Mortality-based Quantification of Injury Severity for Frequently Occurring Motor Vehicle Crash Injuries

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ABSTRACT – The study purpose was to develop mortality-based metrics of injury severity for frequent motor vehicle crash (MVC) injuries. Injury severity was quantified with mortality-based metrics for 240 injuries comprising the top 95% most frequently occurring AIS 2+ injuries in the National Automotive Sampling System – Crashworthiness Data System (NASS-CDS) 2000-2011. Mortality risk ratios (MRRs) were computed by dividing the number of deaths by occurrences for each of the 240 injuries using National Trauma Data Bank Research Data System (NTDB-RDS) MVC cases. MRR_{MAIS} was computed using only patients with a maximum AIS (MAIS) equal to the AIS severity of a given injury. Each injury had an associated MRR and MRR_{MAIS} which ranged from zero (0% mortality representing low severity) to one (100% or universal mortality representing high severity). Injuries with higher MRR and MRR_{MAIS} values are considered more severe because they resulted in a greater proportion of deaths among injured patients. The results illustrated an overall positive trend between AIS severity and the MRR and MRR_{MAIS} values as expected, but showed large variations in MRR and MRR_{MAIS} for some injuries of the same AIS severity. Mortality differences up to 83% (MRR) and 54% (MRR_{MAIS}) were observed for injuries of the same AIS severity. The MRR-based measures of injury severity indicate that some lower AIS severity injuries may result in as many deaths as higher AIS severity injuries. This data-driven determination of injury severity using MRR and MRR_{MAIS} provides a supplement or an alternative to AIS severity classification.

INTRODUCTION

Classification of the severity of an injury is designed to grade the threat to life and mortality associated with an injury. The severity in motor vehicle crash (MVC) injuries is commonly measured using the Abbreviated Injury Scale (AIS). The AIS is an advanced trauma-specific, anatomically-based injury coding lexicon defining injury type and severity [AAAM, 2008]. The "post-dot" component of each AIS code grades injury severity according to the threat to life, tissue damage, complexity of treatment, and impairment using the following severity scores and descriptions: Minor (1), Moderate (2), Serious (3), Severe (4), Critical (5), and Maximum/Unsurvivable (6). These severity scores, or "AIS severity," are consensus-derived assessments assigned by a group of experts that were last updated in 2008.

The mortality associated with injuries can also be measured using mortality risk ratios (MRRs), the probabilistic complement of survival risk ratios (SRR) first proposed by Osler et al. [Osler, Rutledge, Deis et al., 1996]. An injury's MRR is both lexicon- and database-specific. MRRs and SRRs have been calculated for both of the major trauma coding systems, AIS and International Classification of Diseases version 9 (ICD-9), and several data sources including the National Trauma Data Bank (NTDB) [Meredith, Evans, Kilgo et al., 2002; Kilgo, Osler and Meredith, 2003; Meredith, Kilgo and Osler, 2003a]. The MRR, a measure of the proportion of people who died that sustained a given injury, is reported to be among the most powerful discriminators of mortality following trauma [Sacco, MacKenzie, Champion et al., 1999; Meredith et al., 2002].

The objective of this study was to develop a mortality-based metric for quantifying the injury severity of frequently occurring MVC injuries.

METHODS

Top 95% AIS 2+ NASS-CDS Injuries

The top 95% most frequently occurring AIS 2+ injuries in MVCs were identified using the National

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Automotive Sampling System – Crashworthiness Data System (NASS-CDS) [National Highway Traffic Safety Administration, 2011]. NASS-CDS has detailed data on a representative, random sample of thousands of minor, serious, and fatal tow-away crashes in the United States (US). By applying weighting factors to NASS-CDS data, a representative population of MVCs in the US can be analyzed. NASS-CDS includes nearly 1,000 variables specifying vehicle, crash, and occupant characteristics, as well as injuries coded with the AIS coding lexicon.

NASS-CDS 2000-2011 was used in this study. National Highway Traffic Safety Administration (NHTSA) requirements for NASS-CDS crash investigations changed in 2009 and many variables (including all injury data) are not collected for model year (MY) vehicles greater than 10 years old. Thus, NASS-CDS 2009-2011 cases with MY vehicles greater than 10 years old were excluded from this analysis. This resulted in approximately 1/3 of the unweighted NASS-CDS 2009-2011 cases being excluded (11,814 distinct occupants excluded). After applying the exclusion criteria, the resulting NASS-CDS 2000-2011 dataset contained 54,703 cases, 94,283 vehicles, 134,846 occupants, and 303,230 injuries.

This study focused on a list of the top 95% most frequently occurring AIS 2+ injuries in NASS-CDS 2000-2011 (termed the “Top 95% List”). The Top 95% List was composed of 240 injuries located in the head, face, chest, abdomen, upper extremity, spine, and lower extremity body regions (Figure 1). Inclusion of 100% of the NASS-CDS 2000-2011 AIS 2+ injuries would have resulted in 848 unique AIS codes. The approach taken in this study simplifies the analysis to 240 unique injuries that frequently occur in MVCs.

Mortality Risk Ratios

The NTDB Research Data System (NTDB-RDS) version 7.1 was used to calculate the MRR for each of the 240 injuries on the Top 95% List [Committee on Trauma; American College of Surgeons, 2007]. NTDB is the largest aggregation of trauma registry data ever assembled. It is supported by the American College of Surgeons (ACS) which collects information about patients, injuries, and treatments from participating trauma centers on an annual basis. Data submitted to NTDB is rigorously examined using both the National Trauma Registry of the ACS (NTRACS) software institutionally and an additional logical checks system created and enforced by NTDB administrators.

