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The distribution of survival times after injury

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Abstract

Introduction—The distribution of survival times after injury has been described as "trimodal", but several studies have not confirmed this. The purpose of this study was to clarify the distribution of survival times after injury.

Methods—We defined survival time (ts) as the interval between injury time and declared death time. We constructed histograms for t_s <=150 minutes from the 2004-2007 Fatality Analysis Reporting System (FARS, for traffic crashes) and National Violent Death Reporting System (NVDRS, for homicides). We estimated statistical models in which death times known only within intervals were treated as interval-censored. For confirmation, we also obtained EMS response times (t_r), prehospital times (t_p), and hospital times (t_h) for decedents in the 2008 National Trauma Data Bank (NTDB) with t_s=t_p+t_h<=150. We approximated times until circulatory arrest (t_x) as t_r for patients pulseless at the injury scene, t_p for other patients pulseless at hospital admission, and t_s for the rest; for any declared t_s, we calculated mean t_x / t_s. We used this ratio to estimate t_x for hospital deaths in FARS or NVDRS, and provide independent support for using interval-censored methods.

Results—FARS and NVDRS deaths were most frequent in the first few minutes. Both showed a second peak at 35-40 minutes after injury, corresponding to peaks in hospital deaths. Third peaks were not present. Estimated t_x in FARS and NVDRS did not show second peaks, and were similar to estimates treating some death times as interval-censored.

Conclusions—Increases in frequency of survival times at 35-40 minutes are primarily artifacts created because declaration of death in hospitals is delayed until completing resuscitative attempts. By avoiding these artifacts, interval censoring methods are useful for analysis of injury survival times.

Introduction

In an influential 1983 *Scientific American* article, Trunkey[1] characterized the time interval from injury until death (survival time) as having a "trimodal distribution": "Data from several parts of the country" were said to demonstrate an initial peak of "immediate deaths", followed by a second peak of "early deaths" in the first few hours, and finally a third peak of "late deaths" days or weeks later. The American College of Surgeons (ACS) still uses this classification to teach physicians about the different causes of early and late mortality, and the different potential interventions for injured patients.[2]

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However, subsequent studies have called into question whether the distribution of injury survival times is really trimodal. There is no doubt that the instantaneous rate of death is highest immediately, but it is difficult to think of a biological reason for a second or third peak. Review of Trunkey's graph[1, 2] suggests that the third peak was simply an artifact produced by changing the units of the time axis from hours to days or weeks, and it has only been replicated this way in subsequent studies from the United States or other countries. Several authors[3, 4, 5, 6, 7, 8] have been unable to demonstrate a second peak, although one study[9] described four peaks rather than three.

Recently, prehospital and hospital data have become available that enable calculations of survival time in minutes instead of hours. With these new data, we sought to reexamine the distribution of survival time after trauma. We considered that some death times recorded as "immediate" were probably not actually observed by Emergency Medical Services (EMS) personnel arriving several minutes later. Furthermore, we considered that a second peak in survival times might result as an artifact because physicians typically declare the time of death not when circulatory arrest occurs, but only after they have decided that resuscitative measures are ineffective. In view of these considerations, it may be appropriate to use "interval censoring" methods of survival analysis, in which the time of death is treated as having occurred during some interval of time rather than at a specific time.

The purpose of this study was to clarify the distribution of survival times after injury, in order to enable valid statistical analyses. We especially wanted to determine the degree to which declared times of death in hospitals might overestimate the actual times of circulatory arrest. In addition, we wanted to account for the possibility that unobserved times of circulatory arrest at the scene of injury might be inaccurately estimated by EMS personnel.

Methods

This study was proposed to an Institutional Review Board at Maine Medical Center, which determined that it was exempt from further review because it used existing deidentified epidemiologic and health services data. Data management, graphing, and modeling were performed using Stata (Version 11, StataCorp, College Station, Texas) and R (Version 2.12.2, R Foundation, Vienna, Austria).

Description of population-based data

Data from 2004-2007 were obtained from the internet site of the Fatality Analysis Reporting System (FARS, www.nhtsa.gov/FARS). FARS (established by the US National Highway Traffic Safety Administration in 1975) is a census (attempted 100% sample) of all traffic-related motor vehicle crashes in the US that result in at least one fatality within 30 days of the event. It includes information on the collision, the vehicles and drivers, and each person involved. These data have been collected from existing documents by a government agency in each state since 1975, and are frequently updated, checked for consistency, standardized, and made available to the public. For this study, only vehicle occupants were considered.

FARS includes variables on exact (to the minute) times of the crash, times of EMS arrival at the crash scene, and declared times of death. These allowed us to calculate EMS response time (t_r) as the difference between time of crash and time of EMS arrival, and survival time (t_s) as the difference between time of crash and declared time of death. FARS also specifies whether each person was taken to a hospital, but only provides the time for each crash when the first person arrived at a hospital, not the time for each person.

Data from 2004-2007 were also obtained from the National Violent Death Reporting System (NVDRS, www.cdc.gov/ViolencePrevention/NVDRS/index.html), in compliance with its standard Data Use Agreement. NVDRS (established by the US National Center for Injury Prevention and Control in 2002) collects and combines data on homicides and suicides from a variety of sources, including death certificates, police reports, medical examiner reports, and crime laboratories. It is similar in many ways to FARS, with appropriate innovations specific to this population, and is currently active in seventeen states (Alaska, California, Colorado, Georgia, Kentucky, Maryland, Massachusetts, New Jersey, New Mexico, North Carolina, Oklahoma, Oregon, Rhode Island, South Carolina, Utah, Virginia, Washington). Although primarily designed to facilitate injury prevention research, NVDRS does contain some data useful for trauma system evaluation, including whether the person was taken to a hospital and the exact (to the minute, in many cases) time elapsed from injury until declaration of death (survival time, or t_s). However, EMS arrival times and hospital arrival times are not given.

