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Triangle Simplex Plot for Representing Multiple Cause of Death Dynamics*

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Abstract: Underlying causes of death offer only a partial insight into cause-specific mortality trends. A complementary approach, known as multiple cause of death analysis, which includes all conditions listed on the death certificate, can deepen understanding of cause of death dynamics in at least two ways – through the development of mortality rates from contributory causes and the analysis of changes in the roles that diseases play in the lethal process. The objective of this paper is to revisit cause of death analysis in Czechia, Denmark and the United States (USA) over the last two decades, focusing on the context of underlying cause of death (UCD) mortality trends. This includes trends in contributory causes and changes in the roles played by causes of death in the death process. We use a visualisation tool that combines age-standardised death rates with simplex plots and Lexis plots to illustrate changes in the role that diseases play, differentiating between UCD, contributory cause in Part 2, and non-UCD in Part 1. The simplex plot assigns a colour based on the role composition of a disease by age and year. It then serves as a colour legend for the Lexis diagram to display role shifts in leading causes of death by age and period. Dementia and Alzheimer's disease, ischemic heart disease, and cerebrovascular disease experienced temporal role changes in the death process across all countries studied. Age-dependent role changes were observed in particular in Denmark for pneumonia, alcohol-related diseases, and other infections. Some diseases exhibited contradictory trends in mortality rates from both the underlying and contributory cause perspectives, especially diabetes and chronic obstructive pulmonary disease (COPD) in Czechia, and sepsis and dementia in the USA and Denmark. By combining simplex and Lexis plots with mortality rates, we provided context for trends in mortality rates by underlying causes, which is in turn relevant for understanding cause of death dynamics. It is important to underscore the variations in death certification processes specific to each country.

Keywords: Multiple causes of death · Death certification · Contributory causes · International comparison

* This article has an Online Appendix with supplementary material: https://www.comparativepopulationstudies.de/index.php/CPoS/article/view/768/464

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1 Introduction

The aim of cause of death data is to provide information on the health profiles of individual populations (*Fedeli et al.* 2015; *Redelings et al.* 2006; *Trias-Llimós/Permanyer* 2023). The underlying causes of death – conditions initiating the chain of morbid events leading to death (*WHO* 2024) – constitute the primary empirical evidence for formulating fundamental health theories that describe the transition from infectious and parasitic mortality to chronic, degenerative, and man-made diseases (*Rogers/Crimmings* 2011; *Mackenbach* 2022).

Low-mortality countries, however, have reached a point where the majority of deaths occur in old age, typically following a prolonged period of disease accumulation. Consequently, relying solely on the underlying cause of death (UCD) has become increasingly restrictive in terms of accurately describing the health profile of such populations, as attributing death to a single cause in old age becomes problematic (*Meslé* 2007; *Alpérovitch et al.* 2009). Moreover, the UCD offers a limited perspective on health even in populations experiencing high premature mortality. This is because it fails to consider the multimorbidity burden typical of such populations, as well as other key factors contributing to death, such as drug overdoses (*Hoopsick/Yockey* 2023).

Consequently, the past decade has seen an increase in the use of multiple cause of death (MCD) data (*Bishop et al.* 2023a), thus offering a complementary approach to UCD analysis by incorporating all medical information recorded on death certificates.

The research on MCD has produced several key findings about the death process: frequently underestimated conditions that accompany death but are not recorded as the UCD have been identified (*Mackenbach et al.* 1999; *Fedeli et al.* 2015, 2016; *Romon et al.* 2008; *Adair et al.* 2022; *Désesquelles et al.* 2014; *Quinones et al.* 2015; *Redelings et al.* 2006; *Park* 2016); associations and interactions among causes have been estimated (*Egidi et al.* 2018; *Désesquelles et al.* 2010; *Pechholdová* 2017; *Goldberger et al.* 2015; *Ukolova* 2025); methods for combining multiple causes into a single mixture of causes (so-called weighting techniques) have been proposed (*Piffaretti et al.* 2016; *Moreno-Betancur et al.* 2017; *Dobson et al.* 2023); diversification of causes has been examined (*Trias-Llimós/Permanyer* 2023); and algorithms for reconstructing multimorbid death processes have been developed (*Grippo et al.* 2024). The importance of MCD became particularly evident during the COVID-19 pandemic, which pushed non-COVID conditions into non-underlying positions on death certificates and thereby limited understanding of the burden of associated diseases (*Petit et al.* 2024; *Li et al.* 2025) – even for common disease groups such as dementias (*Basso et al.* 2023) and cardiovascular diseases (*Ukolova/Burcin* 2024).

This paper builds on the perspective of MCD as a complementary approach to UCD analysis, viewing time trends in mortality intensity from UCD as merely the tip of the iceberg of changes in health status, which can be analysed using death certificate data. In addition to UCD trends, we use this data to track shifts in the roles that diseases listed on death certificates play in the lethal process. The role of a condition in the lethal process can be inferred from its location on the death

certificate. In developed countries, the section of the death certificate where causes of death are recorded is typically divided into two parts (see Online Appendix A1). Part 1 records the sequence of morbid events leading to death, fundamentally categorising the causes based on their roles as initiators of this chain (possibly UCD) and their subsequent conditions, often referred to as immediate and intermediate causes (*Eurostat* 2026; *National Center for Health Statistics* 2023). Part 2 comprises conditions that are merely contributory, without a direct relation to the UCD but possessing the potential to elevate the risk of death (*Eurostat* 2026; *National Center for Health Statistics* 2023).