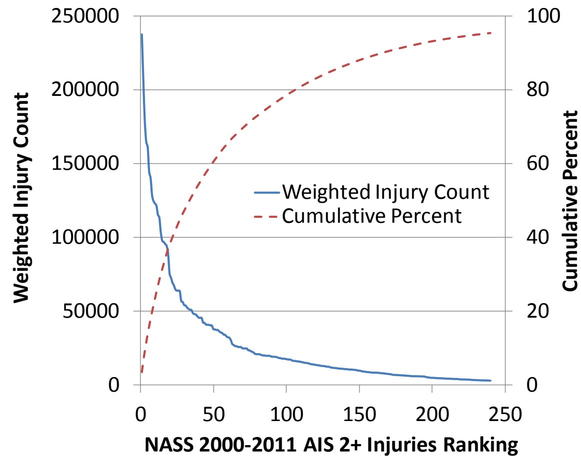

Figure 1. The weighted injury count and cumulative percent for injuries on the Top 95% List.

NTDB-RDS version 7.1 contains 1,926,245 cases from 2002-2006 admission years (Table 1). Cases having at least one AIS code in the Top 95% List were selected for analysis (823,499 cases). ICD-9 external cause codes (ecodes) that indicated MVC to be the cause of the injury were used to sub-select MVC cases. Ecodes 810-819 with post-dots of 0 or 1 were used to designate MVC cases, resulting in 241,935 cases used for the computation of MRRs.

Table 1. NTDB-RDS version 7.1 admission counts.

Year	Admission Count
2002	324,907
2003	356,577
2004	342,881
2005	430,667
2006	471,213
Total	1,926,245

The MRR was calculated by dividing the number of deaths by occurrences for each AIS code in the Top 95% List (Equation 1). Each AIS code therefore had an associated MRR which could range from zero to one with zero representing 0% mortality and one representing 100% or universal associated mortality.

Equation 1. Mortality Risk Ratio (MRR)

$$\frac{\text{Number of patients who died that sustained a given injury}}{\text{Number of patients that sustained a given injury}}$$

Trauma patients often sustain multiple injuries and the impact of some of these injuries can have an effect on the computation of MRRs for single injuries, particularly if the co-injuries are of higher severity [Meredith, Kilgo and Osler, 2003b]. Thus, a MRR metric, MRR_{MAIS} that accounts for the patient's maximum AIS (MAIS) was computed. To compute MRR_{MAIS} for a given injury, only patients with a MAIS equal to the AIS severity of the given injury were included in the calculation (Equation 2).

Equation 2. Mortality Risk Ratio Adjusted by Maximum AIS (MRR_{MAIS})

$$\frac{\text{Number of patients who died that sustained a given injury and that had a MAIS} = \text{AIS severity of the given injury}}{\text{Number of patients that sustained a given injury and that had a MAIS} = \text{AIS severity of the given injury}}$$

The MRR and MRR_{MAIS} values for injuries on the Top 95% List were analyzed and compared to other injury severity measures using a variety of descriptive methods and regression analyses.

RESULTS

Sample Sizes

The sample sizes of injured and dead patients available for MRR computation varied depending on the injury. The number of patients sustaining a given injury ranged from 8 to 35,651 with a mean of 2,934, median of 1,314, and standard deviation of 4,332. The first and third quartiles indicated that 50% of the sample sizes of the total injured patients fell within the range of 509 to 3,865. The number of patients who died that sustained a given injury ranged from 0 to 3,223 with a mean of 225, median of 111, and standard deviation of 349. The first and third quartiles indicated that 50% of the sample sizes of the fatally injured patients fell within 42 to 283.

The sample sizes of injured and dead patients available for MRR_{MAIS} computation also varied depending on the injury. The number of patients sustaining a given injury ranged from 1 to 22,852 with a mean of 1,378, median of 595, and standard deviation of 2,285. The first and third quartiles indicated that 50% of the sample sizes of the total injured patients fell within the range of 229 to 1,684. The number of patients who died that sustained a given injury ranged from 0 to 686 with a mean of 54, median of 9, and standard deviation of 111. The first and third quartiles indicated that 50% of the sample sizes of the fatally injured patients fell within 2 to 46. In general, the number of fatally injured patients included in the MRR_{MAIS} calculation was much lower compared to the population of fatally injured patients used for the MRR calculation which could affect statistical power. There were no fatally injured patients available for 14% of the injuries when calculating MRR_{MAIS} and 1% of the injuries when calculating MRR, respectively.

MRR Results and AIS Comparison

The MRR and MRR_{MAIS} values ranged from zero (0% mortality) to one (100% mortality) for the 240 injuries on the Top 95% List. The distributions of the MRR and MRR_{MAIS} values for the 240 injuries on the Top 95% List were right-skewed. The MRR mean and median were 0.13 and 0.07, respectively, with a standard deviation of 0.17. The first and third quartiles indicated that 50% of the MRRs fell within the 0.04 to 0.14 range. The MRR_{MAIS} mean and median were 0.07 and 0.01, respectively, with a standard deviation of 0.16. The first and third quartiles indicated that 50% of the MRR_{MAIS} values fell within the 0.00 to 0.05 range. A complete list of the MRR and MRR_{MAIS} values for the 240 injuries on the Top 95% List is provided in the Appendix.

