Chest Injury Biomechanics and Standards

Basic anatomy, injury mechanisms
Biomechanical response, injury criteria & tolerances

New Delhi, December 4, 2010

Epidemiology

Incidence of Injury to Each Torso Part

<table>
<thead>
<tr>
<th>Torso Part</th>
<th>Frontal Impact</th>
<th>Side Impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sternum</td>
<td>14%</td>
<td>4%</td>
</tr>
<tr>
<td>Heart</td>
<td>10%</td>
<td>13%</td>
</tr>
<tr>
<td>Ribs</td>
<td>50%</td>
<td>63%</td>
</tr>
<tr>
<td>Aorta</td>
<td>9%</td>
<td>17%</td>
</tr>
<tr>
<td>Thoracic spine</td>
<td>4%</td>
<td>8%</td>
</tr>
<tr>
<td>Other chest</td>
<td>39%</td>
<td>47%</td>
</tr>
<tr>
<td>Spleen</td>
<td>7%</td>
<td>23%</td>
</tr>
<tr>
<td>Liver</td>
<td>25%</td>
<td>34%</td>
</tr>
<tr>
<td>Other Abdomen</td>
<td>18%</td>
<td>31%</td>
</tr>
</tbody>
</table>

Thorax: Basic anatomy

Thoracic aorta

1-AAscending aorta, 2-Aortic arch, 3-Descending aorta
Thorax: Basic anatomy (cont’d)

Respiration - air flow

Inspiration

Expiration

Less negative pressure
(More negative pressure
Never positive normally)

Respiration - muscles

Injury mechanisms

- Compression of the thorax -> rib fractures, lung injuries
  - Single rib fractures -> AIS 1 or 2
  - 2 - 3 rib fractures -> AIS 2 or 3
  - rib multiple fractures may lead to life threatening complications -> flail chest
  - lung injuries
    - pneumothorax
    - hemothorax
    - lung contusion + flail chest -> pneumonia -> ††
- shock waves (viscous loading within the thoracic cavity) -> lung injuries
- inertia loading -> rupture of aorta

Common thoracic injuries

Rib fractures are most common
- Fractures were observed in 93.5% of severely injured belted drives

Other injuries are:
- Sternal fractures
- Liver lacerations
- Clavicular fracture
- Separation of the sternoclavicular joint

Rib fractures

- Belt restraints produce fractures along a path near regions of loading under the belt (distribution around rib 6)
- Airbag restraints without belts produce fractures at anterolateral rib locations

Kent et al. STAPP 2001
Lung injuries – haemo- or pneumo-thorax

Lung collapse and mediastinal shift due to haemo or pneumo-thorax

Injuries to heart and arteries - 1

Upward motion of heart

Injuries to heart and arteries - 2

Force from below to above on the right side can result in aortic tear just beyond left sub-clavian artery

Injury to the heart and arteries: Neck hyperextension and chest compression

Biomechanical Response

Thoracic biomechanical response studies
- Volunteers
- Cadavers
- Animals (rabbits, dogs, monkeys, pigs)

Types of cadaver thorax tests
- Impactor test
- Drop test
- Sled test
- Full scale crash test

Biomechanical Response - Techniques

Determination of Thoracic Deflection:
- Deflectometer Rod
- Induction Coil Deflection Gage
- High Speed Film Analysis
- Chest Band (EPIDM) - External Peripheral Instrument for Deformation Measurement (Strain gage circuits mounted on a steel band)

Biomechanical Response - Techniques

method developed to improve chest deflection measurements (12 accelerometers on the test subject)

<table>
<thead>
<tr>
<th>Accelerometer location</th>
<th>Direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>The most lateral point on the 4th right and left ribs. The most lateral point on the 8th right and left rib. At the top of the sternum At the lowest part of the sternum 1st thoracic vertebra 12th thoracic vertebra</td>
<td>From left to right along the normal direction of the body. Parallel with the body in a forward direction. Forward direction. Three-axial, head-foot, left-right, forward-backwards shoulders Three-axial, head-foot, left-right, forward-backwards shoulders</td>
</tr>
</tbody>
</table>
Force-deflection plots for quasi-static loading

Techniques to Determine Thoracic Deflection

Frontal impact - biomechanical response

- frontal loading
  - static loading ≠ dynamic loading
  - plateau influenced by impactor velocity
  - high hysteresis

Based on: Lobdell T.E. "Impact response of the human thorax" from: Kroell, C.K.: "Thoracic response to blunt frontal loading"

