UNDERLYING AND MULTIPLE CAUSE MORTALITY AT ADVANCED AGES: UNITED STATES 1980-1998

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INTRODUCTION

The period 1980-1998 witnessed substantial improvements in the health and mortality of the elderly (age 65+), the old-old (age 75-84), and the oldest-old (age 85+). Overall life expectancy at age 75 increased by 8.7 percent. Among males, however, the increase was 13.6 percent; and among females, 6.1 percent. Improvements in life expectancy resulted from declines in mortality, and these declines exhibited different patterns for different sexes, causes of death, and time periods. For example, during 1980-1998 stroke mortality declined 39 percent, heart disease mortality declined 37 percent, and cancer mortality declined 7 percent. The temporal rates of change were not constant, however. During 1980-1990 stroke declined 32.1 percent, heart disease declined 24.8 percent, but cancer increased 1.7 percent. During 1990-1998 stroke declined 9.4 percent, heart disease declined 16.7 percent, and cancer declined 8.4 percent.

Actuaries are generally familiar with the use of cause specific mortality data to analyze and forecast future mortality patterns. Such data are based on death certificate reports of the single disease, medical condition, or event judged to be solely responsible for each death, termed the "underlying cause of death". Less well known is the fact that several causes of death are typically listed on death certificates of elderly decedents. These are termed the "multiple cause of death" listings, and are routinely recorded in U.S. national data files prepared annually by the National Center for Health Statistics.

Increasingly it is the case that death is due not just to one single disease but to a complex set of interacting pathological processes. In these cases the designation of any single disease as the underlying cause of death provides a distorted description of the causal pathways. The multiple cause of death data, with its listing of each disease contributing to death, provides the opportunity to quantify the nature and extent of distortions induced by the underlying cause of death concept, and simultaneously provides the information needed to develop appropriate remedies.

This paper evaluates age and sex specific patterns of change in underlying and multiple cause of death reports for the period 1980-1998 for 14 leading causes of death at ages 65 and older. The complexity of disease processes leading to death will be measured using the joint frequency distributions of the multiple cause death reports for the 14 leading causes and a residual cause category. Changes in four types of mortality measures will be analyzed: (1) underlying cause death rates; (2) multiple cause death rates; (3) associated (i.e., non-underlying) cause death rates; and (4) death rates based on the joint occurrences of multiple cause conditions.

Implications of the results are discussed in the context of existing models for analyzing and forecasting future mortality patterns in the U.S.

DATA

We focus on mortality data for three years: 1980, 1990, and 1998. For these three years, the total number of deaths in the United States was 1.99 million, 2.15 million, and 2.34 million, respectively. Death certificate data for each individual death were obtained from the National Center for Health Statistics (NCHS, 2001b). Mortality data were tabulated for all ages and the results for age 65+ were extracted for the analyses reported in this paper.

Tabulations were conducted by age (last birthday) at death, sex, underlying cause (UC) of death, and multiple cause (MC) of death. The MC tabulations employed the

record axis multiple cause of death codes, which are the codes that best describe the overall medical certification portion of the death certificate. We also constructed an associated cause (AC) of death tabulation by removing the UC information from the MC information.

To understand the MC tabulations, it is useful to consider the form of the medical certification. This portion of the death certificate is completed by the person who pronounces or certifies the death. There are two parts:

1. Part I describes the chain of events that directly cause the death. These events are listed in reverse chronological order and include relevant diseases, injuries, or complications forming the causal chain. The first item listed is the immediate cause, defined as the final disease or condition causing death; the second item is the disease or condition, if any, that led to the immediate cause; the third item is the disease or condition, if any, that led to the secondary cause; and so on. The underlying cause is generally defined as the last listed cause on Part I.
2. Part II is used to list other significant conditions contributing to death that are not part of the causal sequence leading to the underlying cause listed in Part I. Where there is ambiguity or uncertainty in the causal sequence, Part II is used to list other conditions or diseases not included in Part I.

Under these rules, the underlying cause of death is defined as:

> "(a) the disease or injury which initiated the train of events leading directly to death, or (b) the circumstances of the accident or violence which produced the fatal injury" (WHO, 1977).

The multiple causes of death are the entire set of diseases, injuries, or complications listed on Parts I or II of the medical condition field of the death certificate. The associated causes of death are all listed multiple causes of death except the underlying cause.

