d y		d y		d y	d y	d y
1	d y	d y		d y	**d y**	**d y**	d y		d y		d y	d y	d y
2	d y	d y		d y	**d y**	**d y**	**d y**		d y		d y	d y	d y
↓													
i	d y	d y		d y	**d y**	**d y**	**d y**		$\mathbf{d_{ij}y_{ij}}$		d y	d y	d y
↓													
103	d y	d y		d y	**d y**	**d y**	**d y**		**d y**		**d y**	d y	d y
104	d y	d y		d y	**d y**	**d y**	**d y**		**d y**		**d y**	**d y**	d y
105	d y	d y		d y	**d y**	**d y**	**d y**		**d y**		**d y**	**d y**	**d y**

d, number of deaths; y, total person years.

baseline expectations between sexes and between countries, the predicted gains are similar, particularly in terms of expected life years.

APPLICATION TO IMPACT ASSESSMENT

For a typical impact assessment, for example, of a change in air pollution concentration, we need first to predict how a change in concentrations will affect future hazards, then to quantify the ensuing change in predicted mortality, using measures such as life years.

To estimate impacts on a whole population, it is important to distinguish clearly between the separate dimensions of age and calendar time. This can be seen in the layout of table 4, which highlights that the hazard rates for each age specific cohort lie on a diagonal of this table (shown in bold type), and we calculate cumulative survival probabilities and life years down each diagonal. This layout has similarities to the Lexis diagrams of age-period cohort analyses in epidemiology.[11] The rectangular layout is easily set up in standard spreadsheet applications. Then outputs such as numbers of deaths and life years can be calculated for each cell of the layout, as in table 5.

The entry populations and hazard rates for 1995 in table 4 are easily completed using available published data, but subsequent columns represent the unknown future. The standard assumption would use hazards from 1995 for England and Wales (1996 for Scotland). We emphasise that this is only one of many possible assumptions, but that any projection into the future must be based on some assumptions, which need to be stated explicitly. Whatever assumptions are made, the matrix layout can accommodate the appropriate hazards.

Impact assessment requires quantification of the impact of a *change* in hazard rates. We treat the calculations done so far as representing a *baseline* future scenario; then, we may change the hazard matrix in table 4 to reflect the impact in which we

Key points

- Standard life table methods of calculation are useful for impact assessments.
- We can compare future predictions between a range of hypothesised scenarios, including impacts on specific causes of death.
- Spreadsheets are a convenient tool for organising the calculation across age and calendar year.
- There is complete flexibility in how the results are summarised.
- Weights for economic or other values can be applied to the results.

are interested, representing an *impacted* future scenario; and quantify the predicted impact on mortality by comparing the outputs of table 5 for baseline and impacted scenarios.

We may set up any pattern of change we desire in the impacted hazard rates, either by age or by calendar time. Thus impacts can be restricted to particular age groups, or differ by age; they may follow an intervention immediately, or after a fixed delay, or phase in gradually. Choices will be guided by the assumptions that seem plausible in a particular application.

The spreadsheet approach has the advantage that results of intermediate calculations are always visible by inspection of the relevant worksheet. Complete flexibility in patterns of assumed impacts is achieved by storing age specific and year specific impact factors (1 for no change, <1 for a reduction in hazard, >1 for an increase) in a separate worksheet, which is multiplied cell-wise by the hazard matrix to produce hazards for the impacted scenario.

QUANTIFYING AND SUMMARISING IMPACTS

Once more, the matrix layout of table 5 allows for great flexibility to answer a variety of questions that might interest the policy maker. For example, we might envisage a change taking place that would affect mortality hazards from the year 2000 onwards, and ask what would be the impact on the population alive at the start of 2000. Their mortality experience will lie within the area of bold type in table 5. Thus one way to quantify the impact is as the difference between the life years experienced under the baseline and impacted scenarios, totalled over the grey triangle. Alternatively, we might ask about the predicted change in life years for everyone over a given time period, and include part-life contributions from cohorts born in 2000 and later, summarising over a rectangular area of table 5 rather than a triangle.