The importance of the role aspect can be illustrated by the following example: standard cause of death statistics based on UCD indicate a decreasing trend in mortality intensity due to condition i. Assuming that a death has been certified in the proper manner, this decline could be attributed to two main effects. First, the disease burden of this condition in the population may indeed be decreasing. Second, the role of disease i in the lethal process may have changed, for instance, due to the rise of another disease that often leads to the development of i, thereby pushing i into non-UCD positions. Even when condition i is pushed into a non-UCD position, it may still be classed as a necessary condition for the transition to the "death state". This implies that both effects offer different yet important insights into the dynamics of population health. However, the second effect (role change) is often overlooked in cause of death analyses. Focusing on this effect, this paper offers a novel visual approach to exploring the compositional changes in causes of death by age and over time.

An equally important finding highlighted by the published MCD studies is the substantial regional variability in the recording of deaths (*Désesquelles et al.* 2012). This is evident in the average number of conditions reported on death certificates (authors' calculations based on *MultiCause Network Data* 2009), as well as in the significant disparities in the prevalence of certain conditions (*Désesquelles et al.* 2012, *Goldberger et al.* 2015; *Lu/Lin* 2010). We therefore use three distinct independent cause of death (COD) data sources to demonstrate our approach: those from Denmark, Czechia, and the USA.

These three countries differ widely in both cause-specific mortality and how COD data is collected and processed (see Online Appendix A2). However, they share one common trait: despite all being high-income countries, they each lag behind other lowest mortality "western" countries for different reasons. In Denmark, stagnation in mortality improvements began as early as 1975 (*Juel et al.* 2000), leaving the country behind other Nordic nations with which it shares similarities in terms of culture, history, and healthcare systems (*Aburto et al.* 2018). The key factors behind these unfavourable trends are the late effects of smoking-attributable mortality and high burden of cancer (*Juel et al.* 2000; *Jarner et al.* 2008). In contrast, mortality in Czechia is still heavily shaped by residual factors of the socialist regime from the 1960s to the 1990s (*Lotrič et al.* 2019; *Rychtarikova* 2004). During this period, not only did life expectancy stagnate, but in men, it even declined due to cardiovascular disease mortality and unhealthy lifestyle (*Bartoňová* 2008). Since the 1990s, Czechia has shown a promising recovery; however, it remains burdened by high levels of

avoidable mortality and multimorbidity (*Burcin/Kučera* 2008; *OECD/European Commission* 2024; *Burcin* 2008). In the USA, the rate at which life expectancy has been improving has been slowing since the 1980s, with an even more pronounced stagnation starting in the 2010s (*Woolf* 2023). This is primarily attributed to rising mid-life mortality caused by drug overdoses, alcohol-related diseases and obesity, which was not offset by further declines in old-age mortality (*Case/Deaton*, 2017). The objective of this paper is to revisit cause of death analysis in these three countries over the last two decades, focusing on the context of UCD mortality trends – which includes trends in contributory causes and changes in the roles of COD in the death process – using a visual approach. This makes the paper a substantive contribution because it provides a multidimensional analysis of causes of death by type over time using three data sources.

2 Data

For each country, we extracted individual death records that include all medical information documented on the death certificate for the entire analysis period: from 2002 to 2022 in Denmark, from 1998 to 2023 in Czechia, and from 1999 to 2022 in the USA. The process of collecting cause of death data varies between the three countries and is described in greater detail in Online Appendix A2. Notably, in Czechia, there were significant changes in this process around 2007 and 2012, linked to the implementation of automated cause of death data processing and updates to the death certificate form (*UZIS* 2025; *Daňková* 2016). This form is now similar across all three countries and is consistent with the WHO format (see Online Appendix A1). However, there are differences in the total number of conditions that can be recorded, which may, in turn, influence MCD data. In Part 2, the maximum number of conditions allowed is five in Denmark, nine in Czechia, and up to 20 in the USA (*Statistics Denmark* 2025; *UZIS* 2025; *NCHS* 2025a).

Above, we described how the positions in which causes of death are recorded on the death certificate can distinguish the roles that these causes have played in the lethal process. Based on these positions, we classify causes into three separate types to derive their respective roles in the death process:

1. The underlying cause of death (UCD) is the medical condition identified at the end of the automated selection process as having initiated the sequence of morbid events leading to death.
2. Non-underlying conditions in Part 1 (non-UCD1) are defined as the conditions recorded in Part 1 of the death certificate that are not automatically selected as initiators of the identified chains.
3. Contributory conditions in Part 2 (CC2) refer to all conditions listed in Part 2 of the death certificate as recorded by the death certifier.

In the definitions above, we use the term "automated selection" of the UCD. This refers to the application of decision tables that describe all possible causal relationships between diseases, in order to identify a disease that likely did not occur due to another condition. In the USA, this process of automated selection is carried

out using the Automated Classification of Medical Entities (ACME) tables, while both Denmark and Czechia use the Iris software (*Iris* 2022; *NCHS* 2025b). Iris integrates the ACME tables with additional algorithms that convert raw medical records written in different languages into internationally standardised codes for diseases, which are used for statistical purposes (*Kretschmerová* 2006; *Poppová* 2011).

Using the positions on the death certificate to identify the roles inherently introduces biases stemming from the subjective judgment of death certifiers, as has been documented in a number of earlier studies (*Fedeli et al.* 2015; *Wall et al.* 2005; *Laanani et al.* 2023). However, our emphasis focuses specifically on how the judgment of the death certifier evolves over time, particularly with regard to which causes they believe directly lead to death (recorded in Part 1) and which do not (recorded in Part 2).