Each injury's MRR and MRR_{MAIS} were compared to its AIS severity counterpart (Figure 2). Overall positive trends when regressing MRR or MRR_{MAIS} with the AIS severity were observed, but large variations in MRR and MRR_{MAIS} are evident between injuries of the same AIS severity. The variations at a given AIS severity are diminished for MRR_{MAIS} compared to MRR. Figure 2 shows that the MRR and MRR_{MAIS} ranges overlap between AIS severity levels (particularly for the AIS 2-4 levels). Overlap occurs even for MRR_{MAIS} that is adjusted for the patient's MAIS. Linear and quadratic regressions were fit to the data (R^2 values of 0.51 and 0.68, respectively for MRR, and 0.65 and 0.88, respectively for MRR_{MAIS}). The quadratic regressions provided a better fit to the data, but there are many injuries in Figure 2 that are outliers that do not adhere to the linear or quadratic regression relationships.

When stratifying by AIS severity, the mean and median of the MRR and MRR_{MAIS} distributions increased as AIS severity increased (Table 2). The MRR and MRR_{MAIS} values also varied within a given AIS severity level as the minimum and maximum measures in Table 2 demonstrate.

The discrepancies between MRR and MRR_{MAIS} were larger for lower severity injuries, with AIS 2-4 injuries having an MRR that was generally higher than its MRR_{MAIS} counterpart (Figure 3). Linear correlations indicated that MRRs for AIS 2-3 injuries tend to be two times higher than their MRR_{MAIS} counterparts (Table 3). However, the correlation between MRR and MRR_{MAIS} was low (R^2 = 0.11) for

AIS 2 injuries due to large variation in the MRR-MRR_{MAIS} difference. The MRR-MRR_{MAIS} difference was as much as 0.82 for some injuries. These large differences were likely affected by the smaller sample sizes, particularly in the dead population, that resulted from excluding patients with an MAIS higher than the injury of interest. MRR-MRR_{MAIS} correlations are improved for AIS 3-6 injuries. The linear relationship for AIS 4 injuries indicated that MRRs are approximately 1.2 times higher than their MRR_{MAIS} counterparts (Table 3). Controlling for MAIS affects AIS 5 injuries minimally and does not affect AIS 6 injuries at all since there are no injuries of higher severity that would exclude patients (Table 3 and Figure 3).

AIS 6 Injuries

There were five AIS 6 injuries on the Top 95% List with MRRs ranging from 0.68-1.00. The sample sizes of total injured and total dead used for MRR calculations are provided along with the average number of co-injuries (Table 4). Two of these injuries (441016.6, major heart laceration; 140218.6, brainstem transection) had 100% or near 100% mortality. However, three injuries had 68-83% mortality (113000.6, crush head injury; 140212.6 brain stem laceration; 420218.6 major thoracic aorta laceration). The sample sizes of injured and dead for these three injuries appear sufficient, suggesting these mortality rates are not biased by small samples. The injury with the MRR of 0.68 (113000.6) had a lower average number of AIS 2+, 3+, and 4+ co-injuries which could affect the mortality incidence. However, a single AIS 6 injury (with or without co-injuries) is considered to be highly unsurvivable by the AIS lexicon. The AIS lexicon classifies AIS 6 injuries as "Maximum/Unsurvivable" and patients with an AIS 6 injury are automatically assigned the maximum Injury Severity Score (ISS) of 75. While 68-83% mortality rates are certainly high and indicative of high injury severity, this data suggests a substantial number of patients are surviving some AIS 6 injuries. MRRs provide a quantitative measure of the mortality associated with AIS 6 injuries to distinguish between injuries that are truly unsurvivable and those that are severe, but potentially survivable.

Select Injury Examples

Observations on MRR and MRR_{MAIS} values for select AIS codes are provided in Table 5. The most common AIS 2+ head injury is an AIS 2 injury (160414.2, GCS 15, unconsciousness < 1hr) which has a MRR of 0.001 (<0.1% mortality) and a MRR_{MAIS} of 0 indicating a low severity injury. The most common AIS 2+ lower extremity (852602.2, closed pelvis fracture) and abdomen (544222.2, spleen laceration) injuries are AIS 2 injuries with much higher MRRs of 0.064 and 0.071, respectively (6-7% mortality). The respective MRR_{MAIS} values for these injuries were lower (0.007 and 0.003) indicating that AIS 3+ co-injuries were responsible for some of the increase in mortality associated with these AIS 2 injuries. Interestingly, the most common AIS 2+ chest injury, an AIS 3 unilateral lung contusion (441406.3), has an MRR of 0.064 identical to that of the AIS 2 closed pelvis fracture and less than that of the AIS 2 spleen laceration. However, when controlling for patient MAIS, the MRR_{MAIS} for the AIS 3 unilateral lung contusion is 0.018 which is higher than the MRR_{MAIS} of the aforementioned AIS 2 pelvis and spleen injuries.

In a comparison of chest injuries, an AIS 2 multiple rib fracture injury (450210.2) has a higher MRR (0.107) and similar MRR_{MAIS} (0.020) to the AIS 3 unilateral lung contusion. An AIS 3 diaphragm laceration has much higher MRR and MRR_{MAIS} (0.250 and 0.094, respectively) compared to an AIS 3 unilateral lung contusion. Finally, the AIS 2 injury with the highest MRR (441602.2, pericardium laceration/puncture) has an MRR of 0.825 indicating 83% mortality, but an MRR_{MAIS} of 0 computed from a single injured patient. In the case of an AIS 2 pericardium laceration, all but one patient had accompanying AIS 3+ injuries. AIS 3+ co-injuries were most common in the chest region and were present in 95% of patients sustaining a pericardium laceration with an average of 2.6 AIS 3+ chest co-injuries per patient. AIS 3+ co-injuries in the abdomen, head, and lower extremity regions were also present in 46%, 42%, and 29% of patients. AIS 3+ injuries to the face, spine, and upper extremity occurred in less than 13% of patients. While patient mortality estimated for the pericardium laceration is certainly affected by the co-injuries, MRR is superior to MRR_{MAIS} in capturing the mortality associated with sustaining this particular injury since it is accompanied by AIS 3+ chest injuries 95% of the time.