It is also possible to apply weights to the elements of table 5 before we summarise, and again the weights may be held in a separate worksheet so that they can vary across the age and/or time dimensions of the matrix. This permits the calculation of quality adjusted or disability adjusted life years (QALYs or DALYs), which give less weight to years lived at older ages because average quality of life is reduced.[12] If a summary in terms of economic value is desired, additional or alternative weights can be economic values attached to a life year, and again we can choose to apply lower values per life year at older ages. In addition, for cost-benefit analyses informing policy, it is customary to apply discounting (at a fixed rate per year, akin to compound interest). The effect of discounting is to reduce the current economic value of future life years, and place more emphasis on changes in life years in the immediate future. Combinations of age specific values and discounting are easily set up in the spreadsheet format.

CAUSE SPECIFIC IMPACTS

In some circumstances, we may wish to consider the effect of a change on a specific cause, or group of causes, of death. In the context of air pollution, the data suggest that effects are concentrated in cardiorespiratory causes.[3]

Broad groups of causes of death behave as if statistically independent, and hazard rates are then additive.[13] The introduction of cause specific impacts then becomes three separate steps:

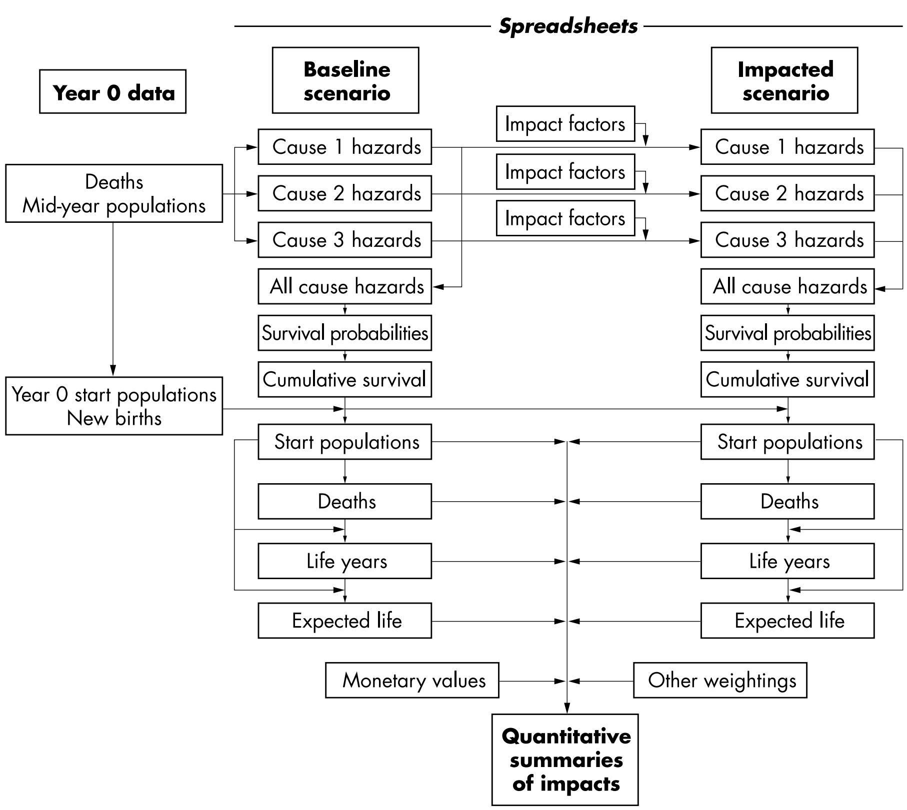

Figure 3 Schematic diagram showing sequence of spreadsheet calculations.

Table 6 Predicted gain in total life years for 1% and 5% reductions in hazard rates for ages 30 and above in populations alive in 2000 in England and Wales and in Scotland, by delay to full impact on hazards

Country	Population alive at start of 2000 (estimated)	Response	Reduction in all cause hazards	Delay to full impact (y)		
				0	15	30
England & Wales	52452000	Total life years gained (millions)	1%	4.7	3.7	2.7
			5%	23.5	18.8	13.7
		Life years gained (thousands) per 100000 population	1%	8.9	7.0	5.1
			5%	44.8	35.8	26.1
Scotland	5146000	Total life years gained (millions)	1%	0.46	0.36	0.26
			5%	2.4	1.9	1.6
		Life years gained (thousands) per 100000 population	1%	9.0	7.0	5.0
			5%	45.9	36.1	30.7

- obtain a breakdown of baseline hazard rates by cause group;
- apply separate impact factors to each group;
- recombine the impacted hazard rates into impacted all cause hazard rates.