Lateral impact - biomechanical response

Force Deflection Characteristics in Lateral Impacts with Flat Circular Impactor

Lateral impact - biomechanical response

Force Deflection Characteristics in Lateral Impacts with Padded Armrest

Animals - biomechanical response

Biomechanical response

- Lobdell thorax model: belt loading significantly different response than flat circular impactor
- animals experiment: level of the plateau force correlates with weight of the animal
- lateral loading
  - lateral stiffness < frontal stiffness
  - plateau force less apparent
Loading conditions of the chest

- Belt loading produces significantly different load distribution
- Dynamic thoracic stiffness much larger

Injury criteria & tolerances

1: Chest deflection due to compression mechanism

- Compression Criterion (CC): maximum chest compression is much better indicator of injury severity than acceleration or force!
  - frontal, blunt impact, quasi static: \( V_{\text{imp}} < 3 \text{ m/s} \)
  - use normalized chest deflection: 35% deflection \( \rightarrow \text{AIS 3} \)

Why is chest deflection a better thoracic injury predictor than chest acceleration?

- Chest compression directly relates chest loading to the risk of serious or fatal compression injury for the vital organs protected by the rib cage
- Chest acceleration does not separate how much of the force is applied to the rib cage, shoulders or lumbar and cervical spine
- Distributed force can generate high thoracic acceleration with very little chest deformation

Compression guide

- 20% Onset of rib fracture
- 32% Tolerance for rib stability
- 40% Flail Chest
- 45% Sternum contacts spinal vertebrae

Injury tolerance vs. thorax deflection in frontal blunt thoracic impact

Compression criterion - story

- 1975: Neathery recommended a chest injury assessment value of 76 mm -corresponding to a 50% risk of AIS3+ thoracic injury
- 1984: Merz revised his maximum chest deflection from 75 mm to 65 mm for blunt impact
- 1988: Viano and Lau recommended 65 mm maximum chest deflection
- 1988: Horsch found that the HIII chest may be much stiffer than the human chest in lower impact velocities, and therefore the recommended injury criteria of 65 mm was too high.
- 1991: Merz found that 50 mm chest deflection corresponded to a 40% risk of injury (seat belt loading)
- 1991: Horsch et al. determined that 40mm chest deflection of a HIII was associated with a 25% risk of an AIS3+ injury (seat belt loading)

Kleinberger et al., NHTSA, 1998.
Injury criteria & tolerances

2: Acceleration and force due to compression mechanism & inertial loading

- Single acceleration: <60 g at CG when t < 3 ms (specified in United States regulations FMVSS 208), limited validation
- Chest severity index (SI): 1000 (not used, bad validation)
- Force on the sternum: 3.3 kN => minor injuries
- Distributed load shoulder + chest: 8.0 kN
  \[ \Rightarrow \text{resulted in only minor injuries, compare } F = 60 \text{ g (acc criterion)} \times 30 \text{ kg (chest mass)} = 18 \text{ kN} \]
- Thoracic Trauma Index (TTI)
  - "*" mass, age
  - "*" pure statistical function

Thoracic Trauma Index (TTI)

- \[ TTI = 1.4 \times \text{AGE} + 0.5 \times (\text{RIBY} + \text{T12Y}) \times \frac{\text{MASS}}{\text{Mstd}} \]
  where:
  - TTI = Thoracic Trauma Index (dimension: g)
  - AGE = age of the subject in years
  - RIBY = maximum absolute value of lateral acceleration in g's of the 4th and 8th rib on struck side after signal filtering
  - T12Y = maximum absolute value of lateral acceleration in g's of the 12th thoracic vertebra after signal filtering
  - MASS = test subject mass in kg
  - Mstd = standard reference mass of 75 kg
- \[ TTI(d) = 0.5 \times (\text{RIBY} + \text{T12Y}) \]
  where:
  - TTI(d) = definition of the TTI used for 50th percentile dummies

Used as criterion in side impact in USA

Severity Index (SI)

SI was introduced by Gadd, 1966

\[ SI = \int a^{2.5} dt \]

\( a = \text{acceleration (g)} \)
\( 2.5 = \text{weighting factor based on the slope of the tolerance curve} \)
\( t = \text{time (sec)} \)

(bad validation)

Thoracic Trauma Index (TTI)

The tolerance level of a 50% probability for an AIS 4+ injury was found to be TTI = 170 g

The tolerance level of a 50% probability for an AIS 3+ injury was found to be TTI = 125 g

Injury criteria & tolerances

3: Viscous criterion due to compression mechanism & viscous response

\[ VC = V(t) \times C(t) = \frac{d[D(t)]}{dt}, \frac{D(t)}{D} \]

See: SAE J211

- Viscous Criterion (VC) is a time function formed by the product of the velocity of deformation: \( V(t) \) and the instantaneous compression function: \( C(t) \)
  - \( V(t) \) is calculated by differentiation of the deformation, and \( C(t) \) is calculated in relation to initial torso thickness (D)
  - valid if 3 m/s < \( V_{\text{impact}} < 30 \text{ m/s} \)

VC: ranges of validity

- less compression produce similar injury levels when impact velocity is increased!