In all three countries, causes of death are originally recorded using at least 3-digit ICD-10 codes. We aggregated the causes of death in accordance with the Multiple Causes of Death list created by *Bishop et al.* (2023b), which is provided in Online Appendix A3. This list categorises diseases into approximately 100 categories while maintaining sufficient medical detail and enabling the study of interrelations between MCD (*Bishop et al.* 2023b). At this level of detail, we identify the leading diagnoses recorded on death certificates in 2019 across major cause of death groups: cardiovascular, respiratory, infectious, metabolic, and mental and nervous diseases. We exclude neoplasms because preliminary analyses have shown that they are almost exclusively classified as the UCD when listed on the death certificate, with rates of 96.7 percent in the USA and Czechia, and 98.5 percent in Denmark in 2019 (authors' calculations). For such selected conditions, we present the main results. Additionally, in Online Appendix A5, we provide results at the level of main ICD chapters to illustrate the general trends in changes to the roles that diseases play, primarily distinguished by the organ systems they affect.

To calculate the mortality rates, we also use population exposure data, downloaded from the Human Mortality Database (*HMD* 2025) for Czechia and the USA. For the most recent years in Czechia (2022-2023) and the complete period for Denmark, population exposure data are sourced from national statistical offices (*Statistics Denmark* 2025; *Czech Statistical Office* 2025).

3 Methods

For each disease and country, we present a figure with three panels: (i) a line plot showing trends in age-standardised rates by UCD and contributory condition (CC); (ii) a Lexis diagram illustrating the changing roles of the causes of death and (iii) a simplex plot that functions as a colour legend for the Lexis diagram, detailing the magnitude of compositional change. A description of these panels is provided below.

The first panel of each visualisation, starting from the left, presents age-standardised death rates over time by UCD and CC, which encompasses deaths with CC in Part 2, as well as non-UCD in Part 1. These rates are computed by dividing

the respective number of deaths by cause and role by the population exposure, then multiplying by the standard population, which was the European Standard Population 2013 (*Eurostat* 2013).

The second panel of each visualisation shows a Lexis diagram illustrating both age-specific and time-specific changes in the roles of diseases. The colour legend for the Lexis diagram is displayed in the third panel as a triangle simplex plot. Simplex plots are equilateral triangles, where each axis defines a unique coordinate of compositional data across three dimensions (Fig. 1): the proportions at which a cause was recorded as UCD, CC in Part 2, and non-UCD in Part 1. These proportions are calculated by age and over time, with each point on the simplex plots representing a single age group for a specific year. The points are assigned a shade of RGB colour, which is subsequently used to fill the corresponding age-period region within the Lexis diagram.

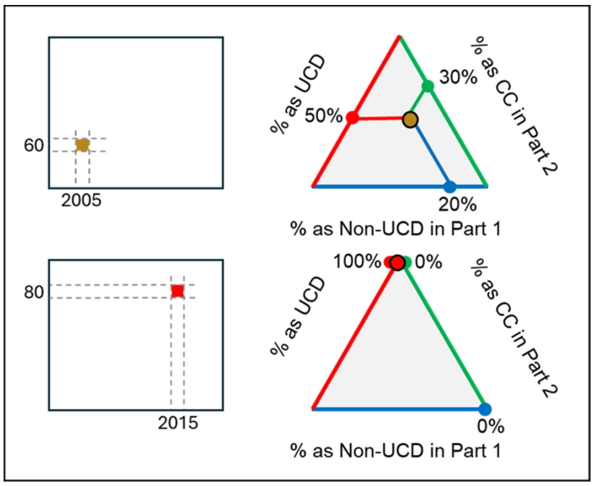
Changes in the composition of each COD (or role changes) are reflected in the Lexis plots through variations in colour. Shades of red indicate a high occurrence of a disease recorded as UCD, while blue denotes a dominance of non-UCD in Part 1, and green signifies that the COD is primarily recorded as a CC in Part 2. Diseases that have experienced substantial changes in their role composition are represented by vibrant Lexis plots and by a high degree of variability in the points on the simplex plots. A similar method for visualising compositional data was used previously by *Schöley/Willekens* (2017).

Figure 1 provides an example of how to interpret the Lexis plots and simplex diagrams for a hypothetical disease *i*. In 2005, at age 60, this disease was classified as UCD in half of its records, as non-UCD in Part 1 in 20 percent of its records, and as CC in Part 2 in the remaining 30 percent. This composition determines both the position of the data point for age 60 in 2005 on the simplex plot and the colour of the corresponding age-period region on the Lexis plot. The same interpretation applies to disease *i* at age 80 in 2015, where the disease is recorded exclusively as UCD.

To read the coordinates of a point, draw a line that intersects this point and runs parallel to the previous side of the triangle, in a clockwise direction. For example, to read the weight in UCD, draw a line parallel to the "Non-UCD in Part 1" axis. In other words, we determine that the point for age 60 in 2005 is recorded as 50 percent UCD by drawing a line through that point which is parallel to the base of the triangle (the axis representing weights as non-UCD in Part 1). Similarly, the weight of 30 percent recorded as CC in Part 2 was determined by drawing a line parallel to the UCD axis through the data point for age 60 in 2005.

The visualisations were produced in R version 4.4.1. In Online Appendix A4, we provide the R code used for this purpose. We used the following packages to produce the figures: Ternary (*Smith* 2017), gridExtra (*Baptiste* 2017), png (*Urbanek* 2022), ggplot2 *(Wickham et al.* 2016), dplyr (*Wickham et al.* 2023), tidyr (*Wickham et al.* 2025).

