Resource Document 3: Kinematics of Trauma

I. Introduction

In trauma, as other diseases, an accurate and complete history, correctly interpreted, can lead to an indication or suspicion of 90% of a patient's injuries. The history begins with information that occurred in the precrash phase, e.g., alcohol and/or other drugs ingested. History related to the crash phase should include:

1. The type of traumatic event, e.g., automobile or motorcycle collision, fall, penetrating injury.

2. An estimation of the amount of energy exchange that occurred, e.g., speed of vehicle at time of impact, distance of fall, and caliber and size of weapon.

3. The collision or impact of the patient with the object, e.g., car, tree, knife, baseball bat, bullet.

Generally, the causes of injury are divided into blunt, penetrating, and blast injuries. Several energy laws need to be considered when obtaining the crash-phase history.

1. Energy is neither created nor destroyed; however, it can be changed in form.

2. A body in motion or a body at rest tends to remain in that state until acted on by an outside source.

3. Kinetic energy is equal to mass multiplied by velocity squared divided by two.

4. Force is equal to mass times deceleration (acceleration).

For a moving object to lose speed, its energy of motion must be transmitted to another object. This energy transfer occurs when the human body tissue cells are placed in motion directly away from the site of impact by the energy exchange - cavitation. Rapid movement of tissue particles away from the point of impact creates damage by tissue compression, and at a distance as the cavity expands by stretch. (See Figure 1, Cavitation.)

These same factors are involved whether the skin is penetrated. Assessing the extent of injury is more difficult when no skin penetration is apparent than when an open wound is present. For example, swing a baseball bat with equal force into a steel barrel and into a similar sized and shaped piece of foam rubber. After impact, the barrel shows the site and depth of the impact, but no indentation is visible in the foam rubber.

This same concept holds true with the trauma patient. For example, a fist driven into the abdominal area may sink in deeply but leaves no visible depression after the fist is removed. If bones are fractured, the significance of the impact may be visible, but if no fractures occur or if the bones rapidly resume a normal position, the extent of injury cannot be determined by physical examination alone. A history of the injury-producing event also must be obtained. A visible cavity after impact is referred to as a permanent cavity, and an
invisible cavity is referred to as a temporary cavity. The amount of elastic tissue determines the size of each cavitation, since the energy exchange is the same.

The size of cavitation is determined by the amount of energy exchange. Energy exchange is determined by the number of tissue particles impacted by the moving object. The number of tissue particles impacted is determined by the density of the tissue in the path of the impacted object. The larger the surface area and the denser the tissue, the greater number of particles affected. The reverse also is true. A narrow object, with a small surface area, passing through tissue that is not very dense, e.g., small bowel or lung, does not create much of a cavity because only a few tissue particles are affected. Bone is very dense, and when impacted by an object with a large cross-section area, it breaks, shatters, and frequently travels some distance from the initial impact and surrounding structures. These two scenarios represent the extremes. Most energy exchange lies somewhere between the two.

II. History

Information obtained from prehospital personnel related to the vehicle's interior and exterior damage frequently are clues to injuries sustained by its occupants. Prehospital care personnel are trained to make such observations. Knowledge of these facts facilitates the identification of occult or difficult-to-diagnose injuries. For example, a bent steering wheel indicates chest impact; a bull's eye fracture of the windscreen indicates head impact and possible cervical spine injury; an indentation on the lower dashboard indicates a knee impact and possible dislocation of the knee, femur fracture, or posterior hip dislocation; and door intrusion into the passenger compartment indicates a later injury to the patient's chest, abdomen, pelvis, and/or neck.

III. Blunt Trauma

The common injury patterns and types of injuries identified with blunt trauma include:

1. Vehicular impact in which the patient is inside the vehicle
2. Pedestrian impact
3. Motorcycle crashes
4. Assaults
5. Falls

A. Vehicular Impact

Vehicular collisions can be subdivided further into (1) collision between the patient and the vehicle, and (2) the collision between the patient's organ(s) and the external framework of the body (organ compression).

The interactions between the patient and the vehicle depends on the type of crash. Five crashes depict the possible scenarios - frontal, lateral, rear, angular (front quarter or rear quarter), and rollover.
1. Occupant collision

a. Frontal impact

A frontal impact is defined as a collision with an object in front of the vehicle that suddenly reduces its speed. The unrestrained occupant in the vehicle continues to travel forward (Newton's First Law of Motion) until some portion of the passenger compartment slows the occupant or the occupant is ejected.