Based on Lau I.V., Viano, D.C. "The Viscous Criterion: Bases and Applications of an Injury Severity Index for Soft Tissues"
Viscous response

- Serious injury to soft tissue and organs occurs at the time of peak viscous response, well before maximum deflection.
- The maximum chest compression is needed to protect against crushing injuries, which may occur during slow or static deformation of the chest and abdomen.

VC criterion

- The tolerance level for a 25% probability of severe injury (AIS 4+) was found to be \( V_{C} = 1 \text{ m/s} \).
- VC has been criticized that it is a measure of the energy stored in the thorax and not the energy dissipated.
- It has also been hypothesized that varied loading conditions by different restraints need a more restraint specific injury criterion.

Combined Thoracic Index (CTI) - 1

\[
CTI = \left[ \frac{A_{\text{max}}}{A_{\text{int}}} \right] + \left[ \frac{D_{\text{max}}}{D_{\text{int}}} \right]
\]

- \( A_{\text{max}} \): Maximum chest acceleration (g)
- \( A_{\text{int}} \): X-axis intercept (dummy specific), 85 g’s for 50% HIII
- \( D_{\text{max}} \): Maximum chest deflection (mm)
- \( D_{\text{int}} \): Y-axis intercept (dummy specific), 102 mm for 50% HIII

Combined Thoracic Index (CTI) - 2


Thorax: Frontal impact injury tolerances

<table>
<thead>
<tr>
<th>Tolerance level</th>
<th>Injury level</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Force</td>
<td>Minor injury</td>
<td>Patrick et al. (1969)</td>
</tr>
<tr>
<td>3.3 kWh to sternum</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.6 kWh to chest and shoulder</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Acceleration (g’s)</td>
<td>60</td>
<td>3 ms limit for Hybrid II &amp; III, FMVSS 208</td>
</tr>
<tr>
<td>58</td>
<td>No rib fracture</td>
<td>Stalnaker and Mohan (1974)</td>
</tr>
<tr>
<td>78</td>
<td>L2 to L3 for Hybrid III</td>
<td>FMVSS 208</td>
</tr>
<tr>
<td>Deflection (mm)</td>
<td>35</td>
<td>Compression (% to half thorax)</td>
</tr>
<tr>
<td>20</td>
<td>Onset of rib fracture</td>
<td>Krossel et al. (1971, 1974)</td>
</tr>
<tr>
<td>40</td>
<td>Fracture chest</td>
<td>Krossel et al. (1971, 1974)</td>
</tr>
<tr>
<td>32</td>
<td>Tolerance for rib cage stability</td>
<td>Viano (1978)</td>
</tr>
<tr>
<td>Vimax (m/s)</td>
<td>1.0</td>
<td>25% probability of AIS 3</td>
</tr>
<tr>
<td></td>
<td>1.3</td>
<td>50% probability of AIS 3</td>
</tr>
</tbody>
</table>

