THORACIC INJURY POTENTIAL

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ABSTRACT

Nonskeletal injuries, such as lesions to organs and ruptures to major vessels, pose the most significant "threat-to-life" resulting from thoracic impact. Previous human cadaver impact studies have concentrated on assessing the severity of human injury according to a cumulative AIS, which classifies skeletal and nonskeletal trauma on a common scale. In many situations skeletal injuries dominate the response picture and, as such, may have influenced ultimate interpretations of injury potential away from the less frequent nonskeletal trauma. In-depth statistical analyses of 52 cadaver tests, involving blunt thoracic impact, were conducted to delineate parametric dependencies for both nonskeletal (i.e., organ and vascular trauma) and skeletal injuries with biomechanical responses and specimen characteristics. Despite a demonstrated linear dependence between overall and skeletal injury severities on the level of normalized thoracic deflection, "life-threatening" injury seems more reasonably associated with a normalized deflection limit (P/D $\sim$ 0.32). Deformation beyond this limit appears to trigger a structural instability and cause a collapse of the rib cage, which results in multiple rib fractures and a realistic hazard for intrathoracic organ and vascular injury. The latter encompass a spectrum of serious injury (AIS 3-6). Nonskeletal injury occurrences are also shown to be a statistically significant function of the specimen's age, level of normalized thoracic deflection and extensiveness of skeletal damage.

OVERVIEW

Restraint and protection of occupants in an automotive collision is currently provided, in part, by distributed thoracic loads applied by torso belts, inflatable air cushions and in some instances by a steering column. In all cases the thorax encounters restraint loads. Loading the thorax can produce various biomechanical responses in the highly compliant and anatomically complex region of the body. Considerable literature has developed during recent years covering experimental and analytical efforts to improve our understanding of biomechanical responses and injury mechanisms. This work has led to the development of injury avoidance guidelines for the human thorax, so that meaningful measures of injury potential are slowly becoming available. Such tools are vital to design and development efforts aimed at improving automotive interior and restraint system performance during a car crash. Current forms of active and passive occupant restraint generally utilize thoracic loads to mitigate the effects of the secondary impact of the occupant with the automotive interior. Increased usage of restraints should result in a decrease in the frequency and severity of head impact. The overall potential for thoracic injury should also decline but may increase in prominence as the relative site of serious injury. Design related questions already strain our understanding of the biomechanical response and injury phenomena associated with thoracic impacts. Multidisciplinary research using many forms of surrogates is the only means of continuing to improve our understanding of important factors influencing human injury.

INTRODUCTION

A comprehensive series of cadaver experiments involving thoracic impact has been sponsored by the General Motors Research Laboratories at a willed-body research program at the University of California at San Diego. Nearly ten years of research have been invested into studies of the thoracic response of human cadavers exposed to blunt frontal impact. The investigative efforts have been analyzed and regularly reported to the automotive safety-occupant protection community by the primary researchers: Messrs. Kroell, Schneider or Nahum [1-3]. In addition, a detailed summary of thoracic responses to blunt frontal loading was recently presented by Kroell [4]. This biomechanics data has also formed the basis for subsequent dummy development efforts [5, 6], improved thoracic response guidelines and injury criteria [7, 8] and animal model experimentation [9-12].

Kroell's tests [1-4, 13] incorporated a rigid striker mass accelerated to impact velocity by elastic shock cords. The free sliding impactor was allowed to axially impinge against the thorax of an upright oriented specimen. The contacting interface was an unpadded 15.2 cm diameter wooden block with rounded edge to prevent localized loads at the perimeter. The axis of contact was aligned perpendicular and centered midsagitally at the level of the 4th costal interspace on the sternum (see Fig. 3, Ref. [4]). Inertially compensated load and thoracic penetration measurements were obtained in most cases with frequent sternal and/or spinal acceleration and intrathoracic fluid pressures in more recent experiments. The chronology of this experimental effort evinces an improved understanding of the fundamental biomechanics and trauma mechanisms associated with thoracic impacts.

Gadd and Kroell [1] perceived a tendency in the sternal impact data that the level of resultant injury was dependent upon the degree of thoracic penetration. Kroell reasoned that such a dependence was quite plausible and demonstrated that a realistic cause-effect relationship was actually more valid than a relationship between injury and force [3] or thoracic acceleration [14, 8]. Kroell's [3, 14] and Neathery's [7, 8] analyses of the UCSD cadaver data supplied substantive evidence for the utilization of a normalized thoracic deflection measure of injury potential which would superscede a current spinal acceleration injury criterion.

In addition, Neathery [5, 7] utilized adjusted force-deflection corridors established by Kroell [6] as response guidelines for the development of a biomechanically similar dummy chest. Further statistical analyses of the UCSD data by Neathery [7] also expanded the Kroell force-deflection corridors according to occupant anthropometry. He also cataloged the degree of thoracic deflection which would correspond to a serious thoracic injury AIS 3.

Neathery obtained injury potential-normalized deflection relationships by multilinear regression analyses of the cadaver data. Cadaver characteristics were investigated to determine potential effects of biomechanical responses and injuries. Neathery's work [7, 8] constitutes a classical utilization of statistical techniques to extract interdependencies between complex multi-dimensional data. A noteworthy consequence of his analysis was the identification of the influence of specimen age at death on the degree of expected overall injury outcome. In particular, an age differential of 25 years (40 versus 65) could be shown to aggravate the level of expected injury severity by one unit of AIS (AIS 3 versus AIS 2). Since the average cadaver specimen's age for the UCSD series was approximately 65 years, Kroell's and Neathery's average 65 year old subject's linear regression lines were shown to be in essential agreement.

Viano [10] emphasized that as many as eleven different impact conditions were utilized in the UCSD experiments and that the number of cadavers subjected to a particular impact condition varied from a low of 1 to a high of 11. He reasoned that the statistical collation of the individual data could bias various relationships toward the impacts with more specimen experiments. Using average cadaver responses for each set of distinct impact conditions (thereby equally weighing each type of impact event), a series of new features in the linear regression analyses were exposed (see Fig. 14, Ref. [10]). Although Viano's analyses undoubtedly biased the results toward the single or few specimen impact tests, the dependence of resultant injury on the degree of normalized deflection was shown to lose specificity in predicing injury when P/D levels approached 0.40, i.e., resultant injuries were shown to vary from AIS 3-6 without specific dependence of the level of normalized deflection.