Recorded times of death less than or equal to 150 minutes were considered “early deaths”. For FARS and NVDRS, we created histograms of the times (in minutes) from injury until declaration of death (t_s) for these early deaths. Decedents who had been taken to a hospital were distinguished from those who had not been taken to a hospital. For NVDRS, homicide deaths were distinguished from suicide deaths.

Adjustment of survival times using hospital data

Data from 2008 were also obtained from the National Trauma Data Bank (NTDB, www.ntdb.org), in compliance with its standard Data Use Agreement. NTDB (established by the ACS in 1994) collects trauma registry data from hundreds of hospitals across the US. For the first time, the 2008 NTDB data included the number of minutes between EMS activation and EMS arrival (response time or t_r), the number of minutes between EMS activation and hospital arrival (prehospital time or t_p), and the number of minutes between hospital arrival and declaration of death (hospital time or t_h). Declared survival time (t_s) for NTDB cases was calculated as $t_p + t_h$.

Survival times for NTDB cases were grouped into 10-minute intervals. Using International Classification of Diseases, Ninth Revision, External Cause of Injury codes (ICD-9 E-Codes), decedents were also classified as traffic deaths (E810-E819, E958.5, E988.5), homicide deaths (E960-E978), or suicide deaths (E950-E959). Patients were further stratified by whether they had measurable pulse before hospital arrival, whether they had measurable pulse at the time of hospital admission, and whether they had been declared “dead on arrival” (DOA). We considered the absence of measurable pulse or a declaration of DOA to be evidence of circulatory arrest.

For traffic crashes and homicides, patients were grouped into 10-minute intervals of declared survival times ($t_s = t_p + t_h$). Each of these groups was then subgrouped according to when the patient had evidence of circulatory arrest. For each injury mechanism and classification of declared survival times, these subgroups may be summarized as follows:

Subgroup A – Circulatory arrest on admission, and circulatory arrest before admission

Subgroup B – Circulatory arrest on admission, but not before admission

Subgroup C – Neither of the above.

The EMS response times, prehospital times, and hospital times for each of the Subgroups were also calculated. These were designated t_{ra}, t_{pa}, and t_{ha} for Subgroup A, t_{rb}, t_{pb}, and t_{hb} for Subgroup B, and t_{rc}, t_{pc}, and t_{hc} for Subgroup C. Table 1 summarizes the derived variables and their abbreviations.

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For each mechanism of injury, and for each group classified by declared time of death, we also calculated the fractions in each of the Subgroups A, B, or C, among those with declared death times within the listed intervals. These fractions (abbreviated f_a, f_b, and f_c) were used to estimate when circulatory arrest had actually occurred, compared to when death was ultimately declared in the hospital (presumably after resuscitative efforts had been judged futile). The mean time when death was declared is by definition

$$t_s=f_a(t_{pa}+t_{ha})+f_b(t_{pb}+t_{hb})+f_c(t_{pc}+t_{hc}).$$

However, for each category of t_s, the mean time until circulatory arrest can be estimated as

$$t_x=f_a(t_{ra})+f_b(t_{pb})+f_c(t_{pc}+t_{hc}).$$

For any given value of t_s, we tabulated a correction factor (t_x / t_s) from which an estimate of t_x may be obtained.

The correction factor (t_x / t_s) derived from NTDB was then applied to the hospital death times in FARS and NVDRS, and the histograms were replotted to reflect the estimated times of circulatory arrest (t_x). No effort was made to directly link individual FARS or NVDRS subjects to individual NTDB subjects.

Interval censoring analysis

For both FARS and NVDRS cases, we considered that the recorded time of death for subjects not in a hospital probably referred to the estimated time of circulatory arrest. However, in some cases the actual time might not have been witnessed by EMS personnel who had not yet arrived at the crash scene. We also considered that the recorded time of death for subjects in a hospital probably referred to the time when resuscitative efforts were discontinued, recognizing that the actual time of circulatory arrest might have occurred at any time between the crash (although probably after EMS arrival) and the time death was declared by a physician in the hospital. Some of these prehospital and hospital deaths could therefore be considered "interval censored", that is, they were known to have occurred during some interval of time, but not at an exact time.

Using theoretical bounds on the possible times of death (visualizing time as proceeding from left to right), we estimated "interval censored" survival models.[10, 11] Left and right endpoints chosen for the interval censoring approaches are shown in Table 2. EMS response time (t_r) was recorded for fewer than two thirds of the FARS cases, and in none of the NVDRS cases. If t_r was recorded as greater than 150 minutes, we considered this most likely a data entry error and included it with the cases missing t_r. In the rare cases where t_r was recorded as greater than the death time, but the patient had died in the hospital, we also ignored this a probable data entry error. We excluded cases for which a time of death was not recorded. Non-hospital NVDRS death times recorded as "1 hour" were interval censored on a range from 31 minutes to 60 minutes, and non-hospital NVDRS death times recorded as "2 hours" were interval censored on a range from 61 minutes to 120 minutes.

As one approach, using the Stata command "intcens",[12] we assumed that the survival function *S(t)* followed a Weibull distribution, that is,

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$$\Pr(T>t)=S(t)=\exp(-at^{b}),$$

where T is time to death, a is a "scale parameter" and b is a "shape parameter". When $b<1$, this implies a decreasing instantaneous probability of death (hazard). As an alternative, more robust approach for handling interval censored data, we also calculated a nonparametric Turnbull estimator,[13] essentially an extension of the Kaplan-Meier estimator, using the R command "survfit" with "type = 'interval'".[14] The Weibull and nonparametric interval-censored curves were plotted along with the histograms of estimated times of circulatory arrest (t_x).