Three examples of AIS 3 head injuries (150404.3, vault fracture; 160806.3, GCS < 9, unconscious < 1hr; 140660.3, cerebrum injury) have MRRs that range from 0.019-0.240, corresponding to mortality rates of 2-24%. MRR_{MAIS} values for these three head injuries range from 0.017-0.131, corresponding to mortality rates of 2-13%. While MRR and MRR_{MAIS} values are higher for the AIS 3 head injuries compared to the AIS 2 head injury in Table 5, the 11-22% differences in mortality estimated by MRR and

MRR_{MAIS} among the AIS 3 injuries are not captured by AIS severity scoring. Higher AIS severity co-injuries explain some of the elevation in MRRs for the vault fracture and the cerebrum injury since these injuries were accompanied by an AIS 4+ head injury in 56% and 64% of patients, respectively. In contrast, only 1% of patients with loss of consciousness coded as 160806.3 also received an AIS 4+ head injury. However, when excluding the patients with AIS 4+ co-injuries in any body region, the MRR_{MAIS} values are still much higher for the vault fracture and cerebrum injury, suggesting that the mortality associated with these particular AIS 3 head injuries is higher than that of the AIS 3 loss of consciousness injury (160806.3).

Thus, the traditional AIS severity measure appears to not fully capture the mortality associated with some injuries frequently sustained in MVCs. It is evident from these select injury examples that the AIS severity scoring system may have limitations in capturing the true mortality associated with injuries and MRR or MRR_{MAIS} metrics could at the very least serve as a supplement to current AIS severity scoring.

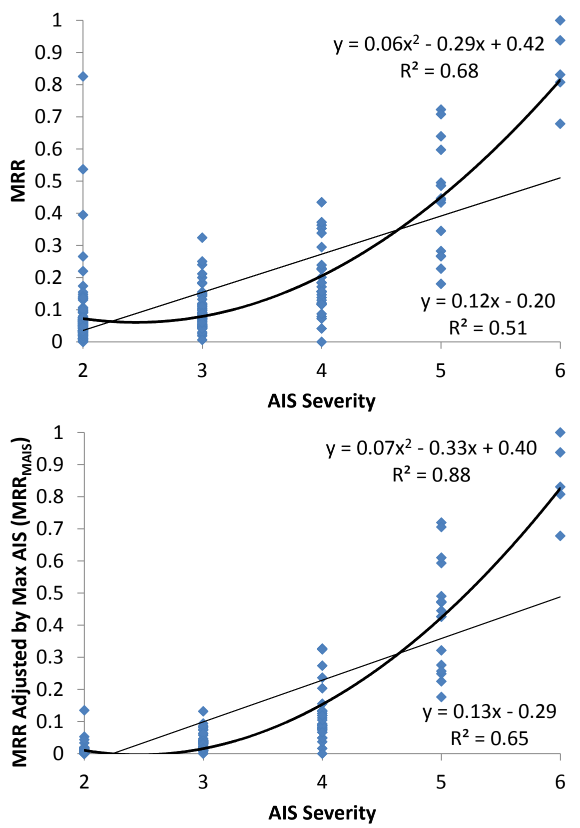

Figure 2. MRR and MRR_{MAIS} versus AIS severity for injuries on the Top 95% List. Linear and quadratic regressions are fit to the data.

Table 2. MRR and MRR_{MAIS} summary statistics stratified by AIS severity.

	Severity	Mean	Median	Min	Max
MRR	AIS 2	0.07	0.05	0.00	0.83
	AIS 3	0.09	0.08	0.01	0.32
	AIS 4	0.19	0.16	0.00	0.43
	AIS 5	0.44	0.44	0.18	0.72
	AIS 6	0.85	0.83	0.68	1.00
MRR_{MAIS}	AIS 2	0.01	0.00	0.00	0.13
	AIS 3	0.03	0.03	0.00	0.13
	AIS 4	0.12	0.09	0.00	0.33
	AIS 5	0.43	0.44	0.18	0.72
	AIS 6	0.85	0.83	0.68	1.00

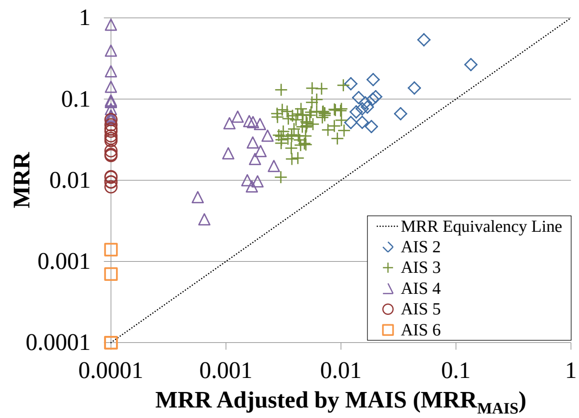

Figure 3. MRR versus MRR_{MAIS} stratified by AIS severity for injuries on the Top 95% List. Axes are plotted using a logarithmic scale. MRR and MRR_{MAIS} values that were equal to zero were assigned a value of 0.0001 to facilitate plotting on the logarithmic scale.