Fig. 1: Simplex plot and Lexis plot for visualising disease dynamics in the lethal process, illustrative example



Source: own design

4 Results

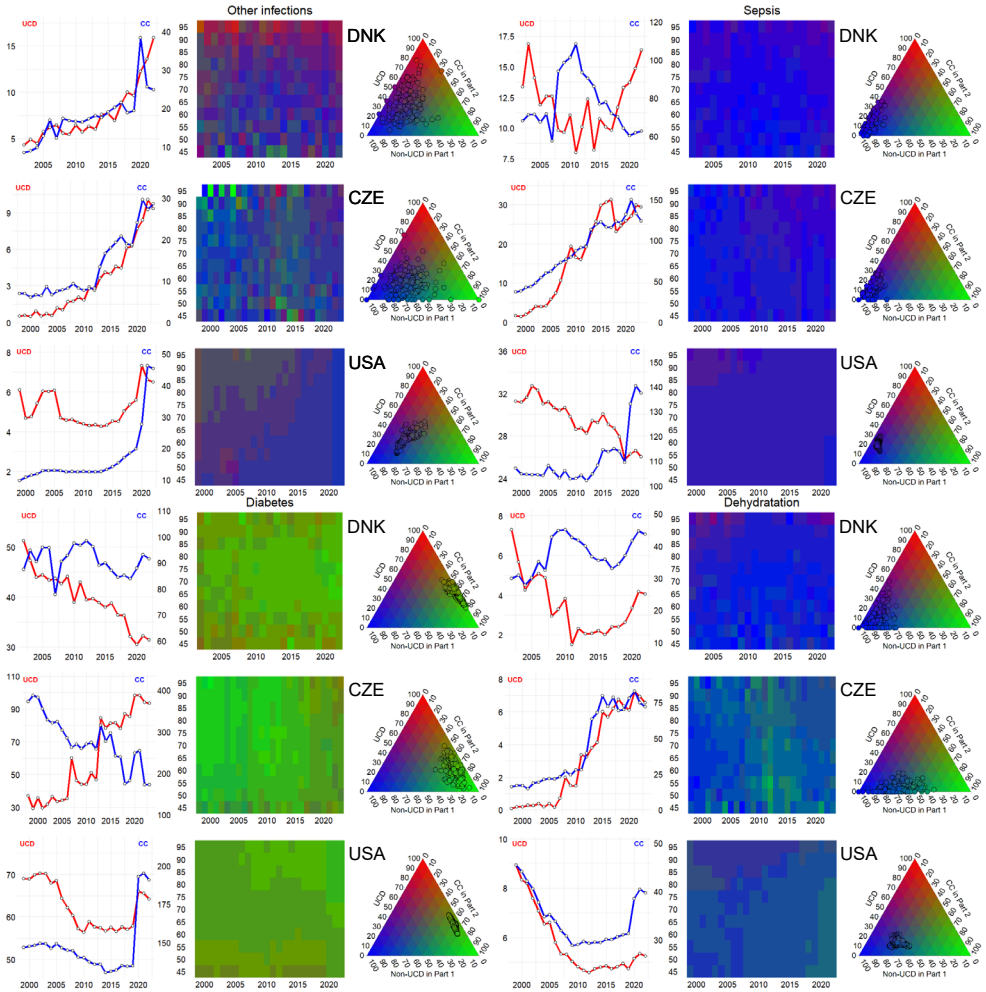
In this section, we interpret the three-panel figures for each country and disease, following the disease list by *Bishop et al.* (2023b). We focus on the leading diseases within the five major categories: infectious diseases, endocrine diseases, mental and nervous diseases, respiratory diseases, and cardiovascular diseases. Additionally, we discuss the results at the ICD chapter level, with reference to Figure in Online Appendix A5.

4.1 Infectious diseases

Infectious disease mortality is higher from the CC perspective than from the UCD (Fig. 2). For the two leading infectious diseases – sepsis and other infections –the Lexis plots are blue, indicating that these diseases are predominantly non-initiating conditions in Part 1. In Denmark, other infections show an age-specific pattern, shifting to UCD (transition to red shades) in the oldest age groups (85+). In the USA before 2010, other infections were more often coded as CC in Part 2.

Figure 1 in Online Appendix A5 shows the death rates, along with the Lexis diagram and the simplex plot for the entire ICD chapter on infectious diseases. The only notable compositional change in infectious diseases is the transition from UCD towards non-UCD in Part 1 in the USA. In Czechia, mortality rates from infectious diseases rise over time in both UCD and CC perspectives, while in the USA and Denmark, UCD and CC mortality show opposing trends (Online Appendix A5, Fig. 1).

Fig. 2: Age-standardised death rates, simplex plots and Lexis plots for infectious and metabolic diseases



Source: own design

4.2 Endocrine diseases

When all information on death certificates is considered, the leading endocrine disease in all three countries is diabetes, followed by dehydration. In Denmark and the USA, mortality from diabetes as the UCD has declined steadily, interrupted in the latter country only by the COVID-19 pandemic (Fig. 2). Simplex plots show that diabetes is classified predominantly as a CC2 in all countries. Several country-specific shifts are also evident: in Denmark and the USA, the weight of diabetes as a CC2 increases to nearly 80 percent at ages 60-85, whereas a strong period effect around

2012 led to a decrease in the weight of diabetes as a CC2 to around 50 percent in Czechia. This compositional change, which is unique to Czechia, occurred in parallel with a decline in the mortality rate from diabetes as a CC, which runs contrary to trends observed from the UCD perspective.