Results

Description of population-based data

For the years 2004-2007, there were 182,858 fatal cases in FARS, with survival times recorded in 134,778 (74%); during the same time period, there were 21,006 homicides and 38,762 suicides in NVDRS, with survival times recorded in 9,422 (45%) and 10,483 (27%) respectively (Table 3). Recorded times from injury until death were displayed as histograms for traffic deaths (Figure 1a, from FARS), homicide deaths (Figure 1b, from NVDRS), and suicide deaths (not depicted). At least in the first two categories, there was a second peak that appeared to coincide with the peak in hospital deaths; this finding was not as apparent for suicide deaths, which were much less likely to have occurred in a hospital. For NVDRS cases, the analysis was further limited because some survival times were recorded only to the nearest hour. No third peak was apparent for any subgroup, unless artificially created by compressing the time axis into days or weeks.

Adjustment of survival times using hospital data

There were 25,747 fatal NTDB cases; in 15,301 (59%) the time of death was calculated as later than 150 minutes, and in 6,132 (24%) the time of death could not be calculated. Of the remaining 4314 cases ("early deaths"), 1724 (40.0%) were due to traffic crashes, 1608 (37.3%) were due to homicide, and 357 (8.3%) were due to suicide. 1145 (66.4%) of the early traffic deaths, 1191 (74.1%) of the early homicide deaths, and 197 (55.2%) of the early suicide deaths had arrived with evidence of circulatory arrest. The majority of patients declared dead in a hospital within the first hour after injury had evidence of circulatory arrest on admission (Subgroup A or B).

For each of the Subgroups A, B, and C defined above, the mean EMS response times (t_{ra}, t_{rb}, and t_{rc}), mean prehospital times (t_{pa}, t_{pb}, and t_{pc}), and mean hospital times (t_{ha}, t_{hb}, and t_{hc}) are shown in Table 4. For each mechanism and survival time, the percentages of cases in Subgroups A, B, and C are shown in Table 5, and (along with the data from Table 4) have been used to calculate a correction factor (the ratio t_x / t_s) as described above. This correction factor (also shown in Table 5) is relatively small when t_s is small (because most of these patients have evidence of circulatory arrest on admission) and gradually approaches 1 with larger values of t_s.

Among all patients in NTDB who had evidence of circulatory arrest before hospital arrival as well as at the time of hospital arrival, 99.0% eventually died (99.2% for traffic crashes, 98.7% for homicides). Among all patients who had evidence of circulatory arrest at the time of hospital arrival, but not before hospital arrival, 96.5% eventually died (96.7% for traffic crashes, 96.4% for homicides).

Given this evidence from the NTDB, histograms for the hypothetical times of circulatory arrest for cases in FARS and NVDRS (as opposed to the times of declaration of death after hospital evaluation and/or futile intervention) were created by modifying Figures 1a and 1b to produce Figures 2a and 2b: In each case, the time of death for hospitalized patients was multiplied by the applicable correction factor (t_x / t_s) to reflect the delay inherent in the medical assessment and resuscitative effort. With this simple modification, the second peak in each histogram essentially disappeared.

Interval censoring analysis

Interval-censored survival models were estimated as described above. Weibull density functions *f(t)*, approximating the expected number of deaths for a unit interval at time *t*, were obtained by differentiation of 1-*S(t)*, that is,

$$f(t)=\frac{d(1-\exp(-at^b))}{dt}=\exp(-at^b)*ab*t^{b-1}.$$

The values of *a* and *b* for each sample are given in Table 3. For each model, *f(t)* was multiplied by the size of the population at risk (the number of fatal cases with a non-missing time of death), and multiplied again by 10 (corresponding to the frequency histograms grouped by 10-minute intervals). Similar calculations were made using the Turnbull method to approximate the nonparametric estimates at 5-minute intervals. The resulting functions are shown along with the histograms in Figures 2a and 2b. The estimates using interval censoring for some death times were more similar to the histograms based on estimates of t_x than to the histograms of t_s.

Discussion

The longstanding concept that survival times after trauma conform to a “trimodal distribution” has been questioned by numerous authors.[3, 4, 5, 6, 7, 8, 9, 15, 16, 17, 18, 19, 20] Indeed, clinicians familiar with the pathophysiology of serious injuries would expect the incidence of mortality to be highest immediately as a result of major physical disruptions, and to remain relatively high for several hours thereafter due to respiratory compromise, bleeding, and other acute physiologic derangements. However, one would expect that the longer an injured person had survived, the less likely that person would be to die during the next moment in time, especially in the presence of medical intervention.

It is therefore somewhat surprising to find that histograms of the recorded survival times actually do show a second peak (Figures 1a and 1b). This finding has been previously noted in FARS data,[21, 22] and is also present for homicide deaths in NVDRS. However, the simultaneous occurrence of this secondary peak with the peak in hospital deaths suggests an explanation that does not conflict with physiologic intuition, simply involving a difference in defining “time of death”. For most subjects not in a hospital, the “time of death” likely corresponds to the conventional definition of death as circulatory arrest; for most subjects in a hospital, the “time of death” likely corresponds to the cessation of resuscitative efforts attempting to reverse a circulatory arrest that had occurred at some earlier time. A simple adjustment based upon treating some of the death times as truly known only up to intervals of time eliminates this second peak, as does a crude correction using an external data source (Figures 2a and 2b).