Table 3. Linear regressions of MRR with MRR_{MAIS} stratified by AIS severity.

Severity	N	Intercept	Slope	R^2
AIS 2	123	0.05	2.28	0.11
AIS 3	68	0.02	2.00	0.69
AIS 4	28	0.04	1.21	0.88
AIS 5	16	0.01	1.00	1.00
AIS 6	5	0.00	1.00	1.00

Table 4. MRRs, sample sizes, and average number of co-injuries for AIS 6 injuries.

AIS Code	MRR	Total Injured	Total Dead	Avg # Co-injuries		
				AIS 2+	AIS 3+	AIS 4+
113000.6	0.68	59	40	3.25	2.49	1.90
140212.6	0.81	107	87	8.21	5.90	3.62
420218.6	0.83	131	109	6.00	4.05	2.38
441016.6	0.94	16	15	7.81	4.81	2.88
140218.6	1.00	8	8	6.13	5.38	3.25

Table 5. MRR and MRR_{MAIS} observations for select AIS codes. A rank is provided in the first column for each of the selected injuries indicating their frequency among NASS-CDS 2000-2011 AIS 2+ injuries. The percentage (%) of NASS-CDS 2000-2011 AIS 2+ injuries is also provided for each injury in the first column. The number of dead patients and total injured patients (N_D/N_I) used to compute MRR and MRR_{MAIS} is included.

Rank (%)	AIS Code	AIS Description	MRR (N_D/N_I)	MRR_{MAIS} (N_D/N_I)	Observations
1 (3.46)	160414.2	Awake post resuscitation on Admission or Initial Observation at Scene (GCS 15) unconsciousness known to be < 1 hr	0.001 (1/1,410)	0.000 (0/979)	Most common AIS 2+ head injury; AIS 2, low MRR and MRR_{MAIS}
3 (2.61)	852602.2	Pelvis fracture closed	0.063 (1,233/19,526)	0.007 (39/5,399)	Most common AIS 2+ lower extremity injury; AIS 2, moderate MRR and low MRR_{MAIS}
6 (2.10)	441406.3	Lung contusion unilateral with or without hemo-/pneumothorax	0.064 (1,152/18,043)	0.018 (208/11,594)	Most common AIS 2+ chest injury; AIS 3, moderate MRR and low MRR_{MAIS}
27 (0.93)	450210.2	Rib fractures, multiple, NFS	0.107 (210/1,961)	0.020 (11/549)	AIS 2 chest injury; high MRR and low MRR_{MAIS}
31 (0.78)	544222.2	Spleen, laceration, simple capsular tear <=3cm parenchymal depth and no trabecular vessel involvement; minor; superficial [OIS I, II]	0.070 (524/7,453)	0.003 (6/1,765)	Most common AIS 2+ abdomen injury; AIS 2, moderate MRR and low MRR_{MAIS}
57 (0.50)	150404.3	Vault fracture, comminuted; compound but dura intact; depressed <=2cm; displaced	0.151 (289/1,918)	0.041 (31/748)	AIS 3 head injury; high MRR and moderate MRR_{MAIS}
129 (0.18)	140660.3	Cerebrum injury [includes basal ganglia, thalamus, putamen, globus pallidus], brain swelling NFS	0.240 (130/542)	0.131 (18/137)	AIS 3 head injury; high MRR and MRR_{MAIS}
140 (0.16)	160806.3	Unconscious post resuscitation on Admission or Initial Observation at Scene (GCS <9) < 1 hr	0.019 (5/264)	0.017 (4/242)	AIS 3 head injury; low MRR and MRR_{MAIS}
141 (0.16)	441602.2	Pericardium, laceration; puncture	0.825 (85/103)	0.000 (0/1)	AIS 2 chest injury; extremely high MRR and low MRR_{MAIS} due to small sample sizes
175 (0.10)	440604.3	Diaphragm laceration (OIS Grade II thru IV)	0.250 (209/835)	0.094 (29/310)	AIS 3 chest injury; high MRR and MRR_{MAIS}

Age Effects

Patient age was not adjusted for when computing MRR or MRR_{MAIS}, and may be important for the elderly population which is known to have decreased skeletal and physiological resilience and increased morbidity and mortality [Burstein, Reilly and Martens, 1976; Finelli, Jonsson, Champion et al., 1989; Perdue, Watts, Kaufmann et al., 1998; Zioupos and Currey, 1998]. Regressing the MRR and MRR_{MAIS} values with the mean patient age for each injury, negative relationships with low correlation (R2 = 0.10 and 0.08, respectively) were found. Since the mean patient age was generally lower for injuries with higher MRR and MRR_{MAIS} values, this suggests that there is not a dramatic effect on MRR metrics due to certain injuries being more common in the elderly. Age does appear to have some effect on patient mortality, as the mean age was higher for the dead patients compared to the surviving patients (44 versus 35 years, respectively). The mean age of the dead patients was higher than the mean age of the surviving patients for 95% of the 240 injuries studied.

DISCUSSION

AIS codes with higher MRR and MRR_{MAIS} values are considered to be more severe injuries because they resulted in more deaths. Determining injury severity from MRR and MRR_{MAIS} was used as an alternative to the severity assigned by the AIS coding system. The results illustrated an overall positive trend between the AIS severity and the MRR and MRR_{MAIS} values as expected, but showed large variations in MRR and MRR_{MAIS} for some injuries of the same AIS severity. There was overlap of the ranges of the MRR and MRR_{MAIS} values between different AIS severity levels such that some injuries of different AIS severities had similar MRR and/or MRR_{MAIS} values. Although MRR_{MAIS} values were generally lower than their MRR counterparts due to the adjustment of patient MAIS, MRR_{MAIS} values still demonstrated variation in injury mortality not captured by the categorical AIS severity score. This data-driven determination of severity indicates that some lower AIS severity injuries may result in as many deaths as higher AIS severity injuries. The MRR and MRR_{MAIS} values provide a quantitative mortality metric on a continuous scale that could be used as a supplement or alternative to AIS severity to better quantify an injury's threat to life.