As with diabetes, dehydration trends in Czechia also diverge from those in the other countries, with dehydration-related mortality increasing over time. Dehydration oscillates between non-UCD and CC2 in the USA and Czechia, while it is almost exclusively non-UCD in Denmark (Fig. 2). Around 2012, when an automated cause of death coding system was introduced in Czechia, dehydration shifted closer to CC for several years.

Overall, endocrine diseases in Czechia and the USA are more likely to be recorded as CC2 than is the case in Denmark (Online Appendix A5, Fig. 1). In Denmark, there is again an age-specific role shift, with metabolic diseases increasingly recorded as non-UCD in Part 1 at the oldest ages.

4.3 Mental and nervous diseases

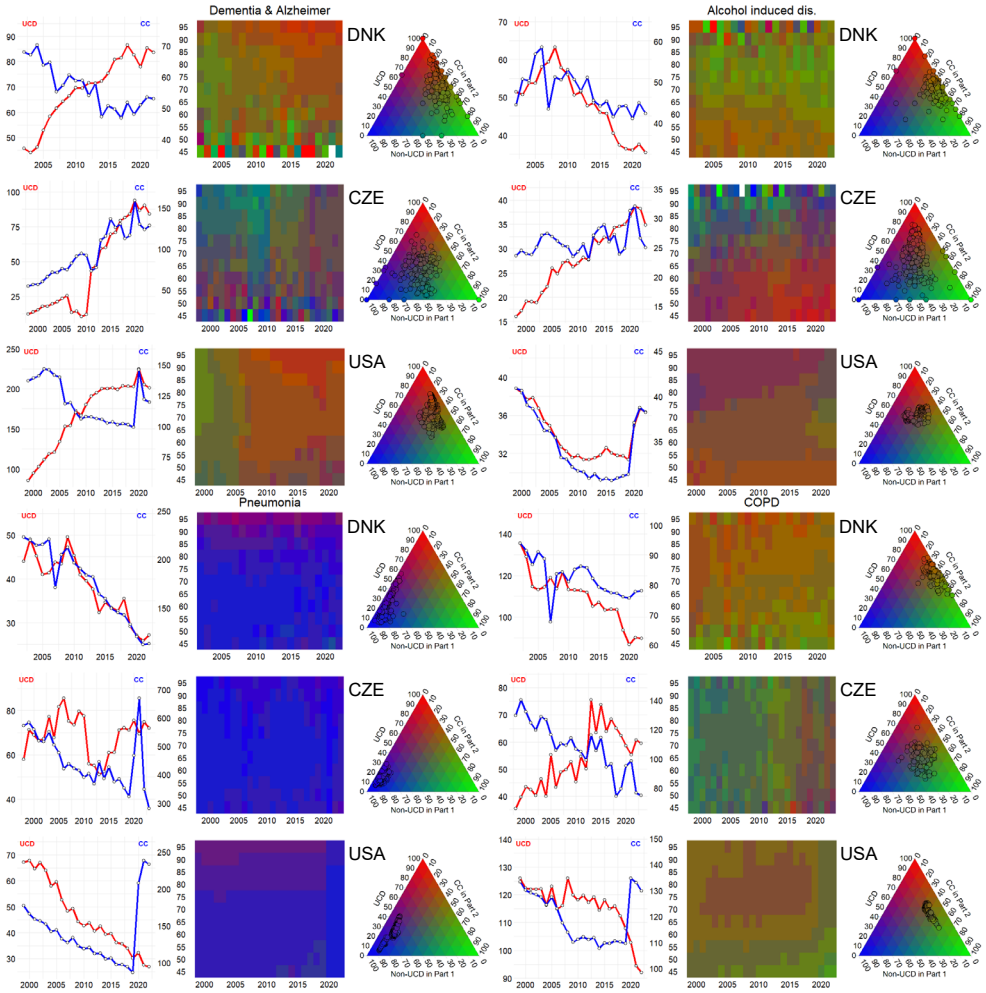
Within the group of mental and nervous diseases, the leading diagnoses are dementia and Alzheimer's disease, and alcohol-induced disorders (Fig. 3). Even at the aggregate level, mental and nervous diseases exhibit the greatest cross-country diversity in terms of both disease composition and mortality rates (Online Appendix A5, Fig. 1).

While mortality with dementia recorded as the UCD increases over time in all observed countries, no corresponding increase in CC mortality is evident in the USA or Denmark. These two countries share a similar pattern in terms of the role composition of dementia, characterised by a substantial shift towards UCD since 2000. Consequently, over the past two decades, the proportion of deaths for which dementia was classified as the UCD in the USA and Denmark has risen from 50 percent to nearly 80 percent. In contrast, the composition of dementia in Czechia remains more balanced, without a clearly dominant role type, although recent years suggest a shift towards UCD as well.

The role of alcohol-induced diseases varies by age, exhibiting distinct country-specific patterns. Although these conditions predominantly appear as UCD at younger ages in both Czechia and Denmark, the trends diverge in later life: in Denmark, there is a shift in alcohol-induced diseases being classified as CC 2, whereas in Czechia, the shift is towards their classification as non-UCD in Part 1 (Fig. 3). In the USA, the proportion of alcohol-induced diseases classified as UCD remains relatively stable across age groups, with a slight shift from CC2 to non-UCD1 as age increases. Cross-country heterogeneity is evident not only in disease roles but also in mortality trends; specifically, rates were declining in Denmark and the USA before the pandemic, in contrast to a gradual rise observed in Czechia (Fig. 3).