The loss of injury-deflection specificity for moderate to large levels of thoracic compression led Viano to question the validity of a general linear injury-deflection relationship. In addition, the mode of specific injury, whether it be primarily skeletal or nonskeletal in nature, and its relationship to biomechanical response parameters had not been investigated. Certainly the relatively frequent occurrence of skeletal injuries, which typically dominate the experimental response picture, may actually have overshadowed potentially more significant nonskeletal injuries which in practice can pose a serious threat-to-life.

Eppinger [15] recently analyzed the UCSD data for interdependencies between the extent of skeletal injuries and biomechanical responses and cadaver characteristics. In essence he extended Neathery's multilinear regression analysis by determining that the degree of normalized thoracic deflection and specimen age are reasonably predictive of the thoracic rib fracture outcome. Eppinger's relationship is slightly inferior to Neathery's due to a much wider dispersion in the resultant cadaver rib fracture data. Eppinger also analyzed the rib fracture occurrences in the experimental results of 6 independent sled test investigations involving belted cadavers by Cromack, Fayon, Melvin, Patrick, Schmidt and Walsh. He found that the number of observed thoracic rib fractures was a statistically significant function of the maximum upper torso belt force and the cadaver's age and weight.

It may seem surprising that Eppinger identified a functional dependence between torso belt force and resultant skeletal damage but it just ellucidates a factor that needs further emphasis. Kroell's earlier analysis work (see Figs. 16 and 17, Ref. [3]) demonstrated that peak applied force was a rather poor correlator with resultant injury as compared to normalized deflection. This was specifically true for the wide range of blunt impact conditions utilized in the UCSD test series. When the results of a similar impact condition are viewed independently, applied force is generally a moderate predictor of the resultant injury outcome. This feature has been shown [10] to become more pronounced as the mass of the impactor increases above 20 kg. Blunt thoracic impacts to an animal model (see multiple correlation coefficient Tables 9-11, Ref [11]) demonstrated that both the overall injury severity and number of rib fractures were well correlated with the peak applied force for reasonably similar impact severities (i.e., 21 kg impactor with a striking velocity of 8.1 to 10.6 m/s). Large variations in the impact conditions resulted in drastic reductions in the correspondence of the level of peak force and injury outcomes. The authors noted that extrapolation of the observed force-injury correlation to a wider range of impact exposures would be falacious.

To follow this point a little further, Viano observed that resultant injury and thoracic deformations in the UCSD data were well correlated with the initial kinetic energy of the impact (see Figs. 12, 13 and 15, Ref. [10]). The study showed that very different impact conditions, i.e., pairs of impactor mass and velocity with similar initial energy produced extremely similar deflection and injury responses. Analysis of response parameters for a range of impact conditions further demonstrated that the peak applied force (see Fig. 16a, Ref. [10]) is essentially impact velocity dependent and only for relatively large impactor mass do the trends in peak force moderately correspond to deflection and injury variations. When human cadavers load against an upper torso belt, the exposure constitutes an impact environment somewhat equivalent to a high mass frontal impact exposure so that resultant injury may reasonably be related to the upper belt force or impact velocity. Eppinger discusses other more subtle dependencies by a nondimensional analysis which parallels Neathery's techniques [7] and results in a rib fraction prediction equation related to the peak belt load normalized by the subject's mass.

Previous analyses of the UCSD data concentrated on the development of relationships between overall or cumulative injury observations and measures of biomechanical response. The current analyses recognizes a potential inherent limitation of assessing skeletal and nonskeletal injuries on a common scale. Eppinger's analyses attempted to remedy this shortcoming by investigating rib fractures only, but we should recognize the importance of improving our understanding of the causative factors associated with the occurrence of potential "life-threatening" trauma, which is generally nonskeletal in nature. In fact, since the skeletal injuries typically dominate the experimental response picture they may have already biased our injury criteria interpretation away from the more serious nonskeletal trauma to the more frequent skeletal injuries. An in-depth statistical analysis of the UCSD data was undertaken where resultant injury data was cataloged according to three injury severity measures: 1) cumulative overall injury (AIS), 2) maximum skeletal injury (AIS_{SK}) and 3) maximum nonskeletal injury (AIS_{NS}). Parametric interdependencies are investigated between the various measures of injury in the cadaver, including the number of rib fractures, and the available measures of biomechanical response.

EXPERIMENTAL DATA ANALYSIS

The blunt thoracic impact data from cadaver tests conducted by Kroell, Schneider and Nahum [1-4] also form the basis for this mode of injury potential analysis. Injury results from this multiyear experimental effort were reviewed and corrected for consistency with the current 1976 Abbreviated Injury Code [16]. Thus the modified cumulative AIS (Table 1) should be consistent in injury severity score for all of the experimental observation of resultant trauma. The actual reported AIS is tabulated for reference purposes only and will not be used in this statistical analysis. In addition to a general revision of the observed injury scores, two modes of resultant trauma were cataloged separately: 1) skeletal injury and 2) nonskeletal injury. Thus, for each impact event at least three modified injury scores are defined: 1) overall or cumulative injury (AIS), 2) skeletal injury (AIS_{SK}) and 3) nonskeletal injury (AIS_{NS}).

TABLE 1

General Data Tabulation (Individual Data)