Most analyses (for example using FARS or NVDRS) will only have the time of declared death for patients taken to a hospital. In view of our findings, we believe it is prudent to consider these times as "interval censored". That is, the actual time of circulatory arrest is not known, but in most cases may be presumed to have occurred some time earlier than the time when death was finally declared. If EMS arrival times are unavailable, the time of circulatory arrest can only be presumed to have occurred sometime between the injury and the time of declared death, and indeed a relatively large proportion of early NTDB deaths had evidence of circulatory arrest even at the time of EMS arrival (Table 5). If EMS arrival times are available, an alternative model could use this time as the left endpoint. Interval censoring also makes it easy to include the NVDRS cases where times are rounded to "1 hour" or "2 hours". The Weibull model is only one of several parametric methods of accommodating interval censoring. The non-parametric Turnbull estimator may also be used, and does not require any assumption about the functional form of the distribution of survival times. Either method does entail an assumption that the observations are independent.[10]

In addition to the anomalies we have identified with hospital deaths using NTDB data, many of the "immediate" prehospital deaths probably occurred prior to the arrival of police or EMS, whereas the actual survival times for some of these subjects may have been at least several minutes. These death times could therefore also be considered as interval censored; they are known only to have occurred after the injury and before EMS arrival (with a shared left endpoint, these are termed "left censored"). Additionally treating these death times as interval censored will further blunt or eliminate any second peak in the overall distribution of survival times, as it will spread the mass contributed by these events to the right.

Our study included population-based sources of data and was not dependent upon hospital data alone. However, as with any analysis based upon retrospectively collected data from multiple sources, we cannot be sure that our data and hypotheses are correct. Indeed, many cases in FARS and NVDRS are missing exact (to the minute) survival times, and those with exact times may be recorded inaccurately or may not be representative of the entire population. Neither of these databases includes information on injury severity or comorbidities, which is a distinct limitation. Similarly, they do not provide autopsy data, which would be a valuable addition to any study of injury mortality.[17] Some homicides may have involved motor vehicles, so there may be some overlap in the FARS and NVDRS populations, although this would not affect our analysis.

The NTDB is composed of trauma registry data pooled from hundreds of hospitals across the United States. However, it is expensive to maintain a trauma registry, so that only hospitals with a strong commitment to the care of injured patients (trauma centers) are included in this group. The findings upon which we have based our estimates therefore may be recorded inaccurately or may not be representative of all hospitals contributing data to FARS and NVDRS. However, some sort of data anomaly seems much more likely than a physiological explanation for the secondary peak, and an "honest" treatment of the death times as known only up to certain intervals of time resolves this issue.

The practice of declaring patients "dead on arrival" (DOA) is variable from one jurisdiction to another. In some places, subjects with no pulse must nevertheless be transported to a hospital so that death may be declared by a physician, while in others there are criteria by which EMS personnel do not need to transport these subjects.[23] These geographic differences may also affect our findings. Circulatory arrest after trauma (especially after blunt trauma) has an extremely poor prognosis. It is instructive that the great majority of early hospital deaths recorded in NTDB had evidence of circulatory arrest (DOA or no pulse) on admission, but even in these cases the mean time between hospital arrival and recorded death time was substantial for both traffic and homicide deaths (Table 5).

Either the interval censoring or the *ad hoc* approach we describe might be modified by making further assumptions about how much time may have elapsed between injury and EMS activation, or at what points the pulse was actually measured. As more years of NTDB data accumulate, more accurate estimates of the elapsed times may be obtainable. The National EMS Information System (NEMSIS) now under development may provide additional detail about prehospital times and physiologic status. Approaches other than a multiplicative adjustment factor might have been considered; indeed, a similar result can be achieved simply by advancing all hospital death times 10-20 minutes to reflect the average delay in confirming the irreversibility of circulatory arrest after trauma. This adjustment serves as support for the interval censored methods, although we are not proposing it as a formal analytic approach.

Obviously, the methods we propose here cannot measure the true difference between the time of circulatory arrest and the time when death was declared in a hospital. In the first place, the pulse before EMS arrival is not recorded, so our estimate of t_x is to some extent an upper bound for the actual time of circulatory arrest. Furthermore, patients who arrive with an intact circulation and subsequently suffer a circulatory arrest will naturally tend to be treated with an even more aggressive and prolonged attempt at resuscitation than the DOA cases. However, attempting to develop a more complicated method would require additional assumptions not generally available in population-based data, and not uniformly recorded even in trauma registry data. One class of patients not addressed by our analysis includes those who die from cerebral rather than circulatory causes, resulting in a time of death that is declared after more complete assessment of the neurologic prognosis. This decision may sometimes be made within a few minutes of admission, but is often delayed for hours or even days to allow for more definitive testing or observation.[16]

Our findings should provide some perspective on the concept of a “trimodal distribution” of survival times after injury. Getting past this artificial limitation may allow construction of improved outcome analyses using standard methods of time-to-event analysis (“survival analysis”), for example hazard regression models to evaluate the effect of age, comorbidity, or other factors. Because a large proportion of hospital deaths occur in the first few hours, time-to-event methods might be more flexible than the traditional binary (lived/died) models commonly used for hospital performance reviews or trauma system evaluations. This is an important consideration when considering rural environments, where the prehospital times may be prolonged and interhospital transfers more frequent. The apparent discrepancy between hospital cases and prehospital cases in defining the time of death should lead to caution when these populations are both included in the same model, but an interval censoring approach allows many of the powerful tools of time-to-event analysis to be applied to injury outcome studies.