MRR and MRR_{MAIS} values are presented together for each injury in this paper as each may be of value in particular scenarios and applications. MRR_{MAIS} controls for patient MAIS by excluding patients with a higher MAIS than the AIS severity of the injury of interest and thus would be expected to be a more accurate estimate of the true mortality associated with the individual injury. However, the calculation of MRR_{MAIS} is also limited by smaller sample sizes and reduced statistical power. To calculate the true mortality associated with an individual injury, only patients with isolated injuries should be included, which would reduce the sample size even further [Meredith et al., 2003b]. In contrast, MRRs are calculated using the complete sample of MVC trauma patients which improves statistical power, but the mortality of lower severity injuries (AIS 2-3) is likely overestimated due to higher severity co-injuries in patients with multiple injuries. As the investigation of the pericardium laceration showed, some injuries rarely occur without being accompanied by higher severity co-injuries and for injuries such as these, MRRs may represent a better measure of mortality compared to MRR_{MAIS}. In a MVC scenario, multiple injury patient trauma occurs frequently and MVC researchers may find that MRR represents occupant mortality risk better than MRR_{MAIS}, especially for particular injuries that occur rarely in isolation. However, we advocate for further investigation and are providing both MRR and MRR_{MAIS} measures for the top 95% most frequently occurring AIS 2+ injuries in MVCs.

The majority (67%) of the injuries had MRRs less than 10%. Thus, it may be important to operate in this lower range of MRRs (0-0.10) when identifying a MRR threshold that best discriminates for mortality. Likewise, the majority (76%) of the injuries had MRR_{MAIS} values less than 5%, indicating the 0-0.05 range may be important for establishing a mortality risk threshold that accounts for patient MAIS. While the focus of this study was not to define such thresholds, the methodology and results presented in this study could be used in the future for this purpose.

MRR-based measures of injury severity could be used as an alternative to AIS-based metrics for estimating patient mortality. The International Classification of Diseases Injury Severity Score (ICISS), derived as the product of all the SRRs of a patient's ICD-9 codes, is a time-tested approach that has been found to be a better discriminator of mortality compared to several AIS-based metrics such as the ISS, New Injury Severity Score (NISS), and MAIS [Sacco et al., 1999; Meredith et al., 2002; Kilgo et al., 2003]. Kilgo et al. (2003) showed that a similar metric to ICISS, known as the Trauma Registry AIS Score (TRAIS) and computed using the product of all the SRRs of a patient's AIS codes, represented the best AIS-based score for predicting mortality [Kilgo et al., 2003]. MRRs could be used instead of SRRs to derive a metric similar to TRAIS since the MRR is the probabilistic complement of SRR (computed as 1-SRR). The maximum MRR of all the injuries sustained by a patient may also prove to be a good discriminator of patient mortality and could serve as a non-AIS alternative to MAIS. In fact, it has been shown that ICISS and TRAIS discriminate for mortality better when only the SRR from the patient's worst injury is included in the calculation as opposed to SRRs from all injuries [Kilgo et al., 2003]. Using just the worst injury's MRR to estimate mortality may reduce the theoretical complexities associated with accounting for interaction between MRRs of individual injuries when mathematically estimating mortality for multiple injury patients. These MRR-based metrics could also be compared to scores such as the Trauma – Injury Severity Score (TRISS) and the Revised Trauma Score (RTS) that account for age or physiological measures [Boyd, Tolson and Copes, 1987; Champion, Sacco, Copes et al., 1989].

Limitations

The exclusion of NASS-CDS 2009-2011 cases with missing data presents a limitation, but allows for inclusion of newer NASS-CDS cases while treating cases with missing data appropriately. An alternate option would be to scale up injury numbers by 50% to account for the 1/3 of cases where this information is missing, but it was decided that excluding the cases with missing data would introduce the least amount of error into the dataset.

NTDB is not a population sample and disproportionately includes large trauma centers with younger and more severely injured patients. These inferences are subject to the biases inherent in any large, retrospective study of a convenience sample. Inter-center variation in measurement standards is known to be inconsistent in the NTDB, particularly with respect to treatment of dead on arrival patients. However, NTDB is the largest aggregation of trauma registry data and is rigorously examined by each institution contributing data and by NTDB administrators to ensure accuracy. The database does not contain information on MVC characteristics, pre-hospital care, or intra-hospital care, and thus these factors are not controlled for in this study. NTDB MVC cases were sub-selected for analysis to broadly control for injury causation, as MRRs for some injuries have been shown to differ for MVC versus non-MVC etiologies [Kilgo PD, Weaver AA, Barnard RT et al., 2013].

MRRs are likely underestimated in the NTDB sample due to an underreporting bias since fatally injured patients that did not survive long enough to be admitted to a hospital or that were dead on arrival may not be included in NTDB. The underestimation of mortality is expected to be higher for higher severity injuries, particularly for AIS 6 injuries. Although MRRs may be underestimated due to limitations associated with the NTDB sample, the data-driven estimation of mortality is still valuable and the data has shown that hundreds of trauma patients do survive after sustaining AIS 6 injuries classified as “Maximum/Unsurvivable” by the AIS coding lexicon.