	Cadaver Characteristics				Impact		Biomechanics		AIS Cumulative		Skeletal Injury			Nonskeletal Injury				
	Test and Cadaver ID	Age (yr)	Weight (kg)	Chest Depth (cm)	Mass (kg)	Velocity (m/s)	Peak Force (kN)	Normalized Deflection (P/D)	Reported AIS	Modified AIS	No. Rib Fractures	Total Fractures	Skeletal AIS	Major Vessels	Organs Thorax	Organs Abdomen	Pneumo-Thorax	Nonskeletal AIS
Region 1	172/43FM	59	54.6	24.1	22.9	4.9	-	.329	3	3	9	9	3	0	0	0	0	0
	171/42FM	61	54.6	21.6	22.9	4.9	2.96	.321	0/1	1	0	0	0	0	0	0	0	0
	177/45FM	64	64.1	25.4	23.0	5.1	2.72	.315	3	3	10	10	3	0	0	0	0	0
	200/60FM	66	79.6	22.2	23.0	4.4	2.49	.269	3	3	9	9	3	0	0	0	0	0
	189/53FM	75	77.3	24.1	23.0	5.3	3.31	.257	2	3	3	3	3	0	0	0	0	0
	FM Avg:	65	66.0	23.5	23.0	4.9	2.82	.298	2.8	2.6	6.2	6.2	2.4					
Region 2	77/19FM	19	71.4	20.3	23.6	6.8	4.27	.375	2	2	0	0	0	0	0	0	0	0
	79/20FM	29	56.8	20.3	23.6	6.8	3.87	.350	0/1	1	0	1	0	0	0	0	0	0
	203/63FM	53	68.2	22.6	23.0	7.0	4.16	.373	4	4	4	4	3	0	0	4	0	4
	204/64FM	72	63.2	21.6	23.0	7.0	3.07	.371	3	3	6	6	3	0	0	0	0	0
	83/22FM	72	75.0	22.6	23.6	6.8	4.00	.417	4	4	10	17	3	0	0	4	0	4
	76/18FM	78	65.9	21.9	23.6	6.8	4.20	.418	4	3	11	14	3	0	0	0	3	3/0
	69/15FM	80	53.2	20.0	23.6	6.9	4.67	.393	4	4	9	13	3	4	0	0	0	4
	65/13FM	81	76.4	24.6	22.9	7.5	4.58	.444	5	5	12	21	4	0	5	0	0	5
	FM Avg:	61	68.8	21.7	23.6	7.0	4.10	.393	3.3	3.3	6.5	9.4	2.8					[illegible]
	82/21FF	45	68.6	21.3	23.6	6.9	4.74	--	4	3	10	18	3	0	[illegible]	[illegible]	[illegible]	
	61/12FF	67	62.7	18.7	22.9	7.3	4.27	.420	4	4	14	22	4	0	4	0	[illegible]	4
	66/14FF	76	57.7	21.6	22.9	7.4	4.54	.435	6	5	6	7	3	5	5	0	0	5
	FF Avg:	63	63.0	20.5	23.1	7.2	4.18	.428	[illegible]	4.0	10.0	15.7	3.3					4.5
	FM+FF Avg:	61	67.2	21.4	23.3	[illegible]	4.12	400	3.[illegible]	3.5	[illegible]	[illegible]	2.[illegible]					4.3
Region 3	104/37FM	48	74.1	24.8	22.9	9.9	[illegible].91	.328	6	5	6	9	3	5	5	5	0	5
	93/31FM	51	75.0	23.8	23.1	10.3	6.64	.459	6	6	11	14	3	0	6	0	0	6
	86/24FM	65	81.8	25.1	22.9	9.7	6.81	.425	4	5	16	24	4	0	0	5	0	5
	94/32FM	75	54.5	24.8	22.9	10.0	5.80	.458	6	6	13	20	4	0	6	0	0	6
	FM Avg:	60	71.4	24.6	23.0	10.0	6.79	.418	5.5	5.5	11.5	16.8	3.5					5.5
R4	47/5FM	60	86.4	25.7	19.6	5.2	2.07	.289	-	4	17	17	4					
	50/6FM	83	77.3	25.4	19.6	5.2	2.02	.325	-	3	11	11	3					
	FM Avg.	74	81.9	25.5	19.6	5.2	2.05	.307	-	3.5	14	14	3.5					
Region 5	178/46FM	46	95.0	28.6	19.3	7.4	4.03	.310	0/1	0	0	0	0	0	0	0	0	0
	99/36FM	52	75.0	22.6	19.0	7.2	4.85	.346	4	5	7	7	3	0	0	5	0	5
	96/34FM	64	59.1	24.1	19.0	8.3	4.96	.447	4	3	11	13	3	0	0	0	0	0
	FM Avg:	54	76.4	25.1	19.1	7.7	4.61	.368	3.0	2.7	6.0	6.7	2.0					5
	190/54FF	49	37.3	20.5	19.6	6.8	2.63	.407	5	5	7	7	3	5	0	5	0	5
	85/23FF	58	61.4	22.6	19.5	7.8	5.67	.410	4	4	11	23	4	0	0	0	4	4/0
	FF Avg:	54	49.4	21.4	19.6	7.3	4.5	.412	4.5	4.5	9.0	15.0	3.5					5
	FM+FF Avg:	54	65.6	23.7	19.3	7.5	4.43	388	3.6	3.4	[illegible]	10.0	2.6					5
R6	191/55FF	46	81.4	24.1	19.6	10.0	6.04	.407	6	6	9	[illegible]	[illegible]	0	6	0		6
R7	C11, C14-C23	65	59.0	20.3	10.0	5.9	4.80	.220	1.2	1.2	[illegible]	[illegible]	0	0	0	0	[illegible]	0
Region 8	220/123FM	58	72.3	25.5	4.3	13.4	6.68	.370	3	3	[illegible]	[illegible]	3	0	0	0	0	0
	87/25FM	65	54.6	20.7	5.5	13.9	4.83	.395	4	5	11	18	3	0	0	5	0	5
	219/120FM	66	68.7	23.7	4.3	13.4	9.73	.350	3	3	6	6	3	0	0	0	0	0
	218/119FM	69	65.0	21.0	4.3	13.4	11.08	.370	3	3	11	[illegible]	3	0	0	0	0	0
	FM Avg:	65	65.0	22.7	4.6	13.5	8.08	.371	3.3	3.5	9.8	10.5	3					5
R9	88/26FM	75	63.6	24.8	1.9	11.3	5.34	185	0	0	0	0	0	0	0	0	0	0
R10	92/28FM	54	68.2	23.8	1.6	14.6	9.06	194	0	0	0	0	0	0	0	0	0	0
	92/30FF	52	40.2	18.0	1.6	13.3	4.57	.310	2	3	3	3	3	0	0	0	0	0
	FM+FF Avg:	53	54.2	20.9	1.6	13.8	6.82	.252	1.0	1.5	1.5	1.5	1.5					
Region 11-RB	187/51FM	60	82.3	25.4	10.5	6.[illegible]	[illegible].33	.377	0	0	[illegible]	[illegible]	[illegible]	0	0	0	0	0
	192/56FM	65	74.1	20.3	10.5	7.0	3.16	.394	2	3	3	3	3	0	0	0	0	0
	188/52FM	65	51.8	21.6	10.5	7.2	3.05	.486	4	3	9	[illegible]	3	0	0	0	0	0
	186/50FM	66	60.0	22.9	10.5	7.3	3.95	.431	6	5	10	12	3	5	0	0	0	5
	196/58FM	68	69.1	22.9	10.5	6.8	2.62	.390	3	4	4	4	3	0	0	4	0	4
	182/48FM	69	64.5	22.9	10.5	7.1	2.83	.397	0	0	0	0	0	0	0	0	0	0
	FM Avg:	66	67.0	22.7	10.5	7.0	2.99	.413	2.5	2.5	4.3	5.0	[illegible]					4.5

The experimental data are further grouped according to the similarity of impact conditions so that average biomechanical and injury response data can be obtained for the eleven reasonably different impact severities. The region 11 response data involves rigid back restraint, whereas the test data from regions 1-10 involve free torso impacts.