Czechia exhibits fundamental differences to Denmark and the USA, even when examining mental and nervous diseases separately at the aggregate level (Online Appendix A5, Fig. 1). In Denmark, and especially the USA, mental diseases

Fig. 3: Age-standardised death rates, simplex plots and Lexis plots for mental and nervous diseases and respiratory diseases



Source: own design

are predominantly CC2. In Czechia, however, mental diseases are predominantly classified as UCD at younger ages (45-70), gradually shifting to CC2 in older ages.

The role of nervous diseases also evolves. At the beginning of the study period, in both the USA and Denmark, nervous diseases at younger ages were typically recorded as non-UCD in Part 1, transitioning to CC in Part 2 at ages 70 and above. More recently, however, this transition has shifted towards UCD. In contrast, Czechia once again stands alone, as nervous diseases are consistently recorded as non-UCD in Part 1 in over half of its total records (Online Appendix A5, Fig. 1).

4.4 Respiratory diseases

Pneumonia, COPD, and other residual respiratory diseases are the predominant conditions within the group of respiratory diseases. In Denmark and the USA, pneumonia, like several conditions mentioned above, is moving towards becoming the UCD in the oldest age groups (85+) (Fig. 3). In Czechia, however, pneumonia largely remains non-UCD in Part 1, and this is consistent across both age and time.

Mortality rates from pneumonia decline over the study period, with the exception of Czechia. Here pneumonia mortality, especially as UCD, remained stable and relatively high compared with other countries, despite a sharp, temporary decline observed in 2012, which coincided with changes in COD data processing.

Like pneumonia, the role of COPD in the lethal process in Denmark and the USA also follows an age-dependent pattern. Before the age of 50, COPD is more frequently listed as a CC in Part 2 (around 50-60 percent). This then gradually shifts, with COPD becoming the UCD in over half of the records at older ages (Fig. 3).

In Czechia, COPD does not exhibit a clear predominant role; only in recent years has it become more distinctly identifiable as the UCD. This transformation, observed exclusively in Czechia, may be reflected in the divergent trajectories of mortality rates from UCD and CC. The observed increase in mortality from UCD, which occurs at the same time as a decrease in mortality from CC, might be related to the aforementioned rise in the weight of COPD as the initiator of the chain. In Denmark and the USA, where the role composition of COPD over time remained unchanged on the whole, COPD exhibits similar decreasing trends in both UCD and CC perspectives (considering the pre-pandemic period).

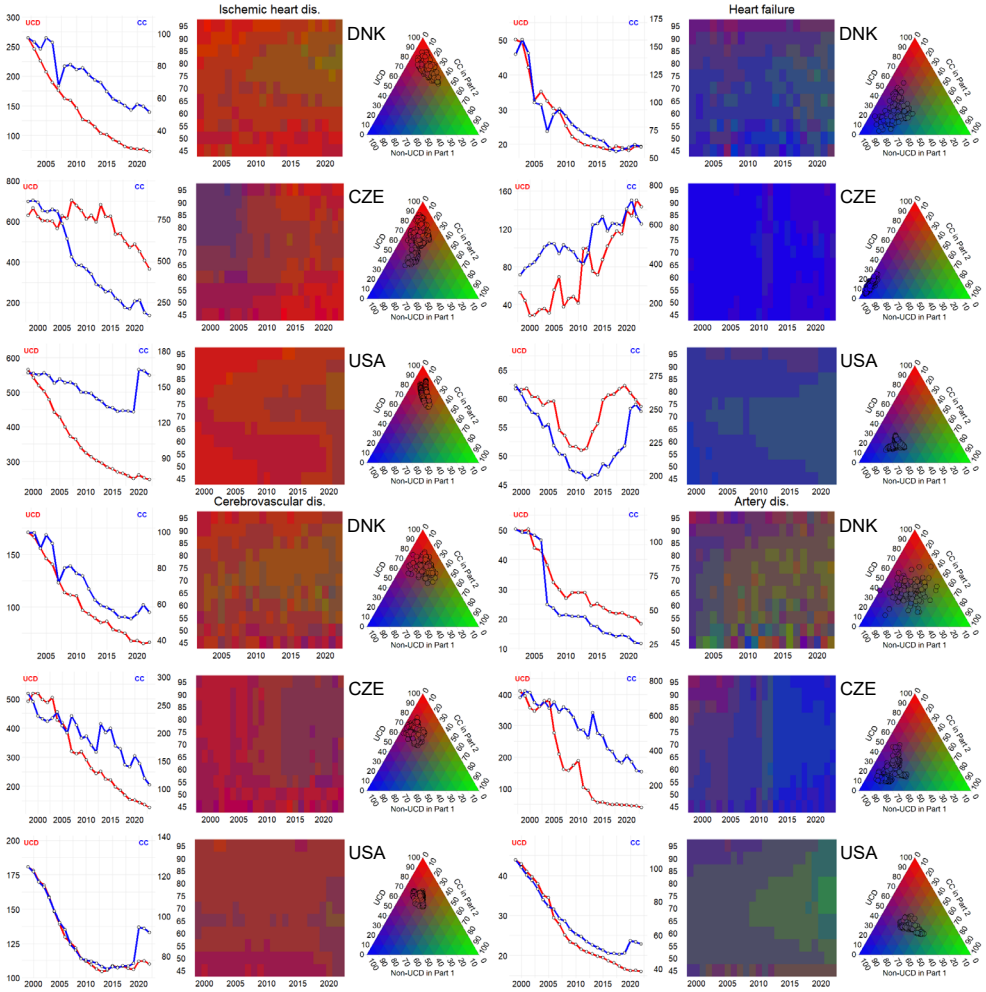
At the aggregate level, respiratory diseases mostly appear as non-UCD in Part 1 on the death certificates in all of the countries studied (Online Appendix A5, Fig. 1)