There are fundamental flaws in the estimation of MRRs in any study since the impact of some injuries gets mathematically transferred to other injuries [Meredith et al., 2003b]. The MRR_{MAIS} metric accounted for patient MAIS to demonstrate the effect higher severity co-injuries can have on MRR estimation. The analysis showed a decrease in the estimated mortality when excluding patients with a MAIS higher than the AIS index of the injury of interest, but excluding these patients resulted in much smaller sample sizes and further investigation is warranted. Additional covariates such as the anatomical region of co-injuries and patient age were not directly adjusted for in this study when computing MRR and MRR_{MAIS} and present a limitation that could be addressed in the future using multivariate statistical models. Despite the limitation in the calculation of MRR, MRR-based measures are still leading discriminators of mortality following trauma and are important to consider when assessing the severity of common MVC injuries [Sacco et al., 1999; Meredith et al., 2002].

Future Work

In the future, the expert opinions of physicians could be used in conjunction with the MRR and AIS severity measures to further quantify injury mortality. Detailed studies on injury combinations could be undertaken to better quantify the mortality associated with single injuries and with particular combinations of injuries. Multivariate statistical studies could be undertaken to adjust for many covariates including the patient age and the anatomical region and severity of co-injuries. The MRR-based measure of severity described in this study will be used as part of a larger study to identify injuries necessitating treatment at a trauma center for incorporation into an advanced automatic crash notification algorithm.

CONCLUSION

MRRs for the top 95% most frequently occurring MVC injuries were computed by dividing the number of deaths by occurrences for each injury using MVC cases in the NTDB-RDS. An MRR-based metric, MRR_{MAIS}, was also computed by including only patients with a MAIS equal to the AIS severity of the injury of interest. Injuries with higher MRR and MRR_{MAIS} values are considered to be more severe because they resulted in a greater proportion of deaths among injured patients. An overall positive trend between AIS severity and the MRR/MRR_{MAIS} values was observed, but there were large variations in MRR and MRR_{MAIS} for some injuries of the same AIS severity. Up to an 83% difference in mortality (0.83 difference in MRR) was indicated by MRRs for injuries of the same AIS severity. When controlling for patient MAIS, up to a 54% difference in mortality (0.54 difference in MRR_{MAIS}) was indicated by MRR_{MAIS} values for injuries of the same AIS severity. Some lower AIS severity injuries had MRRs that were greater than the MRRs for higher AIS severity injuries and similar results were observed for MRR_{MAIS}. The data-driven determination of injury severity using MRR or MRR_{MAIS} provides a supplement or an alternative to AIS severity that may better quantify the true mortality associated with injuries.

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APPENDIX. MRR and MRR_{MAIS} values for the AIS codes on the Top 95% List. Injuries are sorted by ascending AIS severity and then by ascending AIS pre-dot code.

AIS Code	MRR	MRR_{MAIS}	AIS Code	MRR	MRR_{MAIS}	AIS Code	MRR	MRR_{MAIS}
110604.2	0.090	0.016	542020.2	0.155	0.012	815000.2	0.066	0.033
150400.2	0.104	0.014	542022.2	0.092	0.000	840402.2	0.000	0.000
150402.2	0.099	0.006	542810.2	0.142	0.000	840404.2	0.010	0.000
160202.2	0.008	0.002	544210.2	0.046	0.005	840600.2	0.023	0.000
160406.2	0.006	0.001	544212.2	0.053	0.005	840802.2	0.010	0.000
160410.2	0.003	0.001	544220.2	0.130	0.003	841002.2	0.020	0.000
160414.2	0.001	0.000	544222.2	0.070	0.003	850210.2	0.036	0.004
160602.2	0.001	0.000	650200.2	0.011	0.000	850214.2	0.031	0.000
160606.2	0.011	0.003	650204.2	0.069	0.005	850218.2	0.056	0.000
160610.2	0.000	0.000	650208.2	0.537	0.053	850610.2	0.027	0.004
160699.2	0.015	0.003	650209.2	0.043	0.000	850614.2	0.028	0.005
161000.2	0.010	0.002	650216.2	0.073	0.009	850806.2	0.046	0.018
210604.2	0.043	0.004	650218.2	0.063	0.005	850818.2	0.035	0.004
241202.2	0.057	0.000	650220.2	0.061	0.001	850822.2	0.008	0.000
243404.2	0.096	0.000	650230.2	0.067	0.007	850826.2	0.010	0.002
250200.2	0.033	0.000	650232.2	0.057	0.003	851400.2	0.022	0.001
250608.2	0.035	0.000	650416.2	0.059	0.007	851605.2	0.070	0.014
250610.2	0.075	0.009	650418.2	0.066	0.003	851606.2	0.047	0.009
250612.2	0.035	0.003	650420.2	0.064	0.005	851608.2	0.019	0.004
250616.2	0.040	0.000	650430.2	0.049	0.002	851610.2	0.052	0.012
250800.2	0.063	0.005	650432.2	0.029	0.003	851612.2	0.029	0.002
250802.2	0.076	0.010	650616.2	0.040	0.003	852000.2	0.032	0.003
250806.2	0.051	0.005	650618.2	0.063	0.000	852002.2	0.137	0.043
251004.2	0.052	0.002	650620.2	0.054	0.002	852200.2	0.018	0.002
251200.2	0.070	0.007	650630.2	0.028	0.005	852400.2	0.035	0.004
251202.2	0.050	0.001	650632.2	0.023	0.002	852600.2	0.070	0.006
251604.2	0.048	0.000	740400.2	0.055	0.010	852602.2	0.063	0.007
251800.2	0.076	0.004	750230.2	0.021	0.000	853200.2	0.018	0.004
441602.2	0.825	0.000	751030.2	0.035	0.002	853404.2	0.076	0.015
441800.2	0.395	0.000	751230.2	0.080	0.017	853406.2	0.033	0.009
450210.2	0.107	0.020	751430.2	0.011	0.000	853412.2	0.025	0.004
450220.2	0.052	0.015	751800.2	0.266	0.135	853414.2	0.031	0.004
450804.2	0.091	0.006	751900.2	0.220	0.000	853420.2	0.047	0.005
540610.2	0.075	0.000	752002.2	0.033	0.003	140466.3	0.324	0.081
540810.2	0.174	0.019	752200.2	0.070	0.007	140602.3	0.091	0.046
541410.2	0.136	0.006	752402.2	0.056	0.000	140604.3	0.055	0.015
541610.2	0.062	0.004	752500.2	0.041	0.011	140606.3	0.052	0.010
541612.2	0.060	0.000	752600.2	0.100	0.019	140612.3	0.182	0.084
541620.2	0.093	0.000	752602.2	0.067	0.007	140614.3	0.098	0.036
541622.2	0.056	0.004	752800.2	0.042	0.008	140620.3	0.142	0.037
541810.2	0.072	0.010	752802.2	0.036	0.003	140622.3	0.115	0.022
541812.2	0.060	0.003	753000.2	0.065	0.004	140660.3	0.240	0.131
541820.2	0.148	0.010	753200.2	0.045	0.005	140662.3	0.048	0.011
541822.2	0.074	0.003	753202.2	0.035	0.005	140682.3	0.117	0.030
542010.2	0.134	0.007	810604.2	0.049	0.006	140684.3	0.184	0.063