Underlying features of injury response characteristics are best described by the average grouped data responses (Table 2, see also Table I and II, Ref. [10]). These averages will also constitute the basis for the injury analyses in the main body of this paper. The importance of analyses based on the individual data is acknowledged by paralleling the types of statistical and parametric presentation in the body of this paper with similar analyses based on individual data. Although individual data statistics are not presented in this paper, results and interpretations of grouped responses have been checked and verified for consistency with individual response statistics.

TABLE 2

General Data Tabulation (Grouped Data)

Number Subjects	Age (yr)	Weight (kg)	Chest Depth (cm)	Region	Mass (kg)	Velocity (m/s)	Kinetic Energy (J)	Peak Force (kN)	Normalized Deflection (P/D)	Cumulative Injury (Modified) AIS	Skeletal Injury: No. Rib Fractures (#)	Skeletal Injury: AIS_{SK}	Nonskeletal Injury: Normalized* Deflection (P/D)	Nonskeletal Injury: No. Rib* Fractures (#)	Nonskeletal Injury: Frequency (%)	Nonskeletal Injury: AIS_{NS}
5	65	66.0	23.5	R1	23.0	4.9	280	2.82	.298	2.6	6.2	2.4	-	-	0	-
11	61	67.2	21.4	R2	23.3	7.1	590	4.12	.400	3.5	7.5	2.7	.407	9.2	60	4.3
4	60	71.4	24.6	R3	23.0	10.0	1150	6.79	.418	5.5	11.5	3.5	.418	11.5	100	5.5
2	74	81.9	25.5	R4	19.6	5.2	260	2.05	.307	3.5	14.0	3.5	-	-	-	-
5	54	65.6	23.7	R5	19.3	7.5	540	4.43	.388	3.4	7.2	2.6	.376	7.0	50	5.0
1	46	81.4	24.1	R6	19.6	10.0	980	6.04	.407	6.0	6.0	3	.407	8.0	100	6
11	65	59.0	20.3	R7	10.0	5.9	170	4.80	.220	1.2	0	0	-	-	0	-
4	64	65.0	22.7	R8	4.6	13.5	420	3.08	.371	3.5	8.8	3	.395	11.0	25	5
1	75	63.6	24.8	R9	1.9	11.3	120	5.34	.185	0	0	0	-	-	0	-
2	53	54.2	20.9	R10	1.6	13.8	150	6.82	.252	1.5	1.5	1.5	-	-	0	-
6	66	67.0	22.7	R11 - R8	10.5	7.0	260	2.99	.413	2.5	4.3	2.0			33	4.5

* Computed on data involving nonskeletal trauma

A considerable range in the severity of frontal impacts has been used in the cadaver experimentation at UCSD. Variations in impactor masses of 1.6-23.0 kg and velocities of 4.9-13.8 m/s cover an order of magnitude in the amount of available kinetic energy for the event. These impacts produced a spectrum of injuries in the cadavers ranging from minimal abrasions and contusions to severe vascular, myocardial and liver lacerations with extensive skeletal damage.

Grouped Data Analyses: Using the modified injury ratings, the overall injury severity is highly correlated with the degree of maximum normalized thoracic deflection (Fig. 1, see also Fig. 14, Ref. [10]). A threshold level of normalized deflection at P/D ∿ 0.20 seems to be consistent with reversible mechanical loads which do not produce injury in the cadavers (see also Fig. 37, Ref [4]). Lobdell and Kroell [6] noted that relaxed and tensed human volunteers could also be subjected to abrupt thoracic deflections producing thoracic deflections up to P/D ∿ 0.16 without injurious effects. For this analysis the linear regression equation has practical significance in defining the expected injury response for midrange thoracic deflections. A noticeable loss of specificity in the injury deformation dependence is encountered as the thoracic compression approaches P/D ∿ 0.40, since the overall injury severity varies nonspecifically from AIS 3-6.

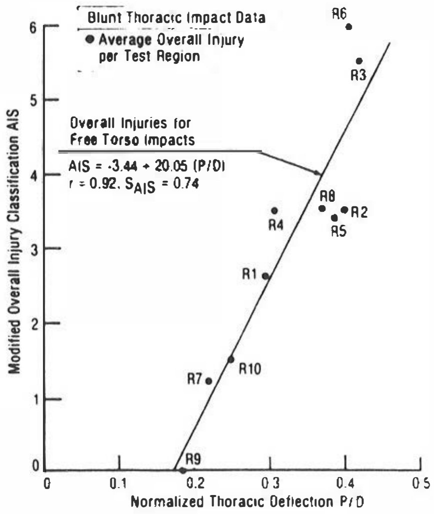

Fig. 1: Overall injury dependence on the degree of normalized thoracic deflection for the grouped response data.

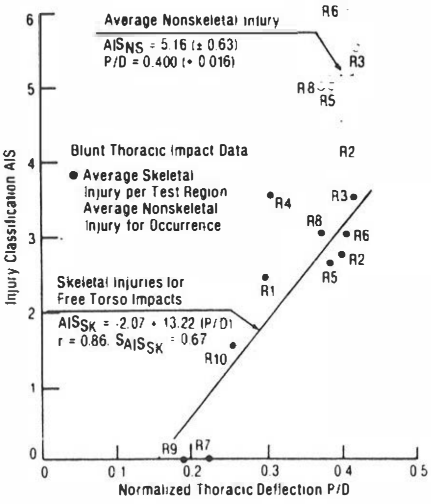

Fig. 2: Nonskeletal and skeletal injury dependence on the degree of normalized thoracic deflection for the grouped response data.