All cause of death data reported on death certificates filed in the period 1979-1998 were computer coded according to the Ninth Revision of the International Classification of Diseases (ICD-9: WHO, 1977). The ICD-9 includes rules for selection of the underlying cause of death in cases where the listed sequence does not conform to medical knowledge (Manton and Stallard, 1984). NCHS has implemented computer editing rules that translate the listed conditions on Parts I and II into an equivalent set that removes ambiguities, discrepancies, or contradictions induced by the ICD-9 coding rules, yielding a set of codes suitable for person-based tabulations of multiple cause of death data. In this paper, we verify that the underlying cause of death is included with the multiple cause of death data, and if not, we add it in.

The ICD-9 includes 5,570 distinct causes of death. This level of detail is far beyond the level needed for our analysis. NCHS uses a list of 72 select causes of death in its tabulations. This is still too detailed for our analysis. However, an appropriate set derives from the top 15 causes in 1998 (Murphy, 2000), modified by deletion of accidents and homicide, and supplemented with aortic aneurysm and a residual category that includes all diseases and conditions not part of the 14 specified diseases (see Table 1).

We deleted accidents and homocide from the list in Table 1 because these are external causes of death which are not under the control of the decedent. We retained suicide, however, because this cause is clearly under his/her control, and it was of interest to evaluate the medical conditions associated with suicide in the elderly. We added aortic

aneurysm to the list because Hoyert et al. (2001) reported that atherosclerosis, which had been ranked in the top 15 causes for over 40 years, was replaced by aortic aneurysm in the top 15 causes in 1999. Our list combines the ranking at the end of the ICD-9 study period 1980-1998 with that at the start of the ICD-10 period in 1999. Thus, this list is constructed to be the most relevant going forward in time.

The MC condition field on each individual death certificate record was edited to reflect the presence or absence of each of the 15 diseases defined in Table 1. Except for Alzheimer's disease in 1980, all of the annual disease mortality counts far exceed Longley-Cook's (1962) standard of at least 1,082 deaths for full credibility. Thus, the use of top ranked diseases ensures that statistical variation will not be an issue in our comparisons.

Population data were obtained from the U.S. Bureau of the Census, along with estimates of net census undercount used to adjust the raw census data. Population counts above age 94 were replaced with population estimates based on national mortality counts using the method of extinct cohorts described in Manton and Stallard (1996). For ages 86-94, the final population estimates were obtained by blending Census-based estimates with extinct cohort estimates, starting with a 90%-10% blend at age 86 and progressing linearly to a 10%-90% blend at age 94.

METHODS

Tabulations

The analyses are based on three tabulations of the UC, MC, and AC mortality data and three tabulations of statistics of the MC data. We distinguish between person-based tabulations and disease-based tabulations. In person-based tabulations, each individual decedent generally contributes a count of one to the table and the entire table reflects the number of decedents with the indicated combinations of characteristics. In disease-based tabulations, each disease on the medical condition field contributes a count of one to the table and the entire table reflects the number of diseases occurring on decedent records with the indicated combinations of disease or decedent characteristics.

We define each table by specifying its dimensions and their sizes. Given the large number of tables, we use the following conventions in their manipulation:

1. For any specified table, lower dimensional marginal tables are indicated by naming only the retained dimensions, with the marginal counts obtained by summing over all omitted dimensions. In cases where the summation is over the age dimension, we will generally employ age-standardization procedures (see below).
2. For ratio tables, lower dimensional marginal tables and subtables are obtained by applying convention 1 to the numerator and denominator tables prior to constructing the ratios.
3. For ratio tables, if the denominator table has fewer dimensions than the numerator table, the denominator table will be replicated for each category of each additional dimension in the numerator table. This convention is useful when the denominator table is a population tabulation and the ratios are, in fact, death rates. (The converse is undefined.)

The UC-Table is a person-based tabulation defined as follows:

UC-Table = UC(15) by AGE(8) by SEX(2) by YEAR(3),

where

UC = Underlying cause of death, using the 15-category classification in Table 1;
AGE = Age last birthday, 8 five-year groupings: 65-69, 70-74, … , 95-99, 100+;
SEX = Sex, 2 categories: male and female;
YEAR = Data year, 3 categories: 1980, 1990, and 1998.