Figure 3 is a schematic diagram that summarises the whole sequence of calculations. It shows the relations between and among the input data and calculated spreadsheets used in doing the calculations. In addition, it shows the steps entailed in dealing with three separate cause groups and their separate impacts. Of course, the number of cause groups can be varied as desired.

EXAMPLE RESULTS

Table 6 shows the results of some sample calculations. These are shown as an example, and no claim is made that the particular set of assumptions adopted are optimal; other assumptions would produce different predictions. In addition, we show results only for an impact operating on all cause hazard rates.

From the 1995 data for England and Wales, an estimated start of year population for 1995 was derived. Age specific baseline hazard rates from 1996 onwards were assumed equal to those for 1995, and the mortality patterns implied by those baseline patterns were calculated. Similar calculations produced baseline predictions for Scotland, based on the 1996 data.

For the impacted scenarios, both sets of hazard rates were reduced uniformly by 1%, from the year 2000 onwards. The reductions were applied to hazards for those aged 30 years and above only. Additional impacted scenarios applied the 1% reduction after delays of various lengths, so that the hazard rates remained unaltered until 2015 or 2030, after which they were reduced by 1%. Mortality patterns were calculated for each impacted scenario. Gains from a 1% change in hazard were very similar in men and women, and have been combined here in a single total. The results shown are for the impact on the population estimated alive at the beginning of 2000, as in the triangle of data in bold type in table 5.

Table 6 shows the total impact of the change, showing a saving of over 5 million life years for a 1% reduction in adult hazards across Great Britain. This scales to about 9000 life years per 100 000 population, which may be more useful when comparing or transferring impacts across national borders. Results could also be scaled per person, but here would represent weighted averages over cohorts of all ages. Despite the differences in underlying hazards, the average scaled impact for Scotland was almost exactly the same as for England and Wales; insensitivity of the total impact to the absolute level of baseline risks has been observed over a number of impact assessment scenarios. In addition, the impacts for a 5% reduction in hazards were almost exactly five times those for a 1% reduction, particularly for immediate effect or short delay. Linearity is to be expected for small changes, and is useful because estimates for other sizes of impacts may be obtained by interpolation.

DISCUSSION

Calculations based on life tables are standard in demography and in actuarial science,[14–16] and have been used to estimate impacts of changes in hazards in a number of contexts, including air pollution effects.[17 18] However, the organisation of the calculations within a matrix that separates the dimensions of age and calendar time seems not to have been made explicit in the present context of health risk impact assessment.

The matrix formulation has a number of useful features. It matches the structure of spreadsheets, which can be set up and programmed to perform all the calculations, and in which all the intermediate calculations and results are accessible by inspection. It permits complete flexibility in specifying age specific, year specific, and sex specific patterns of baseline hazards. There is corresponding flexibility in the choice of the impacts that can be applied to these hazards, and to any economic or other weights to be applied to the outputs. Perhaps most importantly, the process of filling the matrices with actual numbers highlights the many assumptions about future conditions that are implied by that process, but which are not always quite so explicitly stated. There is further flexibility in how, and for what subpopulations, the results are summarised. Finally, the life table formulation requires no assumptions about the functional shape of the survival curve or about relations between hazard rates and the age distribution of the target population.

For reasons of space, we have shown only some example results, but over several projects we have noted some consistent trends. Perhaps the most useful is that, for a given proportional change in hazards, the total predicted impact is not very sensitive to the level of the original hazards. Although Scotland has higher hazards than England and Wales, the impact in life years of a 1% reduction in those hazards is almost identical. We have seen this in comparisons between the sexes and between social classes, and also between countries.[6]

The results given here quantify the effects of a 1% reduction in all cause mortality hazards, independently of the reason for or source of the reduction; we would predict the same total impact for any natural occurrence or human intervention that resulted in a 1% reduction in hazard. In the context of air pollution reduction, the results of the US cohort studies might be taken to suggest that a reduction of 2.5 $\mu g/m^3$ in ambient PM_{10} concentration would be associated with about a 1% reduction in hazard.[3] Gains in life expectancy can be scaled linearly for other hazard reductions or equivalent amounts of pollution reduction.

The results we have shown as examples have been for the impacts of changes in all cause mortality, but we have shown how cause specific impacts can be incorporated. As with the assumptions made at each stage of the calculation process, assumptions can be varied and their effect on results can and should be quantified, in programmes of sensitivity analyses.

ACKNOWLEDGEMENTS

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