Acknowledgments

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References

1. Trunkey DD. Trauma. Sci Am. 1983; 249:28–35. [PubMed: 6623052]
2. American College of Surgeons. Advanced Trauma Life Support. 8th. Chicago: ACS; 2008.
3. Sauaia A, Moore FA, Moore EE, et al. Epidemiology of trauma deaths: A reassessment. J Trauma. 1995; 38:185–93. [PubMed: 7869433]

4. Demetriades D, Kimbrell B, Salim A, et al. Trauma deaths in a mature urban trauma system: Is "trimodal" distribution a valid concept? J Am Coll Surg. 2005; 201:343–8. [PubMed: 16125066]
5. McGwin G Jr, Nunn AM, Mann JC, et al. Reassessment of the tri-modal mortality distribution in the presence of a regional trauma system. J Trauma. 2009; 66:526–30. [PubMed: 19204533]
6. Evans JA, van Wessem KJ, McDougall D, et al. Epidemiology of traumatic deaths: Comprehensive population-based assessment. World J Surg. 2010; 34:158–63. [PubMed: 19882185]
7. Kruger AJ, Søreide K. Trimodal temporal distribution of fatal trauma--fact or fiction? Injury. 2008; 39:960–1. [PubMed: 18586249]
8. Bakke HK, Wisborg T. Rural high north: A high rate of fatal injury and prehospital death. World J Surg. 2011; 35:1615–20. [PubMed: 21538190]
9. Gomes E, Araujo R, Carneiro A, et al. Mortality distribution in a trauma system: From data to health policy recommendations. Eur J Trauma Emerg Surg. 2008; 34:561–9.
10. Lindsey JC, Ryan LM. Tutorial in biostatistics: Methods for interval-censored data. Stat Med. 1998; 17:219–38. [PubMed: 9483730]
11. Zhang Z, Sun J. Interval censoring. Stat Methods Med Res. 2010; 19:53–70. [PubMed: 19654168]
12. Griffin J. Intcens: Stata module to perform interval-censored survival analysis. 2005
13. Turnbull BW. The empirical distribution function with arbitrarily grouped, censored and truncated data. J Royal Statist Soc B. 1976; 38:290–5.
14. Therneau, T.; Lumley, T. 2011. http://CRAN.R-project.org/package=survival
15. Wyatt J, Beard D, Gray A, et al. The time of death after trauma. BMJ. 1995; 310:1502. [PubMed: 7787598]
16. Meislin H, Criss EA, Judkins D, et al. Fatal trauma: The modal distribution of time to death is a function of patient demographics and regional resources. J Trauma. 1997; 43:433–40. [PubMed: 9314304]
17. Søreide K, Kruger AJ, Vardal AL, et al. Epidemiology and contemporary patterns of trauma deaths: Changing place, similar pace, older face. World J Surg. 2007; 31:2092–103. [PubMed: 17899256]
18. Pang JM, Civil I, Ng A, et al. Is the trimodal pattern of death after trauma a dated concept in the 21st century? Trauma deaths in Auckland 2004. Injury. 2008; 39:102–6. [PubMed: 17880967]
19. de Knegt C, Meylaerts SA, Leenen LP. Applicability of the trimodal distribution of trauma deaths in a Level I trauma centre in the Netherlands with a population of mainly blunt trauma. Injury. 2008; 39:993–1000. [PubMed: 18656867]
20. Gunst M, Ghaemmaghami V, Gruszecki A, et al. Changing epidemiology of trauma deaths leads to a bimodal distribution. Proc (Bayl Univ Med Cent). 2010; 23:349–54. [PubMed: 20944754]
21. Luchter S. Fatal injuries in light vehicle crashes - time to death and cause of death. Annual Proceedings, Association for the Advancement of Automotive Medicine. 1998; 42:277–286.
22. Clark DE, Cushing BM. Predicted effect of automatic crash notification on traffic mortality. Accid Anal Prev. 2002; 34:103–9.
23. Clark DE, Ahmad S. Is the number of traffic fatalities in American hospitals decreasing? Accid Anal Prev. 2005; 37:755–60. [PubMed: 15949463]