The MC-Table is a disease-based tabulation defined as follows:

MC-Table = MC(15) by AGE(8) by SEX(2) by YEAR(3),

where

MC = Multiple cause of death, using the 15-category classification in Table 1.

The remaining dimensions are the same as in the UC-Table. The MC-Table may be incremented from 1 to 15 times for each decedent, depending on the number of diseases listed on the medical condition field.

The AC-Table is a disease-based tabulation defined as follows:

AC-Table = AC(15) by AGE(8) by SEX(2) by YEAR(3),

where

AC = Associated cause of death, using the 15-category classification in Table 1.

The remaining dimensions are the same as in the UC- and MC-Tables. The AC-Table may be incremented from 0 to 14 times for each decedent, depending on the number of diseases listed on the medical condition field.

To analyze the information in the MC-, UC-, and AC-Tables, we observe the following identity:

MC-Table = UC-Table + AC-Table,

where addition is performed on a cell by cell basis. Dividing both sides of this equation by UC-Table (on a cell by cell basis) yields:

MC/UC-Table = **1**-Table + AC/UC-Table,

where MC/UC-Table is a table of ratios of MC to UC death counts, AC/UC-Table is a table of ratios of AC to UC death counts, and **1**-Table is a table of one's. These tables reflect the average physiological tolerance of each disease as a factor in causing death, with the more lethal or severe diseases having lower MC/UC ratios (Manton and Stallard, 1982).

There are two additional tables that reflect the complexity of the medical condition fields. The first is a person-based tabulation of the number of listed medical conditions (NC-Table) for each decedent, defined as follows:

NC-Table = UC(15) by AGE(8) by SEX(2) by YEAR(3),

where the table has the same dimensions as the UC-Table. The increment to the NC-Table ranges from 1 to 15 for each decedent, depending on the number of diseases listed on the medical condition field. The average number of listed medical conditions is obtained by dividing the NC-Table by the UC-Table (on a cell by cell basis):

NC/UC-Table = NC-Table / UC-Table.

The second is a person-based tabulation of the joint frequencies of all 15 diseases in the medical condition field (JF-Table), an 18-dimensional table defined as follows:

JF-Table = MC1(2) by … by MC15(2) by AGE(8) by SEX(2) by YEAR(3),

where

$$\text{MC}i = \begin{cases} 1, & \text{if disease } i \text{ is listed in the medical condition field;} \\ 0, & \text{otherwise.} \end{cases}$$

This table yields in MC*i*-category 1 of its MC*i*-AGE-SEX-YEAR marginal table the same count found in MC-category *i* of the MC-Table. Pairwise joint frequencies of causes *i* and *j* obtain from the MC*i*-MC*j*-AGE-SEX-YEAR marginal table. Similarly, 3-way joint frequencies of causes *i, j*, and *k* obtain from the MC*i*-MC*j*-MC*k*-AGE-SEX-YEAR marginal table.

To evaluate the JF-Table and its various marginal tables, we define a table of expected joint frequencies (EJF-Table) under the assumption that the diseases are independent Bernoulli events in the death certification process, with age-, sex-, and year-specific probabilities for each disease *i* proportional to the relative frequencies in the MC*i*-AGE-SEX-YEAR marginal table. Thus, applying those probabilities to the total number of deaths in the AGE-SEX-YEAR marginal JF-table, we obtain:

EJF-Table = MC1(2) by … by MC15(2) by AGE(8) by SEX(2) by YEAR(3).

The ratio of the observed JF-Table to the expected EJF-Table then provides an empirical measure of the association of the diseases:

JF/EJF-Table = JF-Table / EJF-Table,

where division is performed on a cell by cell basis.

Finally, the population data can be arrayed by age, sex, and year as follows:

POP-Table = AGE(8) by SEX(2) by YEAR(3),

which corresponds to the outer dimensions of the mortality tables. Death rate tables are obtained as ratios of mortality to population tables, using convention 3 (defined above) that the POP-Table will be replicated for each category of each disease dimension in the mortality table. For example, the UC death rate table is defined as:

UC/POP-Table = UC-Table / POP-Table.

Similarly, the MC and AC death rate tables are defined as:

MC/POP-Table = MC-Table / POP-Table,

and

AC/POP-Table = AC-Table / POP-Table.

Age Standardization

Comparison of death rates and ratios over time and over subpopulations is facilitated by controlling for differences in the age structures of the different populations. Demographers typically rely on age standardization (or, equivalently, age adjustment) procedures to accomplish this task.

