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.

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 primarily 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, and recent reanalyses of their data 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”) can give approximate estimates for short periods of future prediction, but they can be misleading for long term predictions. However, standard methods of life table calculation, which permits maximum flexibility 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 and to provide updated estimates of impact for the UK Committee on the Medical Effects of Air Pollution (COMEAP). 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. 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. 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 \(m\)

\[
h = \frac{d}{m}
\]

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

$$s = \frac{(2-h)}{(2+h)}$$

and

$$h = 2\frac{(1-s)}{(1+s)}$$

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

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

**Figure 1** Hazard ratios by sex and one year age groups (a) England and Wales, 1993, (b) Scotland, 1996.
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

<table>
<thead>
<tr>
<th>Age at start of follow-up (years)</th>
<th>Country</th>
<th>Male</th>
<th>Female</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Expected life remaining (years)</td>
<td>Expected survival to age 65 (%)</td>
</tr>
<tr>
<td>0</td>
<td>Eng &amp; Wales</td>
<td>74.18</td>
<td>56.02</td>
</tr>
<tr>
<td></td>
<td>Scotland</td>
<td>71.99</td>
<td>49.09</td>
</tr>
<tr>
<td>10</td>
<td>Eng &amp; Wales</td>
<td>64.82</td>
<td>56.52</td>
</tr>
<tr>
<td></td>
<td>Scotland</td>
<td>62.61</td>
<td>49.51</td>
</tr>
<tr>
<td>20</td>
<td>Eng &amp; Wales</td>
<td>55.06</td>
<td>57.75</td>
</tr>
<tr>
<td></td>
<td>Scotland</td>
<td>52.92</td>
<td>49.68</td>
</tr>
<tr>
<td>30</td>
<td>Eng &amp; Wales</td>
<td>45.51</td>
<td>57.26</td>
</tr>
<tr>
<td></td>
<td>Scotland</td>
<td>43.53</td>
<td>50.29</td>
</tr>
<tr>
<td>40</td>
<td>Eng &amp; Wales</td>
<td>35.98</td>
<td>57.93</td>
</tr>
<tr>
<td></td>
<td>Scotland</td>
<td>34.15</td>
<td>51.04</td>
</tr>
<tr>
<td>50</td>
<td>Eng &amp; Wales</td>
<td>26.77</td>
<td>59.45</td>
</tr>
<tr>
<td></td>
<td>Scotland</td>
<td>25.12</td>
<td>52.50</td>
</tr>
<tr>
<td>60</td>
<td>Eng &amp; Wales</td>
<td>18.34</td>
<td>63.90</td>
</tr>
<tr>
<td></td>
<td>Scotland</td>
<td>17.17</td>
<td>56.94</td>
</tr>
<tr>
<td>70</td>
<td>Eng &amp; Wales</td>
<td>11.41</td>
<td>79.42</td>
</tr>
<tr>
<td></td>
<td>Scotland</td>
<td>10.71</td>
<td>70.89</td>
</tr>
<tr>
<td>80</td>
<td>Eng &amp; Wales</td>
<td>6.46</td>
<td>100.00</td>
</tr>
<tr>
<td></td>
<td>Scotland</td>
<td>6.07</td>
<td>100.00</td>
</tr>
</tbody>
</table>
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. 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

<table>
<thead>
<tr>
<th>Table 3</th>
<th>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</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameter</td>
<td>Country</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Expected length of life (y)</td>
<td>Eng &amp; Wales</td>
</tr>
<tr>
<td></td>
<td>Scotland</td>
</tr>
<tr>
<td>% reaching age 65</td>
<td>Eng &amp; Wales</td>
</tr>
<tr>
<td></td>
<td>Scotland</td>
</tr>
<tr>
<td>% reaching age 75</td>
<td>Eng &amp; Wales</td>
</tr>
<tr>
<td></td>
<td>Scotland</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 4</th>
<th>Schematic layout showing organisation of data, and life-table calculations for prediction of mortality effects</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age</td>
<td>Entry popn</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>e0</td>
</tr>
<tr>
<td>1</td>
<td>e1</td>
</tr>
<tr>
<td>2</td>
<td>e2</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>103</td>
<td>e103</td>
</tr>
<tr>
<td>104</td>
<td>e104</td>
</tr>
<tr>
<td>105</td>
<td>e105</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 5</th>
<th>Schematic layout showing pattern of predicted output from mortality simulations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age</td>
<td>Year</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>d0</td>
</tr>
<tr>
<td>1</td>
<td>d1</td>
</tr>
<tr>
<td>2</td>
<td>d2</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>103</td>
<td>d103</td>
</tr>
<tr>
<td>104</td>
<td>d104</td>
</tr>
<tr>
<td>105</td>
<td>d105</td>
</tr>
</tbody>
</table>

| Parameter | Country | Male | | Female |
| | | 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 |
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. 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.

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

![Figure 3](http://jech.bmj.com/)

**Figure 3** Schematic diagram showing sequence of spreadsheet calculations.
rates.

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

impacts. Of course, the number of cause groups can be varied
in dealing with three separate cause groups and their separate
doing the calculations. In addition, it shows the steps entailed
among the input data and calculated spreadsheets used in

• 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 par-
ticular set of assumptions adopted are optimal; other assump-
tions 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 pro-
duced 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 repre-
sent 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% reduc-
tion 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, and have been used to estimate
impacts of changes in hazards in a number of contexts,
including air pollution effects. 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 eco-

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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

<table>
<thead>
<tr>
<th>Country</th>
<th>Population alive at start of 2000 (estimated)</th>
<th>Response</th>
<th>Reduction in all cause hazards</th>
<th>Delay to full impact (y)</th>
</tr>
</thead>
<tbody>
<tr>
<td>England &amp; Wales</td>
<td>52452000</td>
<td>Total life years gained (millions)</td>
<td>1%</td>
<td>4.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Life years gained (thousands) per 100000 population</td>
<td>1%</td>
<td>8.9</td>
</tr>
<tr>
<td>Scotland</td>
<td>5146000</td>
<td>Total life years gained (millions)</td>
<td>5%</td>
<td>44.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Life years gained (thousands) per 100000 population</td>
<td>5%</td>
<td>44.8</td>
</tr>
</tbody>
</table>
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

The methods described here were developed during the European Commission's ExternE project, and in work for the UK power generation industry. Further developments, including the adaptation to spreadsheets, were commissioned by the Department of Health, for its Committee on the Medical Effects of Air Pollution (COMEAP). The work on the Scottish data was funded by the MacRobert Trust.

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Life table methods for quantitative impact assessments in chronic mortality

B G Miller and J F Hurley

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