4.5 Cardiovascular diseases

Although countries do not fully agree on which cardiovascular diseases are most frequently recorded on death certificates, ischemic heart disease is the most common such disease in all three countries, despite its mortality rate declining in all of these nations (Fig. 4). In Denmark and the USA, this decrease is accompanied, or even accelerated, by a slight increase in recognition of ischemic heart disease as a CC2 between the ages of 70-80. Czechia is once again a unique case, as ischemic heart disease has moved towards the top of the simplex triangle from the blue area, signifying a decrease in its weight as non-UCD1 over time and a corresponding increase in its weight as the UCD. This may explain why mortality from ischemic heart disease as the UCD was not declining as steeply in Czechia until 2010 compared with the USA and Denmark.

Heart failure is another cardiovascular disease among the leading diagnoses recorded on death certificates in all three countries. Despite widely varying trends in mortality rates across countries, heart failure is predominantly non-UCD in Part 1, although in Denmark, it has moved slightly towards CC2 in recent years. A similar

Fig. 4: Age-standardised death rates, simplex plots and Lexis plots for cardiovascular diseases



Source: own design

trend can be seen in the USA, where this slight transition began around 2005 in the 65-75 age group, and gradually spread to most other age groups. In Czechia, heart failure is almost exclusively a non-initiating cause in the morbid chain, which has remained stable since 2000. However, the mortality rate from heart failure in both UCD and CC perspectives has increased in this country (Fig. 4).

Like ischemic heart disease, cerebrovascular diseases are predominantly UCD. In Denmark, however, there has been a particular increase in their weight as CC2, which first occurred around 2000 at ages 60-70 and gradually spread to other age groups.

Overall, both the role composition and mortality trends in cerebrovascular diseases show no significant differences between the countries analysed.

This cannot be said about the fourth most prevalent group of cardiovascular diseases, namely artery diseases. In Denmark especially, it is notable that artery diseases are dispersed across the centre of the simplex plot, indicating no leading role, whereas in Czechia, they are consistently classified first and foremost as non-UCD in Part 1. In the USA, artery diseases follow a very similar transformation as in ischemic heart disease, moving over time towards the role of a CC in Part 2.

The transition to CC in Part 2 is a main characteristic of cardiovascular diseases, particularly in Denmark (Online Appendix A5, Fig. 1). This transition is typically observed first around the age of 70-80 and gradually spreads to neighbouring age groups. In Czechia, on the other hand, cardiovascular diseases remain primarily non-UCD in Part 1.

5 Discussion and Conclusion

What did we find?

This study contributed a visualisation of the time-specific and age-specific changes in the composition of causes of death and placed these changes within the context of trends in mortality rates from both UCD and CC perspectives. We compared three countries – the USA, Denmark, and Czechia – which, despite being classified as high-income countries, lag behind those with the lowest mortality rates. Among the leading diseases within each major cause of death group, we identified several diseases with shifting roles over time, particularly dementia and Alzheimer's disease, ischemic heart disease, and cerebrovascular disease. Furthermore, Czechia exhibited distinct temporal role changes in diabetes, COPD, and artery diseases. Compositional shifts were also evident across age groups, most notably in Denmark for pneumonia, alcohol-induced diseases, and other infections. While trends in mortality rates from both UCD and CC perspectives generally developed in parallel, there were notable exceptions: mortality trends in UCD and CC diverged for diabetes and COPD in Czechia, and for sepsis and dementia in the USA and Denmark. This paper illustrates how the UCD and MCD approaches can complement each other. MCD not only reveals "invisible" disease burdens but, in some cases, also anticipates UCD trends, as seen with dementia and Alzheimer's disease, for instance. Additionally, this complementarity broadens our understanding of health dynamics; for example, it allows us to distinguish between a disease that is decreasing in significance and a disease that is changing its role in the death process. Both of these interpretations convey different implications for public health.

How can the results be interpreted?

In general, shifting roles of diseases over time can be driven by two major factors. First, they may indicate shifts in both health and the death process. In this regard, we

observed an increase in the importance of infectious diseases and the transition of cardiovascular diseases towards CC2. A similar transition is occurring in neoplasms, although these were not our explicit focus due to their exclusivity in being classified as the UCD at the population level in 2019. This indicates that mortality related to these diseases is not merely a matter of the past, but rather that their role in the lethal process is changing, as highlighted by a number of earlier studies (*Rogers/ Crimmins* 2011; *Lee et al.* 2008; *Désesquelles et al.* 2015).

Second, temporal changes in disease roles can result from changes in the process for certifying causes of death. This includes changes in diagnostic and data collection practices, such as the introduction of new guidelines for completing death certificates, the implementation of automated coding systems, and improved methods for determining relationships between diseases to identify the UCD. These factors are instrumental in reducing the comparability of results between Czechia and the USA and Denmark, as automated processing of cause of death data was only introduced in Czechia in recent decades (see Online Appendix A2). Consequently, during the study period in Czechia, the format of the death certificate was updated, an automated COD coding system was adopted, and the Iris system was established (*Daňková* 2016; *Czech Statistical Office* 2017).