Thorax: Lateral impact injury tolerances

<table>
<thead>
<tr>
<th>Tolerance level</th>
<th>Injury level</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Force (kN)</td>
<td>Minor injury</td>
<td>Patrick et al. (1969)</td>
</tr>
<tr>
<td>7.4—drop test</td>
<td>AIS = 0</td>
<td></td>
</tr>
<tr>
<td>10.2—drop test</td>
<td>AIS = 3</td>
<td></td>
</tr>
<tr>
<td>5.5—pendulum impact</td>
<td>25% probability of AIS 4</td>
<td></td>
</tr>
<tr>
<td>Acceleration (g’s)</td>
<td>49.2g T12</td>
<td>25% probability of AIS 4</td>
</tr>
<tr>
<td>31.5 g T17</td>
<td>25% probability of AIS 4</td>
<td></td>
</tr>
<tr>
<td>27.1 kg/Upper sternum X</td>
<td>25% probability of AIS 4</td>
<td></td>
</tr>
<tr>
<td>TTI(d) (g’s)</td>
<td>80</td>
<td>25% probability of AIS 4</td>
</tr>
<tr>
<td>60</td>
<td>AIS 1 to chest, 3 to sternum</td>
<td></td>
</tr>
<tr>
<td>45.2g T8y</td>
<td>Max. in SID dummy for 4-door cars</td>
<td></td>
</tr>
<tr>
<td>31.6 g T12y</td>
<td>Max. in SID dummy for 2-door cars</td>
<td></td>
</tr>
<tr>
<td>27.7g Upper sternum-X</td>
<td>25% probability of AIS 4</td>
<td></td>
</tr>
<tr>
<td>Comp. (% to half thorax)</td>
<td>35</td>
<td>25% probability of AIS 4</td>
</tr>
<tr>
<td>20</td>
<td>Includes arm</td>
<td></td>
</tr>
<tr>
<td>£36.4</td>
<td>25% probability of AIS 4</td>
<td></td>
</tr>
<tr>
<td>Vimax (m/s) to half thorax</td>
<td>1.10</td>
<td>25% probability of AIS 4</td>
</tr>
<tr>
<td>£1.0</td>
<td>Viano (1969)</td>
<td></td>
</tr>
<tr>
<td>1.47</td>
<td>Unpublished data</td>
<td></td>
</tr>
<tr>
<td>Comp. (% to whole thorax)</td>
<td>45.2g T8y</td>
<td>25% probability of AIS 4</td>
</tr>
<tr>
<td>31.6 g T12y</td>
<td>25% probability of AIS 4</td>
<td></td>
</tr>
<tr>
<td>27.7g Upper sternum-X</td>
<td>25% probability of AIS 4</td>
<td></td>
</tr>
<tr>
<td>Vimax (m/s) to whole thorax</td>
<td>1.10</td>
<td>25% probability of AIS 4</td>
</tr>
<tr>
<td>£1.47</td>
<td>Viano (1969)</td>
<td></td>
</tr>
</tbody>
</table>
Thorax - Crash Safety Legislation

Frontal Collision EU (96/79/EG)
Thorax Compression Criterion (ThCC): 50 mm
Soft Tissue Criterion (VC): 1.0 m/s

Frontal Collision USA (FMVSS 208)
50% HII
Chest acceleration: 60 g
Thorax compression: 63 mm

5% HII
Chest acceleration: 60 g
Thorax compression: 52 mm

Side Collision EU (96/27/EG)
RDC (Rib Deflection): 42 mm
Soft tissue criterion (VC): 1.0 m/s

Side Collision USA (FMVSS 214)
Thoracic Trauma Index (TTI):
85 g (4-door)
90 g (2-door)

Good or bad thorax injury predictors

- The TTI has been widely criticized since acceleration is not a good measurement of soft tissue injuries to the chest and the abdomen
- Serious internal injury can occur without a significant number of rib fractures or rib cage injury at all
- In a cadaver study it was found that acceleration or force-based injury criteria did not predict injury as well as compression and VC

Chest injury assessment values in frontal impact for the HIII dummies

|                | Large | Pressurized Small | Small | Medium | Large | CRASH
|----------------|-------|-------------------|-------|--------|-------|--------
| Euro NCAP      | male  | female            | female|        |       |        |
| Lung           | 55    | -                 | 60    | -      | -     | -      |
| Shoulder belt  | 60    | 50                | 41    | -      | -     | -      |
| Airbag & steering-wheel bar | 72 | 65 | 65 | 52 | 54 | 52 |
| VC             | 4     | -                 | -     | -      | -     | -      |
| Spine box acc. 3 m/s | 54 | 50 | 72 | - | - | - |
| FNH/120 200 rev rule | - | 60 | 60 | 60 | 65 | 50 |
| Chest acceleration (g) | - | 63 | 52 | 40 | 34 | 34 |

Chest injury assessment values for Side-Impact Dummies

<table>
<thead>
<tr>
<th></th>
<th>SID</th>
<th>EUROSID-1</th>
<th>BIOSID 1</th>
<th>BIOSID 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lat. Rib to spine defl. (mm)</td>
<td>-</td>
<td>42</td>
<td>2</td>
<td>-</td>
</tr>
<tr>
<td>VC (m/s)</td>
<td>-</td>
<td>-</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Deflection rate (m/s)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>TTI for:</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Coupe (g)</td>
<td>90</td>
<td>90</td>
<td>90</td>
<td>-</td>
</tr>
<tr>
<td>Sedan (g)</td>
<td>85</td>
<td>85</td>
<td>85</td>
<td>-</td>
</tr>
</tbody>
</table>

1) US regulation FMVSS 214
2) European regulation (Directive 96/27/EC)
3) The BIOSID 1 is capable of measuring TTI, chest deflection, and VC
4) Recommended procedures for side impact OOP testing

Thanks for your attention! Questions?