On impact, the patient may follow a down-and-under pathway with the lower extremities being the initial point of impact and the knees or feet receiving the initial energy exchange. The forward motion of the torso onto the extremity may cause these injuries:

1) Fracture-dislocation of the ankle
2) Knee dislocation as the femur overrides the tibia and fibula
3) Femur fracture
4) Posterior dislocation of the acetabulum as the pelvis overrides the head of the femur.

The second component of this down-and-under motion is a forward rotation of the torso into the steering column or dashboard.

If the structure of the seat and the patient's position are such that the head becomes the lead point of the "human missile," the skull impacts with the windscreen or the framework around the windscreen. The cervical spine absorbs some of the initial energy while the chest and abdomen impact the steering column or the dashboard. (See Figure 2, Frontal Impact, Unrestrained Driver.)

b. Lateral impact

Lateral impact is defined as a collision against the side of a vehicle that accelerates the occupant away from the point of impact (acceleration as opposed to deceleration). Many of the same type of injuries occur as with a frontal impact. In addition, compression injuries to the torso and pelvis may occur. Internal injuries are related to the side struck, the position of the occupant (driver or passenger), and force of impact (intrusion). The driver who is struck on the driver's side is at greater risk for left-sided injuries, eg, left rib fractures, splenic injury, and left skeletal fractures, including the pelvis. A passenger struck on the passenger side will have similar right-sided involvement, with liver injuries being a particular risk.

In lateral impacts, the head acts as a large mass that rotates and laterally bends the neck as the torso is rapidly pushed away from the side of collision. Basic biomechanics are the same with both frontal and lateral collisions. However, the examining physician also must consider acceleration versus deceleration forces and lateral anatomic considerations when examining the patient.
c. Rear impact

A rear impact represents a different type of biomechanics. More commonly, this type of impact occurs when a vehicle is at a complete stop and is hit from behind by another vehicle. The vehicle, including its occupant, is moved forward as it picks up energy from the impacting vehicle behind it. Because of the placement of seats, the torso usually is accelerated forward along with the car. The occupant's head often is not accelerated with the rest of the body, because the headrest has not been elevated. The body accelerates, the head does not, and the neck is hyperextended back across the unused headrest. Such hyperextension stretches the supporting structures of the neck, producing a "whiplash" injury. (See Figure 3, Rear Impact, Improper and Proper Headrest Use.) A frontal impact also may occur as there often is a second car in front of the vehicle originally hit.

d. Quarter panel impact

A quarter panel impact, either front or rear, produces a variation of lateral and frontal impact collision injury patterns or lateral and rear impact collision injury patterns.

e. Rollover

During a rollover, the unrestrained occupant can impact any part of the interior of the passenger compartment. Injuries may be predicted from the impact points on the patient's skin. The general rule is that this type of collision produces more severe injuries because of the violent and multiple motions that occur during the rollover.

F. Ejection

The injuries sustained as the occupant is ejected from the vehicle may be greater than when the ground is impacted. Nevertheless, the likelihood of injury from this type of mechanism is increased by more than 300%. The examining physician must be attentive to the possibility of occult injuries.

B. Organ Collision

1. Compression injury

Compression injuries occur when the anterior portion of the torso (chest and abdomen) ceases to move forward and the posterior portion continues to travel onward. The organs are trapped from behind by the continued motion of the posterior thoracoabdominal wall and the vertebral column, and in front by the impacted anterior structures. Myocardial contusion is a typical example of this type of injury mechanism. (See Figure 2, Frontal Impact, Unrestrained Driver.)

A similar injury can occur with the lungs or abdominal organs. The lungs and abdominal cavity represent a particular variation of this type of injury - the paper bag effect. Blowing up a paper bag, holding it tight at the neck, and crushing it with the opposite hand causes the bag to rupture. In a collision situation, it is instinctive for the patient to take a deep breath and hold it, thereby closing the glottis. Compression of the thoracic cage then produces
a rupture of the alveoli and a pneumothorax and/or tension pneumothorax. (See Figure 2, Frontal Impact, Unrestrained Driver.) In the abdominal cavity, the same overpressure problem produces a rupture of the diaphragm resulting in translocation of the abdominal contents into the thoracic cavity.