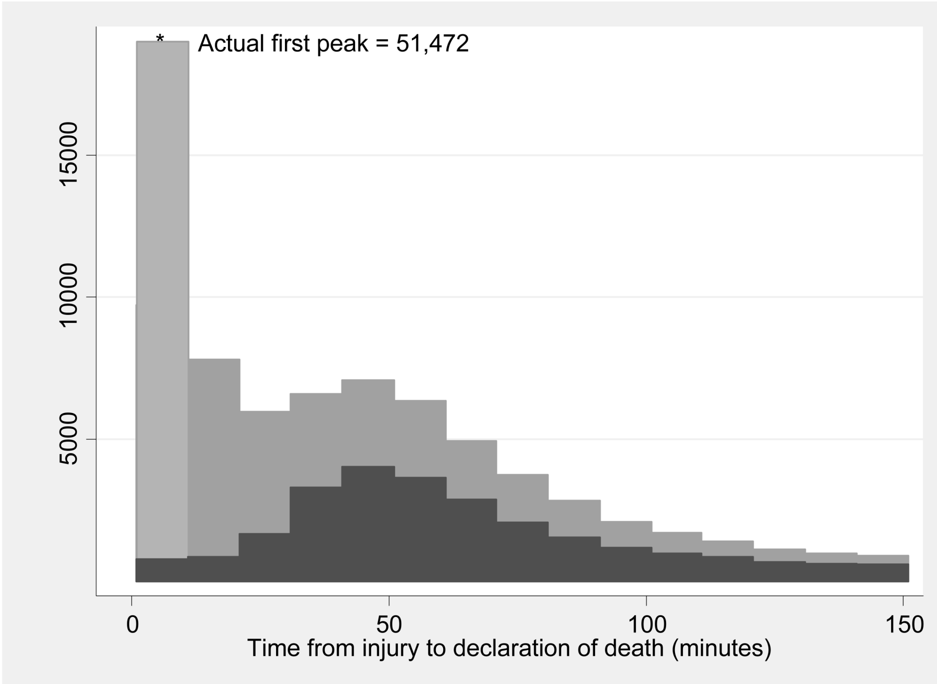

Figure 1a

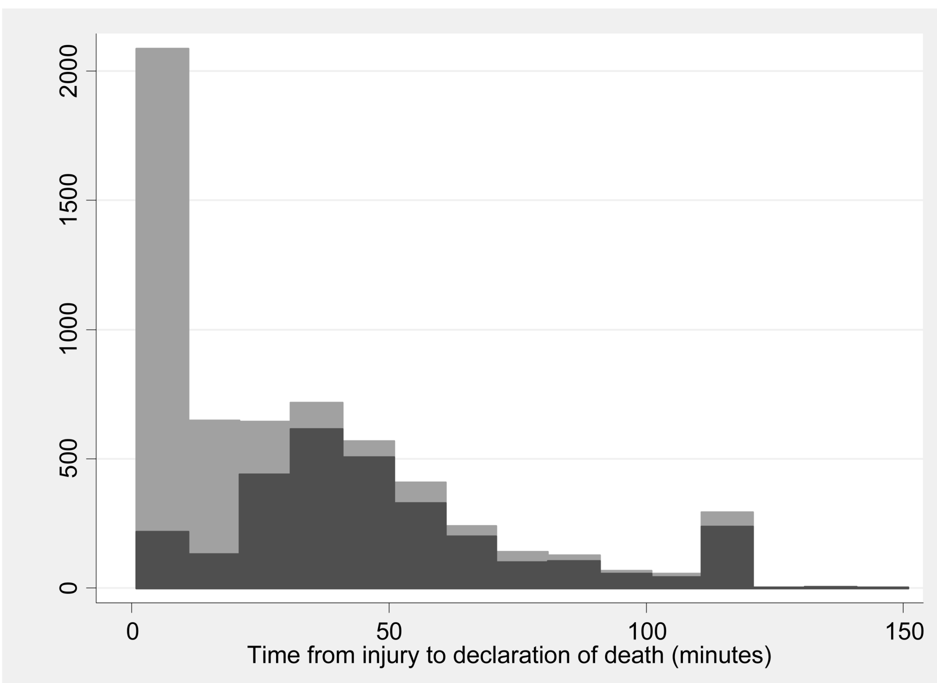

Figure 1b

Figure 1.

Frequency histograms of the recorded times from injury until declared death, for subjects with survival times less than 150 minutes as a result of traffic injury (Figure 1a, from FARS 2004-2007) or homicide (Figure 1b, from NVDRS 2004-2007). The darker shaded histograms represent subjects who were transported to a hospital. In Figure 1a, the first bar of the histogram (*) has been truncated to allow the subsequent pattern to be shown more clearly. In Figure 1b, the bars corresponding to 50-60 or 110-120 minutes include subjects whose survival time was recorded as “1 hour” or “2 hours”.