Similarly, in the United States, efforts to centralise and fully automate COD data processing only began in 2000 (*NCHS* 2025a/b). Even Denmark, despite having the longest-standing tradition of COD data collection, underwent substantial changes in the 2000s. In 2007, responsibility for completing death certificates was transferred from death coders to medical doctors, who then became fully accountable for documenting the causes of death (*Helweg-Larsen* 2011). This may be associated with fluctuations in mortality rates from CC occurring in 2007 in several conditions, such as ischemic heart disease, cerebrovascular diseases, arterial diseases, COPD, pneumonia, and others.

Moreover, all three countries follow international WHO rules for COD classification, which means that the recording of diagnoses and the selection of the UCD may be influenced by gradual updates to ICD-10. In this regard, the most affected diseases were diabetes, which was recommended to be given higher priority as the UCD, as well as psychiatric diseases, including dementia and alcoholic psychosis (*Helweg-Larsen* 2011; *Czech Statistical Office* 2017). Additionally, stricter rules for selecting ischemic heart disease as the UCD were introduced around 2010 in European countries (*Stolpe et al.* 2021; *Daňková* 2016; *Czech Statistical Office* 2017; *Helweg-Larsen* 2011). In Czechia especially, the updated UCD selection rules had an impact on death rates from heart failure and pneumonia (*Daňková* 2016). Furthermore, the UCD mortality rate for dementia in Czechia increased sharply around 2010, coinciding with a notable drop in pneumonia-related UCD mortality (Fig. 3). This is attributed to changes in preferences for UCD selection, favouring dementia as the underlying cause if both dementia and pneumonia were recorded on the death certificate. Similarly, diabetes in Czechia began to be increasingly prioritised as the UCD after 2012, as illustrated by its movement on the simplex plot.

Age-specific changes in the composition of disease roles primarily involved a transition of conditions into Part 1 of the death certificate or directly as the UCD

in older ages. This pattern is understandable: in older age, determining the causal relationship between a condition and the UCD becomes particularly problematic, often leading the death certifier to document all of the diseases in Part 1. Furthermore, in the oldest age groups, there is a general decrease in the total number of causes recorded (*Désesquelles et al.* 2010; *Pechholdová* 2014). This inevitably increases the weight of the UCD, as it is the only mandatory cause to be recorded.

Finally, key findings highlighted divergent trends in mortality rates between UCD and CC perspectives, coinciding with compositional shifts of diseases. This integrated perspective enhances the interpretation of UCD mortality trends, enabling differentiation between a "pure" decline in disease burden (as evidenced by decreases in both UCD and CC mortality rates without compositional shifts) and a shift in the perception of death certifiers concerning how the disease operates within the death process. The latter is exemplified by stable UCD mortality rates, decreasing CC mortality rates, and an increased proportional attribution as UCD, as observed, for example, in ischemic heart disease in Czechia. These distinct scenarios signal distinct disease dynamics, potentially requiring tailored public health intervention strategies.

What are the limitations of the study?

Several important limitations of this study warrant discussion. Firstly, the assignment of a disease's "role" is based on its position on the death certificate, as determined by the death certifier. This information is inherently subjective, being influenced by factors related to the certifier (e.g. experience, type of training, relationship to the deceased) and the deceased individual (e.g. age, place of death, socioeconomic status) (*Fedeli et al.* 2015; *Wall et al.* 2005; *Laanani et al.* 2023). The impact of certifier-related factors is evident in the significant regional differences observed in MCD recording in Czechia, which align closely with the administrative units in which certifiers operate (*Ukolova* 2024). Factors relating to the deceased are demonstrated even in the average number of conditions recorded per death certificate, which, in the USA for instance, differs substantially across subgroups by place of death, education, or the UCD (authors' calculations). Consequently, while our study aimed to analyse physicians' judgment in assigning causes to Part 1 and Part 2 of the death certificate, we must acknowledge that the assigned disease roles may sometimes not accurately reflect certifier intent due to misplacement or incorrect recording on the death certificate.

Secondly, we recognise that our work is descriptive because it does not test any hypotheses about the observed compositional changes and variations in mortality rates. This limits the potential to interpret the complexity of mortality trends and role changes of diseases. For instance, an observed change for cause *i* might originate from altered coding practices for cause *j*, which itself could be undergoing shifts due to its evolving interrelationships with cause *k*. This complexity remains largely unexplored within the scope of this analysis, despite our efforts to contextualise the findings within existing studies on changes in certification of COD. As a result,

attribution of the observed dynamics to their underlying drivers can only be subject to speculation.

A third limitation, inherent to the analysis of MCD data, is the inability to distinguish between missing data and the genuine absence of a cause of death. This inevitably influences role compositions, as all compositional dimensions are interdependent and must sum to unity. Consequently, an observed compositional change can arise when a disease, for instance, simply begins to be recorded on the death certificate as a CC2. Such an occurrence does not necessarily reflect a change in health status but rather the implementation of a new rule or guideline mandating its certification. While such rules are typically embedded in informed medical decisions, their introduction can nonetheless induce artefactual compositional shifts.

What is the key takeaway message of the study?

In conclusion, this study revisits the analysis of causes of death by integrating mortality rates based on UCD and CC with changes in the roles that causes of death play within the death process. This approach facilitates a more nuanced interpretation of cause-specific mortality trends. The observed changes may not always reflect actual changes in health status but may instead result from shifts in reporting or coding practices. Once again, MCD has proven to be a valuable approach in understanding the "language of cause of death statistics" on an international level.

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Data availability statement
The aggregated data tables used in the analysis are available from the author upon request. Due to data protection regulations, they cannot be shared online and are not available at all for Denmark.

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