Compression injuries inside the skull result from the brain being damaged by fractured bone intruding into the intracranial vault or the posterior portion of the brain compressing the anterior part against the skull.

2. Deceleration injury

Deceleration injuries occur as the stabilizing portion of an organ, eg, renal pedicle, ligamentum teres, or descending thoracic aorta ceases forward motion with the torso while the movable body part, eg, spleen, kidney, or heart and arch of the aorta, continues forward. For example, the heart and aortic arch continue to rotate forward while the descending aorta, attached to the thoracic spine, slows rapidly with the torso. The shearing forces are greatest where the movable aortic arch and the stable descending aorta join near the ligamentum arteriosum. This same type of injury may occur with the spleen and kidneys at their pedicle junctions, with the liver as the right and left lobes decelerate around the ligamentum teres splitting the liver down the middle, and in the skull when the posterior part of the brain separates from the skull tearing vessels and producing space-occupying lesions.

3. Restraint injury

The increasing availability of the air bag may reduce some frontal injuries significantly. However, air bags work only in about 70% of collisions. These devices must not be thought of as a replacement for the safety belt, but as supplemental protective devices. Occupants in head-on collisions may benefit from the air bag, but only on the first impact. At the time of the second impact into another object, the air bag already is deployed and deflated. The air bag provides no benefit in rollovers, second crashes, or lateral and rear impacts. The lap and shoulder restraints must be worn for more complete protection.

In side impact collisions, the lap belt is an effective device, providing it is worn effectively. As the vehicle is moved laterally, the occupant is placed into lateral motion by the belt and not the door or the impact. When the occupant has begun to move away from the point of impact, intrusion into the passenger compartment through the door is less likely to produce injury.

When worn correctly, the safety belt can reduce injuries. Worn incorrectly and the device can produce some injuries, although it reduces the overall damage. To function properly, the belt must be below the anterior/superior iliac spines and above the femur. It must be tight enough to remain in place during the motion of the crash. If worn incorrectly, eg, above the anterior/superior iliac spines, the forward motion of the posterior abdominal wall and vertebral column traps the pancreas, liver, spleen, and duodenum against the belt in front. Burst fractures of the kidney, spleen, and liver can occur as well as pancreatic lacerations. Hyperflexion over an incorrectly applied belt can produce anterior compression fractures of the lumbar spine. (See Figure 4, Proper versus Improper Lap Belt Application.)
There may be so much energy exchange occurring in the chest that even a properly worn diagonal strap can cause clavicular fractures or myocardial contusion. In these instances, the patient would not have survived without the belt.

C. Pedestrian Injury

There are three impact phases to the injuries sustained by a pedestrian. (See Figure 5, Adult Pedestrian Injury Triad.)

1. Front vehicular bumper impact

Bumper height versus patient height is a critical factor in the specific injury produced. In the upright adult, the initial impact with the front bumper is usually against the legs and pelvis. Knee injuries are common as are injuries to the pelvis. Children are more likely to receive chest and abdominal injuries.

2. Vehicular hood and windscreen impact

Torso and head injuries occur as the patient impacts with the hood and windscreen.

3. Ground impact

Head and spine injuries result as the patient falls off the vehicle to the ground.

Organ compression injuries also occur - deceleration/acceleration - as described previously.

D. Motorcycle Collisions

Motorcyclists and/or their passengers also may sustain compression, acceleration/deceleration, and shearing-type injuries. However, the way they receive such injuries is different. Motorcyclists are not protected by the vehicle's structure or restraining devices as an occupant in a car would be protected. Motorcyclists are protected only by clothing and safety devices worn on their body - helmets, boots, or protective clothing. Obviously, the lesser protection that is worn, the greater risk for injury. Therefore, the amount of and type of protective clothing worn by injured motorcyclists is important precrash information to obtain from prehospital personnel.

Mechanisms of injury that may occur with motorcycle collisions include frontal impact, lateral impact, ejection, and "laying the bike down."