The ambiguity in the severity of the injury severities is a result of nonskeletal injury occurrences (Fig. 2). An overall injury rating is actually a composite index of the degree of skeletal and nonskeletal gross injury. Skeletal trauma typically dominates the response picture in the low- to mid-range of thoracic deflection. As the level of deflection increases skeletal injuries may be of secondary significance as serious organ and vascular injury occurrences become more frequent. In particular, the average nonskeletal injury severity is approximately two units of AIS greater than that associated with the skeletal injuries. The lack of specificity of the linear regression equation in this regime is a result of the least squares approximation of response data near P/D ∿ 0.40 that compromises the severity differences between skeletal (AIS ∿ 2-4) and nonskeletal (AIS ∿ 3-6) injuries as the most serious resultant injury.

The solid dots (Fig. 2) depict the average severity of skeletal damage. As the normalized deflection increases the extent of skeletal damage severity begins to cluster around AIS 3. In part this is a direct result of the method of rating rib fractures by the Abbreviated Injury Scale [16], which classifies skeletal trauma according to a code that gives an AIS 3 to 2 or more rib fractures. By this general injury severity grouping* of rib fractures, some lack of practical injury severity must be lost, i.e., ten rib fractures may well be more severe than four rib fractures but both would be coded AIS 3. The sensitivity or slope of the linear regression for the skeletal trauma is much lower than observed for the overall injury regression but both relationships demonstrate an injury threshold at P/D ∿ 0.20.

At high penetrations a threat of nonskeletal injury exists. In these tests the nonskeletal injuries were generally limited to a narrow range of thoracic deflections, which consititutes a severe injury response average at P/D = 0.40. It is these serious injuries that are the primary causation of the increased injury sensitivity of the overall injury regression line. Since the overall AIS is a composite of two distinct modes of injury, the high correlation coefficient for the overall injury regression may actually give a false impression of predictive confidence in the linearity of a potential injury outcome. In fact, overall injury severity predictions beyond P/D ∿ 0.32 may not be practical, due to the various modes and severities of resultant trauma. Certainly a serious injury hazard exists for normalized deflections beyond P/D ∿ 0.32, but the actual extent or severity deviates greatly and is not linearly correlated with changes in the degree of thoracic compression.

In summary, the overall injury severity dependence on normalized thoracic deflection is actually a composite of two distinct modes of thoracic injury: 1) a mid-range skeletal injury response, which is well correlated with the degree of deflection, and 2) a high penetration range which approaches an "avalanche limit" where extensive skeletal damage may be concomitant with a wide range of serious nonskeletal trauma. It seems clear that the latter limit is of most concern due to a potential for these injuries to be "life-threatening." An avalanche deflection limit seems apparent (Fig. 3) when the frequency

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* The 1976 Abbreviated Injury Scale classifies rib fractures according to: AIS 2: 1-2; AIS 3: 2 or more; AIS 4: flail chest with +1 in each category for open and/or displaced fractures.

of nonskeletal injuries is compared against the extent of normalized deflection. This representation solidifies the previous discussion in that the occurrence of nonskeletal injury is isolated to high level deflections. An avalanche limit is also supported by the large deviation in occurrence frequency clustered around P/D = 0.40. This wide deviation indicates that actual AIS level predictions are not possible; i.e., a gamut of injuries may occur without control.

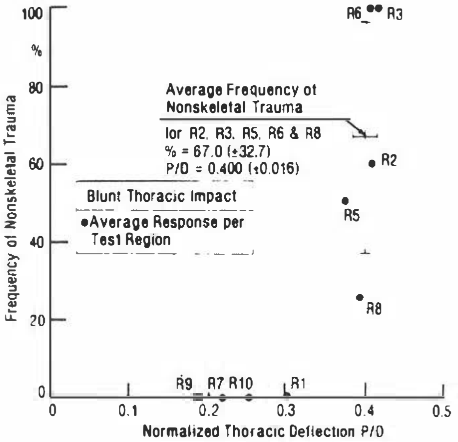

Fig. 3: Frequency of nonskeletal injuries as dependent on the degree of normalized thoracic deflection for the grouped response data.

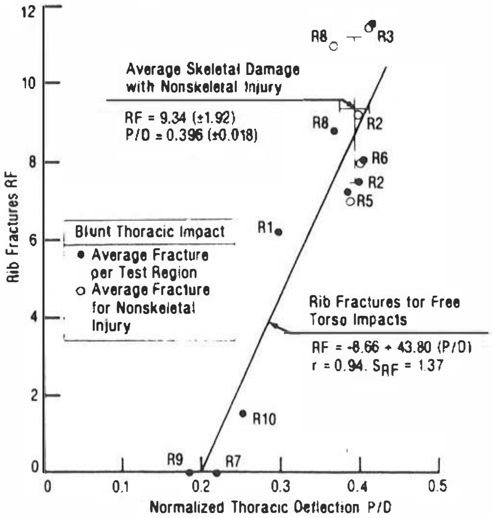

Fig. 4: Number of rib fractures resulting from a particular level of normalized thoracic deflection for the grouped response data.

The extensiveness of rib fractures seems reasonably correlated with the degree of thoracic compression (Fig. 4). Although a linear regression line apparently fits the data, there are insufficient mid-deflection region responses to substantiate a practical trend. In fact, another rib fracture response mechanism may be showing up that involves two modes of skeletal reaction: 1) reasonably reversible low level thoracic compressions which may produce little or no skeletal damage and limit the extent of thoracic compression, and 2) reasonably irreversible high level thoracic compressions which seems to exceed the structural stability of the thorax and may produce extensive skeletal damage by a dynamic collapse of the rib cage. The lack of response data in the deflection mid region lends some support to a thoracic stability limit* somewhere between P/D = 0.28-0.36. Below that level the thorax is structurally stable and protects the intrathoracic contents. Beyond that level the thorax may become structurally unstable. The rib cage may become extensively broken thus allowing the intrathoracic contents to be loaded and become more vulnerable