AIS Code	MRR	MRR_{MAIS}	AIS Code	MRR	MRR_{MAIS}	AIS Code	MRR	MRR_{MAIS}
150200.3	0.105	0.040	851810.3	0.082	0.040	140656.5	0.495	0.490
150202.3	0.090	0.020	851812.3	0.073	0.033	140666.5	0.708	0.705
150404.3	0.151	0.041	851814.3	0.042	0.010	160824.5	0.597	0.593
160802.3	0.049	0.041	851818.3	0.052	0.019	420210.5	0.433	0.426
160806.3	0.019	0.017	851822.3	0.052	0.019	420216.5	0.441	0.427
250808.3	0.103	0.033	852604.3	0.063	0.020	441012.5	0.640	0.610
251204.3	0.069	0.011	852800.3	0.077	0.023	450242.5	0.267	0.248
440604.3	0.250	0.094	853000.3	0.083	0.028	450266.5	0.446	0.445
441402.3	0.071	0.032	853405.3	0.089	0.030	541828.5	0.486	0.473
441406.3	0.064	0.018	853408.3	0.041	0.017	544228.5	0.266	0.257
441430.3	0.200	0.038	853422.3	0.059	0.015	113000.6	0.678	0.678
441499.3	0.092	0.074	140410.4	0.138	0.081	140212.6	0.808	0.808
442202.3	0.111	0.043	140629.4	0.121	0.086	140218.6	1.000	1.000
442204.3	0.100	0.036	140630.4	0.078	0.049	420218.6	0.831	0.831
450211.3	0.148	0.073	140632.4	0.041	0.016	441016.6	0.938	0.938
450214.3	0.071	0.033	140638.4	0.130	0.073			
450222.3	0.089	0.036	140640.4	0.072	0.037			
450230.3	0.075	0.034	140642.4	0.087	0.049			
450250.3	0.089	0.036	140650.4	0.147	0.092			
521604.3	0.212	0.074	140652.4	0.118	0.066			
540824.3	0.155	0.057	140664.4	0.434	0.274			
541424.3	0.089	0.034	140678.4	0.225	0.118			
541824.3	0.119	0.039	140688.4	0.171	0.089			
544214.3	0.073	0.039	150206.4	0.363	0.203			
544224.3	0.098	0.022	150406.4	0.353	0.236			
544240.3	0.146	0.086	160820.4	0.000	0.000			
650222.3	0.046	0.013	420206.4	0.372	0.327			
650224.3	0.048	0.016	420208.4	0.229	0.125			
650226.3	0.051	0.020	440606.4	0.239	0.134			
650228.3	0.077	0.039	441410.4	0.157	0.078			
650234.3	0.087	0.018	441450.4	0.295	0.155			
650424.3	0.071	0.019	450232.4	0.116	0.075			
650426.3	0.044	0.021	450240.4	0.201	0.111			
650434.3	0.053	0.018	450252.4	0.155	0.087			
650624.3	0.025	0.009	450260.4	0.339	0.325			
650634.3	0.030	0.006	450264.4	0.183	0.131			
752604.3	0.066	0.017	541626.4	0.157	0.105			
752804.3	0.044	0.012	541826.4	0.185	0.119			
753204.3	0.047	0.016	544226.4	0.117	0.066			
840406.3	0.006	0.000	140202.5	0.722	0.719			
851614.3	0.041	0.022	140204.5	0.345	0.321			
851800.3	0.132	0.063	140210.5	0.487	0.470			
851801.3	0.111	0.030	140628.5	0.180	0.176			
851804.3	0.056	0.031	140646.5	0.227	0.225			
851808.3	0.045	0.010	140654.5	0.282	0.275			