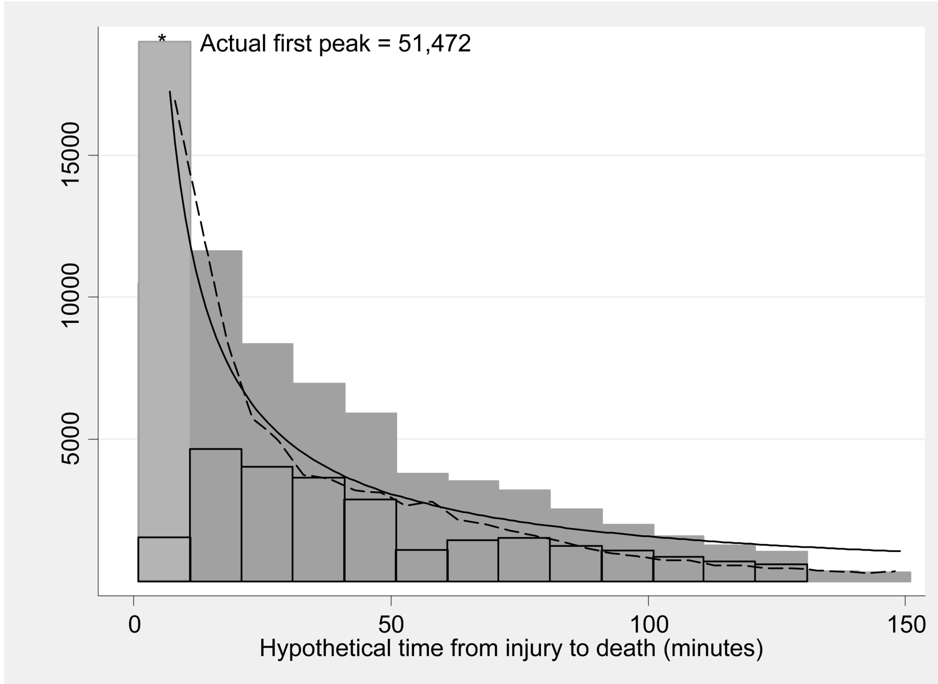

Figure 2a

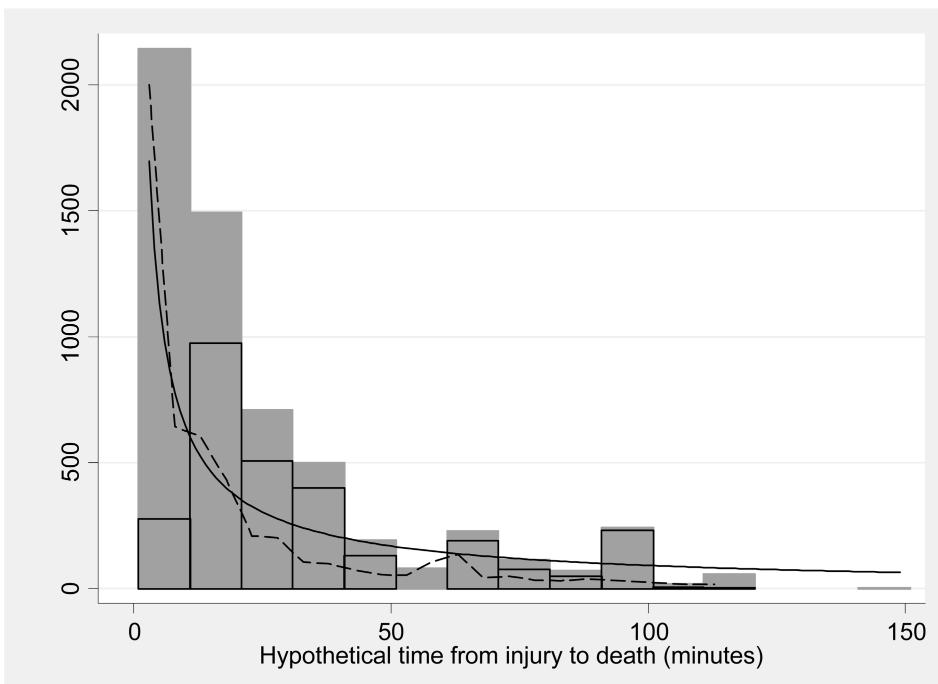

Figure 2b

Figure 2.

Theoretical frequency histograms of the estimated times from injury until circulatory arrest, for subjects with survival times less than 150 minutes as a result of traffic injury (Figure 2a, from FARS 2004-2007) or homicide (Figure 2b, from NVDRS 2004-2007). Figure 2 was derived from the same data as Figure 1, but approximating the actual time of circulatory arrest (t_x) as described in the text. The histograms with open bars depict these hypothetically modified survival times for hospitalized subjects. The solid lines show estimates from interval-censored Weibull models, and the dashed lines show estimates from corresponding interval-censored nonparametric models. In Figure 2a, the first bar of the histogram (*) has been truncated to allow the subsequent pattern to be shown more clearly.

Table 1

Derived variables used in the analysis, including abbreviations. Subgroup A: Evidence of circulatory arrest on admission, and evidence of circulatory arrest before admission; Subgroup B: Evidence of circulatory arrest on admission, but not before admission; Subgroup C: Not in Subgroup A or Subgroup B.

Variable (abbreviations)	Definition
Response time (t_r)	Time from injury until EMS arrival
(t_{ra}) (t_{rb}) (t_{rc})	Response times for Subgroups A, B, and C
Prehospital time (t_p)	Time from injury until hospital arrival
(t_{pa}) (t_{pb}) (t_{pc})	Prehospital times for Subgroups A, B, and C
Hospital time (t_h)	Time from hospital arrival until death declared
(t_{ha}) (t_{hb}) (t_{hc})	Hospital times for Subgroups A, B, and C
Survival time (t_s)	Time from injury until death declared
Circulatory arrest time (t_x)	Time from injury until circulatory arrest (estimated)

Table 2

Assignment of left and right endpoints for interval censoring of survival times with different available data in FARS or NVDRS. Time from injury to EMS arrival (EMS response time) = t_r; time from injury until declaration of death (survival time) = t_s. Values of t_r recorded as >150 are considered missing. Cases with missing values of t_s are excluded. Also, non-hospital NVDRS survival times recorded as "1 hour" were interval censored on a range from 31 minutes to 60 minutes, and non-hospital NVDRS survival times recorded as "2 hours" were interval censored on a range from 61 minutes to 120 minutes.

Relationship of declared death time and EMS response time	**Interval assumed to contain time of circulatory arrest**			
	Not taken to hospital		**Taken to hospital**	
	Left	Right	Left	Right
$t_s \leq 150$, $t_r \leq 150$, $t_r \leq t_s$	t_s	t_s	t_r	t_s
$t_s \leq 150$, $t_r \leq 150$, $t_r > t_s$	1	t_r	t_s	t_s
$t_s \leq 150$, t_r missing	t_s	t_s	1	t_s
$t_s > 150$	t_s	t_s	t_s	t_s

Table 3

Selected characteristics of the subjects who died as a result of the specified external causes of injury, as recorded in FARS and NVDRS for 2004-2007. Time from injury to EMS arrival (EMS response time) = t_r; time from injury until declaration of death (survival time) = t_s.