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* The concept of a thoracic "instability" is somewhat supported by high-speed X-ray evaluation of skeletal and intrathoracic kinematics during blunt thoracic impacts [17-21]. The rib cage has been observed to compress by increased lateral bending of the relatively loosely coupled ribs. If one or two ribs fail at moderate levels of compression and force, the remaining ribs will be rapidly subjected to a higher bending stress. If individual ribs are at the elastic limit when a few ribs break, a cascade effect is quite likely to result in extensive skeletal damage. As the structural integrity of the rib cage is destroyed, the compressive loads on intrathoracic organs and vessels will dramatically increase and serious injuries may occur.

to injury. When the rib cage is extensively damaged, the occurrence of nonskeletal injury may or may not occur in the cadaver subjects. The close proximity of skeletal responses when nonskeletal injuries were or were not observed seems to indicate that extensive skeletal damage is necessary but not sufficient for nonskeletal injury occurrences for this type of thoracic impact. By this observation I don't mean to preclude the possiblilty of very serious nonskeletal trauma in the absence of extensive skeletal damage for other types of impact exposures. In fact, response data is now available to support serious injury occurrence when the blunt impact exposures are midsagitally centered high on the sternum [22] and result in only minor skeletal damage. Certainly, other forms of serious nonskeletal injury (e.g. myocardial conducting system dysfunctions) may occur *in vivo* [12, 11, 19 and 23], which are beyond investigation in cadaver based programs.

Since the overall injury severities and rib fractures produced in the UCSD blunt impact exposures were reasonably correlated with the degree of normalized thoracic compression (although some practical limitations have been identified), a correspondence is possible between the two injury classifications (Fig. 5). As observed earlier, skeletal injuries determine the overall injury severity up to AIS 3 where this mode of injury approaches a severity asymptote. Extensive skeletal damage has a high probability of concomitant nonskeletal trauma (see also Fig. 6), but the correspondence exhibits much greater dispersion. Again, the avalanche effect is apparent with the limit somewhat above six to seven fractured ribs. Skeletal damage that extensive may substantially increase the vulnerability of intrathoracic organ and vessel injury. It should be cautioned that the standard error of the estimate (S = 1.14, Fig. 5) associated with the overall injury dependence on rib fractures is quite large. This indicates that considerable variation in probable overall injury outcome (i.e. actual AIS) may be anticipated with the degree of skeletal damage.

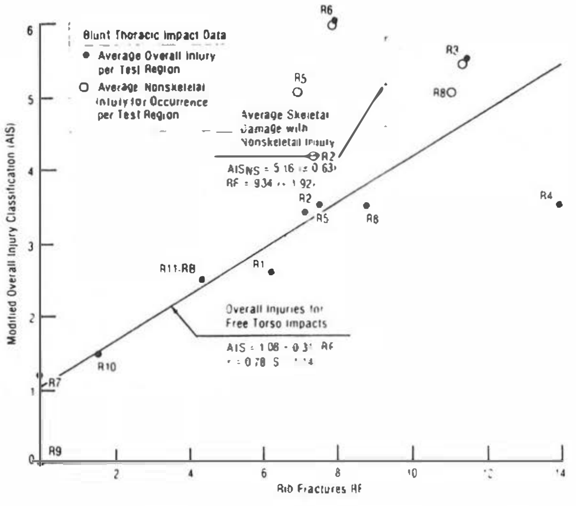

Fig. 5: Overall and nonskeletal injury dependencies on the number of fractured ribs for the grouped response data.

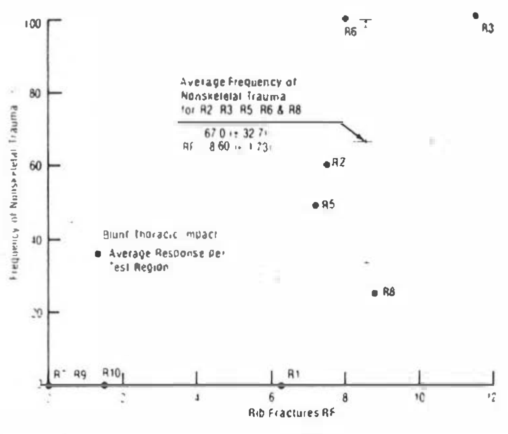

Fig. 6: Frequency of nonskeletal injury as dependent on the number of fractured ribs for the grouped response data.

A summary representation of the current observations (Figs. 7 and 8) was made so that they could be compared with the available statistical evaluations of previous investigators. It is hoped that this comparison will establish a realistic range of applicability for the available analytical results, especially in the context of actual injury-type outcomes. A subjective interface between not "life-threatening" skeletal trauma and potentially

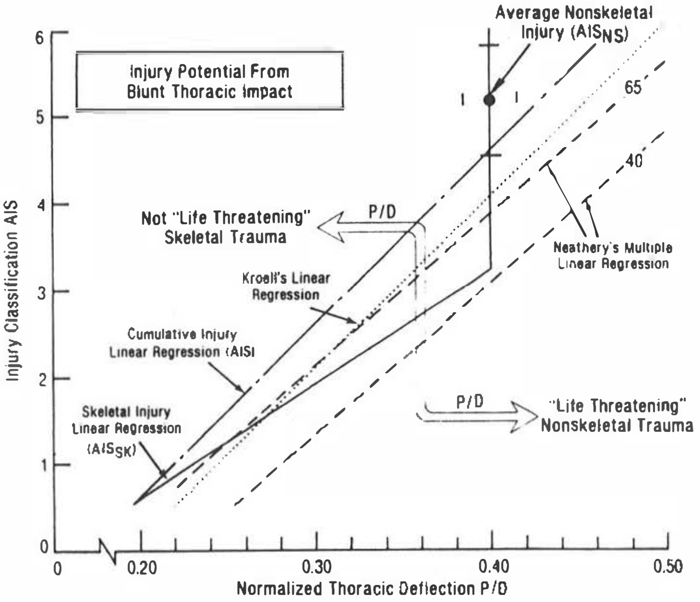

Fig. 7: Summary representation of injury dependencies on the degree of normalized thoracic deflection (published data taken from Kroell [3] and Neathery [8]).