The age standardized death rate (ASDR) for cause *k* in sex *s* in year *y* is defined as the death rate that would occur in a standard population under the schedule of age-specific death rates $\{m_{kasy}\}$ observed for cause *k* at age *a* in sex *s* in year *y*, or

$$\text{ASDR}_{ksy} = \sum_a m_{kasy} P_a^* / \sum_a P_a^* ,$$

where

$$m_{kasy} = n_{kasy} / P_{asy} ,$$

where $\{n_{kasy}\}$ is the age-specific death counts observed for cause *k* at age *a* in sex *s* in year *y*, $\{P_{asy}\}$ is the corresponding exposed population, and $\{P_a^*\}$ is the age-specific standard population.

The age standardized death count (ASDC) for cause *k* in sex *s* in year *y* is the numerator of the ASDR:

$$\text{ASDC}_{ksy} = \sum_a n_{kasy} P_a^* / P_{asy} .$$

ASDCs can be computed for any of the tables defined above. Ratios of ASDCs from any two tables are equal to the ratios of the corresponding ASDRs. For certain tables (e.g. the NC-Table), the ASDCs are more readily interpretable than the ASDRs.

The analyst has discretion with respect to the choice of the standard population. We set the standard population $\{P_a^*\}$ equal to the age-specific unisex population count for 1990. Table 2 shows that there is a gradual shift to older ages in the distribution of component age groups within the age 65+ population, and that the 1990 distribution is intermediate between the 1980 and 1998 distribution. Thus, unisex ASDRs based on the 1990 population will be somewhat higher than the crude (i.e., unstandardized or unadjusted) death rates for 1980 and somewhat lower for 1998, with 1990 unchanged.

RESULTS

Life Expectancies

Actuarial and demographic analysis of mortality typically focuses on the timing of death and little attention is given to the cause or causes of death. To establish the context of the changes in the timing of death over the past 40 years, Table 3 displays unisex and sex-specific life expectancies at age 65 beginning in 1960 and age 75 beginning in 1980. The table shows that there has been a fairly steady increase of 0.9 years per decade (unisex and females; 0.8 for males) in age 65 life expectancy throughout the period, the two

exceptions being the slowdowns for males in the 1960s and for females in the 1990s. The age 75 life expectancies increased 0.5 years per decade (unisex; 0.7 for males, 0.4 for females) with the sex difference attributable to the female slowdown during the 1990s. These results suggest that female mortality data for the 1990s may change less than for the 1980s or for males in both decades.

ASDRs

Table 4 presents ASDRs for the 14 causes of death plus the residual using the UC-, MC-, and AC-Tables to define the causes. The ASDRs in Table 4 are restricted to elderly persons aged 65 and older. Murphy's (2000) rankings are based on the 1998 unisex death counts summed over all ages. Thus, some shifts in rank are expected. For the first six causes, the rank order in Table 4 is the same as Murphy's. Suicide drops from 7^{th} to 14^{th}; chronic liver disease/cirrhosis drops from 9^{th} to 13^{th}; and the remaining shifts are minor.

As expected, large temporal declines in heart diseases and cerebrovascular diseases account for the overall reduction in the ASDR total for all causes of death. Large relative declines also occurred for atherosclerosis. Moderate declines occurred for chronic liver disease/cirrhosis; and for aortic aneurysm. Malignant neoplasms, suicide, and pneumonia/influenza had the highest ASDRs in 1990, consistent with a peaking of death rates for the former and the lack of a trend for the latter two (Murphy, 2000). The rest of the diseases (except residual causes) exhibited upward trends. The 1980-1990 increase for Alzheimer's disease was by a factor of 10, indicating a rapid increase in importance attached to this disease by death certifiers during the early 1980s.

The MC death rates are sums of the UC and AC death rates. The 1998 AC ASDRs deviate significantly from Murphy's (2000) ranking. Hypertension moves from 13^{th} to 2^{nd}; malignant neoplasms move from 2^{nd} to 9^{th}. Of the top 6, only heart diseases hold their rank (1^{st}). Suicide ranks last because it is virtually always selected as the underlying cause – and exception being an unsuccessful attempt followed by death from a natural cause.