1. Frontal impact/ejection

The motorcycle and cyclist travel at the same speed. The pivot point of the cycle is the front axle and the center of gravity is above this point, near the seat. If the front wheel of the motorcycle impacts with an object and stops, the motorcycle tends to tip forward and Newton's First Law of Motion is applied - the cyclist and the rest of the motorcycle continue their forward motion until they impact with an object or the ground. During this forward
projection, the cyclist's head, chest or abdomen may impact with the handlebars. If the cyclist is projected over the handlebars and ejected off the bike, the upper legs may impact with the handlebars resulting in bilateral femur fractures. A variety of other injuries are sustained when the cyclist is ejected off the motorcycle and strikes an object or the ground.

2. Lateral impact/ejection

If a motorcyclist sustains a lateral impact, open, and/or closed fractures or a crush injury to the lower extremity can occur. If the lateral impact is with a car or truck, the cyclist is vulnerable to the same type of injuries sustained by an occupant in an automobile involved in a lateral collision. Additionally, the cyclist can be ejected from the cycle and sustain a multitude of injuries on impact with an object or the ground.

3. "Laying the bike down"

To avoid entrapment between the motorcycle and a stationary object, the cyclist may turn the motorcycle sideways, dropping the bike and his inside leg down onto the ground. This strategy tends to slow the speed of the cyclist, separating him from the motorcycle. The motorcycle continues its forward motion and absorbs most of the energy of the collision with the stationary object. However, the cyclist can sustain rather significant tissue avulsion injuries and abrasions.

E. Falls

Falls are the leading cause of nonfatal injury in the United States and the second leading cause of both spinal and brain injury. The kinematics of motor vehicle crashes and falls are not dissimilar - both are deceleration-type injuries. Whenever an external force is applied to the human body, the severity of injury is the result of the interaction between the physical factors of the force and the body. If the body is in motion, eg, falling, and impacts a fixed surface, the extent of the injury is related to the ability of the stationary object to arrest the forward motion of the body. At impact, differential motion of tissues within the organism causes tissue disruption. Decreasing the rate of the deceleration and enlarging the surface area to which the energy is dissipated increase the tolerance to deceleration by promoting a more uniform motion of the tissues. The fall arresting contact surface also is important since concrete, asphalt, or hard firm surfaces increase the rate of deceleration, and are associated with more severe injuries.

Certain features of living tissue also must be considered, especially the combined cohesive properties of elasticity and viscosity of tissues. The tendency for a tissue following impact to resume its prestressed condition is related to its elasticity. Viscosity implies resistance to change of shape with changes in motion. The tolerance of the organism to deceleration forces is a function of these combined cohesive properties and the point beyond which additional force overcomes this tissue cohesion determines the magnitude of injury. Therefore, the severity of injury is closely related to the kinematics of vertical deceleration, the combined cohesiveness of the body's properties, and the consistency of the impact surface. The severity of the injury increases by increasing the rate of deceleration and decreasing the distance through which the body is decelerated. More severe injury occurs when deceleration forces are applied to the body in the vertical axis compared with the transverse, provided that
mass, velocity, and stopping distance remain the same.

F. Blast Injury

Explosions result from extremely rapid chemical transformation of relatively small volumes of solid, semisolid, liquid, or gaseous materials into gaseous products that rapidly seek to occupy greater volumes than the undetonated explosive occupied. If unimpeded, these rapidly expanding gaseous products assume the shape of a sphere inside which the pressure is greatly increased compared with atmospheric pressure. The periphery of this sphere is a thin, sharply defined shell of compressed air that acts as a pressure wave. The pressure decreases rapidly as this pressure travels away from the site of detonation in proportion to the third power of the distance. As the pressure wave advances, the media through which it moves oscillates. The positive pressure phase may reach several atmospheres in magnitude, but it is of extremely short duration, whereas the negative phase that follows is longer in duration. This latter phenomenon accounts for the phenomenon of buildings falling inward.

Blast injuries may be classified into primary, secondary, or tertiary. Primary blast injuries result from the direct effects of the pressure wave and are most injurious to gas-containing organs. The eardrum is the most vulnerable to the effects of primary blast and may rupture if pressures exceed two atmospheres. The lungs also are vulnerable with changes of contusion, edema, and pneumothorax commonly seen. Rupture of alveoli and pulmonary veins creates the potential for air embolism, which may result in sudden death. Intraocular hemorrhage, retinal detachments, and rupture of intestines also may occur but are more common in underwater blasts. Secondary blast injuries result from flying objects striking the individual. Shrapnel wounds represent a typical secondary blast injury. Tertiary blast injury occurs when the individual becomes the missile and is thrown against a solid object or to the ground. Both secondary and tertiary blast injury may cause trauma typical of penetrating and blunt mechanisms, respectively.