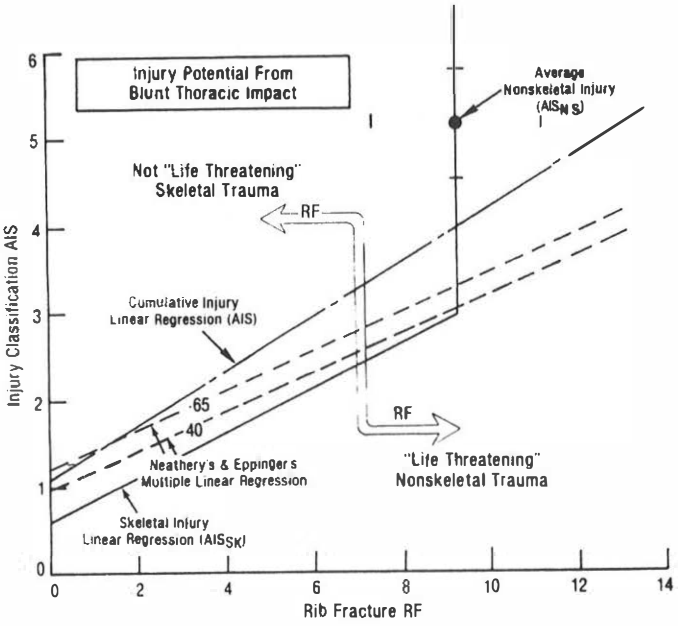

Fig. 8: Summary representation of injury dependencies on the number of fracture ribs (published data derived from Neathery [8] and Eppinger [15]).

"life-threatening" nonskeletal trauma is superimposed on the graphs as a practical guideline which limits the realistic applicability of linear regression relationships involving potential overall injury outcomes. The linear regression equation of Kroell (see Fig. 17, Ref. [3]) and the multilinear regression equation of Neathery (see Eq. 2, Ref. [8], assuming a mean cadaver age of 65 years) are in mutual agreement (Fig. 7) even though a different subset of the UCSD data were used in each analysis. Neathery's dependence for a mean subject age of 40 years indicates that a drop of nearly one unit of AIS can be expected for a particular level of thoracic compression. The cumulative injury regression of this study shows the same injury sensitivity as the previous relationships but the intercept is offset, probably due to the utilization of average impact responses based on all UCSD data and modified injury classifications. Also shown on this graph are the skeletal injury regression line with its lower injury sensitivity and the average nonskeletal injury response. It seems realistic to support the utilization of linear regression relationships of this kind for injury predictions at least up to the avalanche limit of P/D ∿ 0.28-0.36, but beyond that level of compression a wide range of outcomes should be anticipated. It is clear that specimen's age dramatically affects the extent of skeletal damage (also see Fig. 2, Ref. [15]) and as such may well affect the load or response level at which a thoracic structural instability may be expected. At this time such a dependency has not been investigated in detail (see the section on influence of specimen characteristics for additional age related effects) but it should be borne in mind when interpreting the data. It is probable that the considerable range in expected overall injury outcome between Neathery's 40 year and 65 year average specimen is dominated by skeletal response effects. This is substantiated in part by the similarity of the same two (40 and 65 year) age responses when rib fractures are assumed the independent variable (Fig. 8*). Specimen age effects seem to be implicitly incorporated in the rib fracture parameter whereas age effects are more extrinsic to the resultant degree of normalized thoracic compression (see also Fig. 9). The cumulative and skeletal injury regressions exhibit very similar response sensitivities with individual variability primarily in the injury intercept. In this injury potential summary, the avalanche limit is located at about six to seven rib fractures, beyond which the linear regressions lose predictive specificity and should not be utilized. Serious "life-threatening" nonskeletal trauma may well occur with extensive skeletal damage (see Fig. 6) for this type of impact exposure.

Influence of Specimen Characteristics: Neathery utilized multilinear regression techniques in an attempt to extract the dependencies of thoracic injury on biomechanical response parameters and specimen characteristics. His work was based on a select subset of the UCSD data which included experiments from most impact severities. Because of some specific limitations on this statistical technique an alternate investigation of the influences of specimen age was undertaken to refine our understanding of its significance in the injury process. By using the individual male response data for identical impact severity tests (Fig. 9), it was hoped that the influence of age on injury and biomechanical response could be more clearly identified, i.e. with as many of the other confounding factors held constant. It is clear that the number of fractured ribs and extent of overall injury are affected by the specimen's age. The potential for extensive skeletal damage, probably resulting from a thoracic rib cage collapse during loading, and concomitant nonskeletal injuries is potentiated in the older specimen.

Even though the older specimen's thoraces are only slightly more compliant, resultant injuries are significantly greater. In fact, a 25 year age differential has an effect (Table 3) on the probability of more serious injury. This age difference is precisely that encountered in comparing average laboratory and field experience subjects. The laboratory specimen averaged 65 years of age whereas the average male driver in the U. S. is less than 40 years of age.** This age difference increases the probability of serious injury and extensive rib fractures by 40% to 80%. The potential for greater thoracic deflections and more rib fractures is of more practical significance since they increase the potential for surpassing the stable deformation limit of the rib cage, which itself may be age affected.

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* Actually, the multilinear regression equations of Neathery [8], which relate overall injury, P/D and age, and of Eppinger [15], which relate rib fractures, P/D and age were algebraically solved for a relationship among overall injury, rib fractures and age. The author recognizes that mathematical manipulations with regression relationships can be problematical.

** Even though the age range for this severity of impact reasonably encompasses the spectrum of current male driving population, there is no guarantee that the premortem history and/or skeletal condition of the cadaver subjects is not also a biased subset of the current older driver population. From our experience, it would be reasonable to expect the specimen to produce a biased estimate of the injury responses (i.e., developing greater injuries).

TABLE 3

Response and Injury Expectations as Dependent Upon Specimen Ages of 40 and 65 Years[1]

Specimen Age	Normalized Deflection		Injury Classification		Rib Fractures	
	P/D	Prob. P/D > 0.400	AIS	Prob. AIS ≥ 4	RF	Prob. RF ≥ 4
40[3]	.374	11.9	2.4	8.9	2.7	20.7
65[4]	.397	44.6	3.4	46.6	7.3	98.1
Difference with respect to mean driving age	6.1 %	--	41.7 %	--	170.4 %	--
Increase in expected occurrence for 65 year old specimen	--	32.7	--	37.[illegible]	--	[illegible]

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[1] Based on the observed responses for male specimens subjected to region [illegible] impact conditions (i.e., 23.4 kg impactor mass at 7.0 m/s velocity) and assuming a normally distributed response expectation.