MC/UC Ratios

Table 5 presents MC/UC ratios based on the ASDRs in Table 4. The variation over disease in the unisex MC/UC ratios is substantial, ranging from 1.01 for suicide to 12.54 for hypertension. The higher the ratio, the more tolerable the disease or condition. Heart diseases, malignant neoplasms, cerebrovascular diseases, chronic liver disease/cirrhosis, and aortic aneurysm, all have unisex ratios below 2.0 in all three years; and Alzheimer's disease is below 2.0 in 1998. This indicates that when these diseases are mentioned there is a greater than 50% chance that they will be the underlying cause of death. Except for hypertension, the ratios for the remaining diseases (including Alzheimer's disease in 1980 and 1990) are in the range 2.0-5.9 indicating that these diseases are primarily associated causes, not underlying causes. Nonetheless, they are sufficient to cause death in a substantial fraction of cases.

The AC/UC ratios are also presented in Table 5, and are each 1.0 less than the corresponding MC/UC ratios. Since each death must have at least one cause, the AC/UC ratios provide measures of the excess reporting of each cause in the MC data. This is the component of mortality that is missing from traditional analyses of cause-specific mortality based only on UC data.

Table 6 presents the age-specific unisex MC/UC ratios, along with the crude (unadjusted) and adjusted (ASDC) marginal ratios. For these ratios, the impact of age standardization is relatively minor. The age-specific ratios for all causes combined increase from age 65-69 to 80-84 and decline thereafter. Substantial declines (implying decreasing tolerance) over age are noted for heart diseases, cerebrovascular diseases, pneumonia/influenza, nephritis/nephrosis, septicemia, atherosclerosis, hypertension, and residual causes. Substantial increases (implying increasing tolerance) over age are noted for malignant neoplasms, chronic obstructive pulmonary diseases, chronic liver disease/cirrhosis, and aortic aneurysm. Diabetes mellitus, suicide, and Alzheimer's disease are stable over age.

Corresponding results for males and females are presented in Tables 7 and 8, respectively. The age trends follow the unisex trends in Table 6, except for chronic obstructive pulmonary diseases for males, where the 1998 ratios decline with age, indicating decreased tolerance.

Average Number of MC Conditions per UC

Tables 9-11 present the average number of MC conditions reported in the medical condition field, by UC categories and year, in a format corresponding to that of Tables 6-8. The averages over all causes in Tables 9-11 are identical to the MC/UC ratios for all causes in Tables 6-8.

Differences occur in the body of the tables due to the different methods of constructing the numerators of the ratios. The AC and UC components of the numerators of the MC/UC ratios in Tables 6-8 are based on deaths of different persons. The NC counts that form the numerators of the NC/UC ratios in Tables 9-11 are based on summations of the total number of medical conditions reported on the MC condition fields for individuals sharing the same UC. Thus, the average number of conditions per UC in Tables 9-11 reflects the complexity of the mortality process for individuals sharing the same UC. As in Tables 6-8, the minimum value of these averages is 1.0 since each death has at least one cause (the UC). One must subtract 1.0 from the averages to obtain the average number of AC conditions per UC.

The unisex ASDC averages for all causes combined range from 1.99 to 2.04, with almost identical results for males and females. These ratios increased from 1980 to 1990 and dropped slightly in 1998. In other words, the average number of AC conditions increased by about 5% from 1980 to 1990 and dropped 2% by 1998. The highest age-specific ratios are at ages 75-79 and 80-84; the ratios at ages 65-69 and 95-99 are about 0.10 lower; the lowest averages are for age 100+. Depending on the year, there are 10-23% fewer AC conditions at age 100+ compared with age 80-84. This pattern indicates that the greatest complexity in cause of death patterns occurs at age 75-84, which may reflect more aggressive medical treatment of lethal diseases at these ages. The drop-off at older ages may reflect increased frailty and reduced capacity/willingness of older persons to tolerate aggressive treatments.

The variation of the ASDC averages by UC is substantially narrower than that of the MC/UC ratios in Tables 6-8, ranging from 1.84 (heart diseases, 1980) to 2.90 (diabetes mellitus, 1980). In addition to heart diseases, the ASDC averages for malignant neoplasms and residual causes are below 2.0; however, the age-specific averages for malignant neoplasms exceed 2.0 beginning at age 90-94 (1980 and 1990). The temporal

changes in the ASDC averages are monotonic upwards for heart diseases and diabetes mellitus; monotonic downwards for septicemia; and mixed upward-downward for the rest.