	FARS	NVDRS	
	Traffic Deaths	**Homicide Deaths**	**Suicide Deaths**
Total deaths	182,858	21,006	38,762
Deaths with recorded survival time	134,778	9,422	10,483
Died within 150 minutes (“early”)	104,964 (77.9%)	6,002 (63.7%)	7,406 (70.7%)
First mode	1 minute	1 minute	1 minute
Second mode	35-40 minutes	35-40 minutes	?
Died not in hospital			
$t_s \le 150$, $t_r \le 150$, $t_r \le t_s$	19,415 (14.4%)		
$t_s \le 150$, $t_r \le 150$, $t_r > t_s$	26,194 (19.4%)		
$t_s \le 150$, t_r missing	33,652 (25.0%)	3,016 (32.0%)	
$t_s > 150$, t_s not missing	3,584 (2.7%)	212 (2.3%)	
Died in hospital			
$t_s \le 150$, $t_r \le 150$, $t_r \le t_s$	15,407 (11.4%)		
$t_s \le 150$, $t_r \le 150$, $t_r > t_s$	507 (0.4%)		
$t_s \le 150$, t_r missing	9,726 (7.2%)	2,986 (31.7%)	
$t_s > 150$, t_s not missing	26,230 (19.5%)	3,208 (34.1%)	
Weibull model (see text)			
Scale parameter (a)	.238	.178	
Shape parameter (b)	.316	.283	

Table 4

Mean EMS response times, prehospital times, and hospital times for NTDB deaths from traffic crashes and homicides, categorized by mechanism and declared survival time, $t_s = t_p + t_h$. Subgroup A: Evidence of circulatory arrest on admission, and evidence of circulatory arrest before admission; Subgroup B: Evidence of circulatory arrest on admission, but not before admission; Subgroup C: Not in Subgroup A or Subgroup B. EMS response time, prehospital time, and hospital time for Subgroups A are abbreviated t_{ra}, t_{pa}, and t_{ha}, and the corresponding times for Subgroups B or C are abbreviated similarly.

Survival time $t_s = t_p + t_h$	Evidence of circulatory arrest on admission						C: Other		
	A: Circulatory arrest prehospital			B: No circulatory arrest prehospital					
	t_{ra}	t_{pa}	t_{ha}	t_{rb}	t_{pb}	t_{hb}	t_{rc}	t_{pc}	t_{hc}
Traffic									
1 - 10	2	8	2	-	-	-	-	-	-
11 - 20	3	15		4	14	4	-	-	-
21 - 30	5	21		5	23	5	5	19	8
31 - 40	6	28	8	6	28	8	6	25	11
41 - 50	8	34	12	8	35	11	7	30	16
51 - 60	10	41	14	11	43	13	8	34	22
61 - 70	16	48	17	13	50	16	10	38	28
71 - 80	16	55	20	15	58	18	13	44	33
81 - 90	15	59	27	14	64	21	12	44	41
91 – 150	12	43	71	17	61	53	13	44	76
Homicide									
1 - 10	1	7	2	-	-	-	1	4	3
11 - 20	4	15	3	5	15	3	4	14	5
21 - 30	5	22	4	5	22	5	5	21	6
31 - 40	6	28	8	6	27	8	5	25	12
41 - 50	6	32	13	6	33	13	6	26	20
51 - 60	8	37	19	6	35	20	6	31	25
61 - 70	8	39	27	8	42	24	6	30	35
71 - 80	8	32	45	12	46	31	8	28	49
81 - 90	15	49	37	12	39	47	6	28	59

Survival time $t_s = t_p + t_h$	Evidence of circulatory arrest on admission						C: Other		
	A: Circulatory arrest prehospital			B: No circulatory arrest prehospital					
	t_{ra}	t_{pa}	t_{ha}	t_{rb}	t_{pb}	t_{hb}	t_{rc}	t_{pc}	t_{hc}
91 – 150	9	36	80	10	33	86	7	30	88

Table 5

NTDB deaths from traffic crashes and homicides, categorized by mechanism and declared survival time, $t_s = t_p + t_h$. For each mechanism and declared survival time, the percentage of patients in Subgroups A, B, and C are shown. Using these distributions and the data from Table 4, a weighted mean time of circulatory arrest (t_x) has been estimated as described in the text. The last column displays a correction factor (t_x/t_s) that allows t_x to be estimated for any given t_s.

Survival time $t_s = t_p + t_h$	Evidence of circulatory arrest on admission		C: Other	Correction factor t_x / t_s
	A: Circulatory arrest prehospital	**B: No circulatory arrest prehospital**		
Traffic				
1 - 10	1 (100%)	0	0	0.20
11 - 20	22 (69%)	10 (31%)	0	0.37
21 - 30	105 (62%)	49 (29%)	15 (9%)	0.46
31 - 40	175 (56%)	93 (30%)	43 (14%)	0.47
41 - 50	112 (44%)	94 (37%)	46 (18%)	0.54
51 - 60	59 (32%)	76 (41%)	52 (28%)	0.65
61 - 70	36 (27%)	56 (42%)	43 (32%)	0.70
71 - 80	12 (13%)	36 (39%)	44 (48%)	0.81
81 - 90	9 (12%)	17 (23%)	49 (65%)	0.85
91 – 150	24 (7%)	61 (18%)	255 (75%)	0.86
Homicide				
1 - 10	1 (50%)	0	1 (50%)	0.50
11 - 20	40 (68%)	11 (19%)	8 (14%)	0.44
21 - 30	190 (62%)	87 (28%)	31 (10%)	0.46
31 - 40	224 (53%)	35 (32%)	60 (14%)	0.49
41 - 50	111 (45%)	84 (34%)	51 (21%)	0.53
51 - 60	45 (37%)	40 (33%)	36 (30%)	0.61
61 - 70	19 (31%)	19 (31%)	21 (38%)	0.65
71 - 80	3 (6%)	10 (21%)	34 (72%)	0.89
81 - 90	7 (20%)	11 (31%)	17 (49%)	0.76
91 – 150	22 (12%)	33 (18%)	132 (71%)	0.80