[2] Probability actually computed for AIS ≥ 3.5 which adjusts to AIS ≥ 4 for an integer scale

[3] Mean age of male drivers from 1977 MVMA facts.

[4] Approximate mean age of cadaver specimens used in this study.

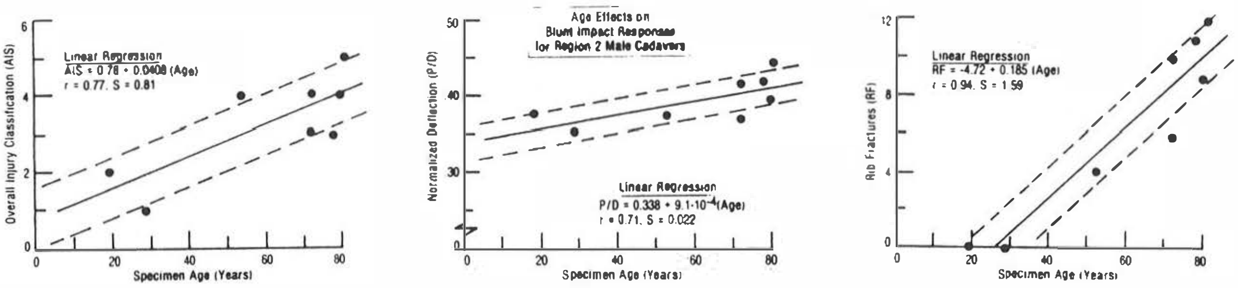

Fig. 9: Dependencies of biomechanical responses and resultant injuries on the age at death of the cadaver subjects, which were impacted with a 23.4 kg mass at 7.0 m/s.

TABLE 4

Occurrence of Nonskeletal Injuries Dependence on Specimen and Response Characteristics[1]

Parameter and/or Characteristic	Average and Standard Deviation		Statistical Significance[4]
	Without AIS_{NS}[2]	with AIS_{NS}[3]	
Specimen			
Age (yr)	40.0 (±2.8)	71.5 (±13.0)	P 5.0%
Weight (kg)	63.8 (±7.3)	73.2 (±14.6)	N.S.
Chest Depth (cm)	20.7 (±0.8)	22.5 (± 1.9)	N.S.
Response			
Force (kN)	3.72 (±0.63)	4.35 (±0.32)	N.S.
P/D	365 (±.013)	407 (±.031)	P 4.9
AIS	2.0 (±1.0)	4.3 (±0.5)	P 0.5
Rib Fractures (#)	2.0 (±3.5)	8.8 (± 3.4)	P 2.5

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[1] Based on the observed responses for male specimens subjected to region [illegible] impact conditions (i.e., 23.4 kg impactor mass at [illegible] m/s velocity).

[2] Specimens: 77/19 FM, 79/20 FM, 204/64 FM

[3] Specimens: 65/13 FM, 69/15 FM, 83/22 FM, 203/63 FM

[4] Single tail t-test; N.S: not significant at the 5 % level

In another analysis of the male region 2 data, the statistical significance (Table 4) of specimen and response characteristics was determined for the occurrence and/or nonoccurrence of nonskeletal trauma. Specimen age is a significant factor associated with the incidence of potentially "life-threatening" nonskeletal trauma. All of the response parameters investigated (see Fig. 9-AIS is an obvious factor) are contributing factors that have a significant influence on the likelihood of nonskeletal trauma. Factors which aggravate the potential for a rib cage collapse are of utmost concern. As normalized deflections approach the avalanche limit P/D 0.28-0.36 and excessive skeletal damage is encountered, a practical threat of serious nonskeletal injury exists. Thoracic responses in specimens below the avalanche limit P/D ∿ 0.32 seem to be within the limit of structural stability of the rib cage so that the skeleton can provide a protective function for the intrathoracic organs and vessels.

SUMMARY

1. Thoracic injury is actually composed of two distinct modes of trauma: skeletal (rib fractures) and nonskeletal (organ and vascular lesions). Even though nonskeletal trauma poses the most significant "threat-to-life," skeletal injuries have dominated the response picture and have influenced current opinions associated with thoracic injury criteria.

2. Despite a demonstrated linear dependence between overall injury severity and degree of normalized thoracic deflection, the potential for serious or "life-threatening" injury is more reasonably associated with a deflection limit (P/D ∿ 0.32). The deflection limit seems to correspond with a structural instability of the rib cage. Deformation beyond a limit poses a likelihood for a spectrum of serious nonskeletal injury (AIS 3-6) which occurs through a collapse of the rib cage with a subsequent avalanche effect on intrathoracic injury potential.

3. The deflection limit (P/D ∿ 0.32), which appears linked to a structural instability of the rib cage, divides moderate and serious thoracic injury. Deformations within the stable response region are mostly reversible with minor skeletal injuries and abrasions dominating the episode. Vital organs and vessels remain well protected by the unaffected structural integrity of the thorax. Deformations beyond the stable limit seem to involve a collapse of the rib cage and result in extensive multiple rib fractures and a realistic hazard for "life-threatening" injury to the intrathoracic organs and vessels.

4. If a dynamic collapse of the rib cage is a possible injury mechanism, it explains the cluster of nonskeletal injury responses near a normalized deflection of P/D ∿ 0.40. Deformations beyond the stable limit of the rib cage (P/D ∿ 0.32) could produce a gross failure of the thoracic skeleton and a jump in thoracic compression to P/D ∿ 0.40. At that compression level the intrathoracic anterior (sternum) and posterior (vertebral) bony surfaces would be in near direct contact. Interestingly, the limit of intrathoracic compressibility for blunt frontal impact has been estimated at P/D ∿ 0.40 in other investigations.

5. For blunt impact to male cadavers with a 23.4 kg impactor mass and a 7.0 m/s striking velocity, the probability of a nonskeletal injury occurrence is a statistically significant function of the specimen's age ($P < 5.0\%$), level of normalized thoracic deflection ($P < 4.9\%$) and the extensiveness of resultant rib fractures ($P < 2.5\%$). Substantial response and injury differences are also expected between a 65 year old specimen (average age of a laboratory cadaver) and a 40 year old specimen (average age of current drivers). The older specimen is much more vulnerable to injury with the probability of AIS ≥ 4, up by 37.7% (46.6% versus 8.9%) and rib fractures ≥ 4 up by 77.4% (98.1% versus 20.7%).

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