The age patterns in Table 9 follow those of Table 6, except for heart diseases and hypertension which are flat in Table 9 but decline in Table 6, and aortic aneurysm which declines in Table 9 but increases in Table 6. Similar patterns are evident for males and females in Tables 10 and 11.

Special coding rules are evident for suicide. Under the ICD-9 (WHO, 1977), each external cause of death must be paired with one or more nature of injury codes ("N" codes) that indicate the precise injury that occurred as a result of the external insult. Thus the average number of MC conditions for each suicide should be at least 2.0. The ASDC average in 2.12-2.15 – indicating that a single injury code is generally sufficient to describe the death. The next subsection will show that there is very little joint reporting of the other 13 ranked conditions with suicide.

Pairwise Disease Associations

To evaluate associations of diseases and changes in those associations one must examine statistics on the joint distributions. Table 12 presents ratios of the observed to expected age standardized joint frequencies of each pair of the 15 diseases, for unisex mortality, by year.

Ratios greater than 1.0 indicate an association (equivalent to a positive correlation of the disease indicator variables). Ratios greater than 2.0 are considered large. The following associations are in rank order by strength of association in 1998, with the 1998 ratio and secular trend indicated in parentheses:

1. Diseases of heart –
   - Diabetes mellitus (1.33 -- increasing);
   - Hypertension (1.20 -- increasing);
   - Atherosclerosis (1.15 – increasing),
   - Nephritis/nephrosis (1.12 -- increasing);
   - Chronic obstructive pulmonary diseases (1.02 -- mixed change).
2. Malignant neoplasms –
   - None.
3. Cerebrovascular diseases –
   - Hypertension (2.13 -- increasing);
   - Atherosclerosis (1.95 – increasing),
   - Diabetes mellitus (1.41 -- mixed changes).
4. Chronic obstructive pulmonary diseases --
   - Pneumonia/influenza (1.50 -- stable);
   - Residual (1.19 -- mixed changes);
   - Diseases of heart (1.02 -- mixed changes).
5. Pneumonia/influenza –
   - Septicemia (2.03 -- increasing);
   - Chronic obstructive pulmonary diseases (1.50 -- stable);
   - Alzheimer's disease (1.41 -- decreasing);
   - Residual (1.18 -- mixed changes);
   - Nephritis/nephrosis (1.08 -- stable).

6. Diabetes mellitus
    Hypertension (2.57 -- increasing);
    Nephritis/nephrosis (1.79 -- increasing);
    Atherosclerosis (1.72 – increasing),
    Cerebrovascular diseases (1.41 -- mixed changes);
    Diseases of heart (1.33 -- increasing);
    Septicemia (1.21 -- stable);
    Chronic liver/cirrhosis (1.08 -- increasing).
7. Suicide –
    Residual (2.18 -- decreasing).
8. Nephritis/nephrosis --
    Septicemia (2.20 -- mixed changes);
    Diabetes mellitus (1.79 -- increasing);
    Chronic liver/cirrhosis (1.70 -- mixed changes);
    Atherosclerosis (1.35 – increasing),
    Residual (1.15 -- decreasing);
    Aortic aneurysm (1.14 -- decreasing);
    Diseases of heart (1.12 -- increasing);
    Pneumonia/influenza (1.08 --stable).
9. Chronic liver/cirrhosis --
    Nephritis/nephrosis (1.70 -- mixed changes);
    Residual (1.58 -- mixed changes);
    Septicemia (1.29 -- increasing);
    Diabetes mellitus (1.08 -- increasing).
10. Septicemia –
    Nephritis/nephrosis (2.20 -- mixed changes);
    Pneumonia/influenza (2.03 -- increasing);
    Residual (1.52 -- decreasing);
    Chronic liver/cirrhosis (1.29 -- mixed changes);
    Diabetes mellitus (1.21 -- increasing).
11. Alzheimer's disease --
    Pneumonia/influenza (1.41 -- decreasing).
12. Atherosclerosis --
    Cerebrovascular diseases (1.95 – increasing),
    Diabetes mellitus (1.72 – increasing),
    Hypertension (1.62 – mixed changes),
    Nephritis/nephrosis (1.35 – increasing),
    Diseases of heart (1.15 – increasing),
    Aortic aneurysm (1.11 – increasing).
13. Hypertension --
    Diabetes mellitus (2.57 -- increasing);
    Cerebrovascular diseases (2.13 -- mixed changes);
    Aortic aneurysm (1.87 -- mixed changes);
    Atherosclerosis (1.62 – mixed changes),
    Diseases of heart (1.20 -- increasing);
    Residual (1.06 -- increasing).

14. Aortic aneurysm --

Hypertension (1.87 -- mixed changes);
Nephritis/nephrosis (1.14 -- decreasing);
Atherosclerosis (1.11 – increasing).

Corresponding results for 1998 for males vs. females are in Tables 10. The following additions and deletions are noted for the unisex associations provided above:

Cerebrovascular diseases –

Residual (1.03 -- add for males).

Chronic obstructive pulmonary diseases --

Aortic aneurysm (1.05 -- add for females).

Diabetes mellitus

Chronic liver/cirrhosis (0.99 -- delete for males).

Nephritis/nephrosis --

Aortic aneurysm (0.98 -- delete for females);

Aortic aneurysm --

Chronic obstructive pulmonary diseases (1.05 -- add for females).

Corresponding results for 1998 for ages 68-84 vs. 85+ in are in Tables 11. The following deletions are noted at age 85+ for the age 65+ associations provided above:

Pneumonia/influenza –

Nephritis/nephrosis (0.96).

Nephritis/nephrosis --

Pneumonia/influenza (0.96);
Aortic aneurysm (0.96).

Aortic aneurysm --

Nephritis/nephrosis (0.96).

Three-Way Disease Associations

The joint frequency tables can be used to evaluate higher order associations of diseases in the MC data. Table 15 presents ratios of the observed to expected age standardized joint frequencies of each 3-way combination of the 15 diseases, for unisex mortality in 1998. The 105 distinct pairwise combinations form the rows of the table; the 13 possible alternative diseases form the columns; the two columns in each panel corresponding to the row pair have null entries. The 23 strongest associations, all with ratios above 2.0 and listed according to Murphy's (2000) ranking, are as follows:

Diseases of heart & Diabetes mellitus & Hypertension (3.32)
Diseases of heart & Diabetes mellitus & Nephritis/nephrosis (2.26)
Diseases of heart & Diabetes mellitus & Atherosclerosis (2.14)

Cerebrovascular diseases & Diabetes mellitus & Hypertension (4.99)
Cerebrovascular diseases & Diabetes mellitus & Atherosclerosis (3.63)
Cerebrovascular diseases & Atherosclerosis & Hypertension (4.35)
Cerebrovascular diseases & Hypertension & Residual diseases (2.04)

Chronic obstructive pulmonary diseases & Pneumonia/influenza & Septicemia (2.08)
Chronic obstructive pulmonary diseases & Hypertension & Aortic aneurysm (2.21)

Pneumonia/influenza & Diabetes mellitus & Septicemia (2.05)
Pneumonia/influenza & Nephritis/nephrosis & Septicemia (3.93)
Pneumonia/influenza & Septicemia & Residual diseases (2.55)

Diabetes mellitus & Nephritis/nephrosis & Chronic liver disease/cirrhosis (2.05)
Diabetes mellitus & Nephritis/nephrosis & Septicemia (3.48)
Diabetes mellitus & Nephritis/nephrosis & Atherosclerosis (3.11)
Diabetes mellitus & Septicemia & Hypertension (2.06)
Diabetes mellitus & Atherosclerosis & Hypertension (4.43)
Diabetes mellitus & Hypertension & Residual diseases (2.39)

Nephritis/nephrosis & Chronic liver disease/cirrhosis & Septicemia (3.84)
Nephritis/nephrosis & Chronic liver disease/cirrhosis & Residual diseases (2.75)
Nephritis/nephrosis & Septicemia & Residual diseases (3.19)

Chronic liver disease/cirrhosis & Septicemia & Residual diseases (2.23)

Atherosclerosis & Hypertension & Aortic aneurysm (3.40).

The three strongest associations, with ratios in the range 4.35-4.99, involve various combinations of cerebrovascular diseases, diabetes mellitus, atherosclerosis, and hypertension. These same four diseases exhibited pairwise ratios in the range 1.41-2.57 for the 1998 unisex results in Table 12. Table 4 shows that two of the diseases (cerebrovascular diseases and atherosclerosis) exhibited strong temporal declines in the MC ASDRs 1980-1998; one (hypertension) exhibited strong temporal increases; and one (diabetes mellitus) exhibited a mixed pattern of temporal changes. The net impact of these changes is that the 3-way ratios, which were in the range 3.08-3.80 in 1980, increased by 1.19-1.35, with most of the increase occurring by 1990.

DISCUSSION

Several lessons can be learned from this analysis.

First, recent declines in mortality rates were not distributed evenly over the 15 disease categories of underlying and multiple causes of death. Major declines were seen for heart diseases and cerebrovascular diseases; malignant neoplasms reached a peak in the early 1990s and have begun to decline since that time; increased mortality rates were seen for chronic obstructive pulmonary diseases, diabetes mellitus, Alzheimer's disease, nephritis/nephrosis, septicemia, hypertension, and residual causes. Thus, successes against the top three major killers did not translate into successes against many of the lower ranked diseases.

Second, diseases can play different roles in the mortality process and it is appropriate to consider models in which certain diseases are viewed as lethal sequelae of other underlying conditions. Infectious diseases appear to fit this model well. This would suggest that the associations of septicemia with nephritis/nephrosis, chronic liver diseases, and diabetes mellitus were all as sequelae of these chronic diseases. Similarly the association of pneumonia/influenza with chronic obstructive pulmonary diseases and

nephritis/nephrosis also occurs as sequelae of these chronic diseases. Alternatively, some diseases may function in a contributory role as background risk factors for other diseases. This could account for the associations of hypertension, diabetes mellitus, and atherosclerosis with each other and with cerebrovascular diseases and heart diseases. These roles may change with age, however, since the MC/UC ratios for all but diabetes mellitus decline, implying decreased tolerance, at older ages.

Third, an understanding of the dynamics of cause-specific mortality in the period 1980-1998 is essential to an understanding of concurrent gains in life expectancy, to an understanding of the apparent slowdown in gains for females in the period 1990-1998, and to our ability to accurately forecast the rates of reduction in mortality in future years. Understanding these dynamics requires that we develop models that integrate the death certificate information on all causes of death and their evolving associations with other information on the health and functioning of the older population in the years preceding mortality.

Hummer et al. (1998, p. 568) noted that, although three types of multiple cause coding schemes have been developed (MC death rates, MC/UC ratios, and joint frequency death rates), the multiple cause mortality data are rarely used because of the complex nature of the outcomes of such analyses. This paper attempted to resolve this problem by recasting the joint frequencies in the more familiar form of ratios of observed to expected counts, where the expectation is based on a simple independence assumption. For the pairwise associations, the ratios attain the value 1.0 precisely at the point where the product-moment correlation is 0.0. Ratios greater than 1.0 correspond to positive correlations; ratios less than 1.0 correspond to negative correlations. However, observed/expected ratios are easier to interpret than correlations and the generalization to higher order associations is more straightforward.

Given that one can manage the complexity of the multiple cause data, the question then arises as to what one gains by doing so. Lee and Tuljapurkar (1998) commented that if the goal is to forecast total death rates then it is unnecessary to consider cause of death data and related risk factors and lifestyle behaviors. On the other hand, if the goal is to model the health status of the population, which is relevant to forecasts of health care costs, then the multiple cause mortality data are relevant as endpoints of the health status process. Any health status model that fails to represent major temporal, age, and gender trends in those data can be rejected. Given the different patterns of change between the AC and UC death rates and ratios, and the changing tolerances for these diseases over age, one could expect that models based solely on UC data would not represent the MC and AC trends with sufficient accuracy for health status forecasting applications.

Additional areas of application of multiple cause mortality data will develop as these data are linked to ongoing national population surveys such as the National Health Interview Survey (NHIS; currently linked for interviews conducted in 1986-1994) and the National Long Term Care Survey (NLTCS; linkage planned for all interviews 1982-1999). By combining data on medical conditions/diseases currently affecting the older population with data from the MC condition fields from death certificates filed after they have died, one could more accurately model the development of chronic diseases and associated conditions. The NLTCS linkage is expected to permit the representation of chronic disability in a more comprehensive model of morbidity, disability, and mortality.

Integrating all of these components into a single model will be a major challenge for actuaries, demographers, and gerontologists.

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