IV. Penetrating Trauma

Cavitation, described previously, is the result of energy exchange between the moving object and body tissues. The amount of cavitation or energy exchange is proportional to the surface area of the point of impact, the density of the tissue, and the velocity of the projectile at the time of impact. (See Figure 6, Cavitation Results.) The wound at the point of impact is determined by:

1. The shape of the missile (“mushroom”)
2. Its relation and position to the impact site, (tumble, yaw) (See Figure 7, Ballistics Tumble and Yaw)
3. Fragmentation (shotgun, bullet fragments, special bullets).

A. Bullets

Lead bullets cannot be propelled above the velocity of 2000 feet per second, because the lead melts. Semijacketed bullets with lead noses or hollow points are designed to mushroom when they strike the target. This effect increases the cross-sectional area of the missile, resulting in more rapid deceleration of the bullet and release of kinetic energy more
rapidly. Higher-velocity missiles, eg, military ammunition, are fully jacketed, using copper-nickel or steel. Teflon bullets, which penetrate flexible body armor, are available as are Glasser Safety Slugs, a lightweight, hollow bullet filled with bird shot pellets. On impact, this bullet ruptures, releases its pellets, and produces severe wounds. Magnum rounds refer to cartridges with a greater amount of gunpowder than the normal round, which increases the muzzle velocity of the missile.

B. Velocity

The velocity of a missile is a significant determinant of its wounding potential. The importance of velocity is demonstrated by the formula relating mass and velocity to kinetic energy. Examples of this relationship are listed in Table 1, Missile Kinetic Energy.

\[
\text{Kinetic Energy} = \frac{(\text{Mass}) \times (\text{Velocity}^2)}{2}
\]

Weapons usually can be divided into three types based on their initial energy.

1. Low energy - Knife or hand energized missiles
2. Medium energy - Hand guns
3. High energy - Hunting or military rifles.

The final determinant is distance from the missile pathway, ie, as the distance increases the kinetic energy is dissipated. The wounding capability of a bullet increases markedly above a critical velocity. This velocity may be as low as 2000 feet per second. At these speeds the bullet creates a temporary cavity due to tissue being compressed radially, outward from the bullet tract. This temporary cavity can have a diameter of up to 30 times that of the diameter of the missile. The maximum diameter occurs at the area of the greatest resistance to the bullet (greatest decrease in velocity and greatest transfer of kinetic energy). The handgun (medium energy) may produce a temporary cavity only five to six times the diameter of the bullet. Knife injuries (low energy) result in little or no cavitation. Therefore, the damage from a high-velocity bullet can occur at a fairly great distance from the bullet tract itself. The difference in the size of the temporary and the permanent cavity is the amount of elastic tissue that can return the organ to its original shape, size, and position.

Other effects of missiles are important in determining the amount of energy dissipated and the injuries produced. **Yaw** (the deviation of a bullet from its longitudinal axis) and **tumble** increase the area it presents to the tissue and subsequently, the kinetic energy release. (See Figure 7, Ballistic Tumble and Yaw.) The later after tissue penetration the bullet tends to yaw, the deeper the maximum injury. Bullet deformation and fragmentation (semijacketed) increase area also, thereby increasing the primary tract and the release of kinetic energy.
Table 1. Missile Kinetic Energy

<table>
<thead>
<tr>
<th>Caliber and Manufacturer</th>
<th>Bullet Weight (Grains)</th>
<th>Velocity (Feet/Second)</th>
<th>Energy (Feet/Pound)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Rifle Ammunition</strong></td>
<td></td>
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<td></td>
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<tr>
<td>.22 Remington Rim Fire</td>
<td>40</td>
<td>1180</td>
<td>124</td>
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<tr>
<td>6 mm, 243 Winchester</td>
<td>75</td>
<td>3500</td>
<td>2037</td>
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<tr>
<td>.300 H and L Magnum</td>
<td>180</td>
<td>3670</td>
<td>3670</td>
</tr>
<tr>
<td>.375 H and H Magnum</td>
<td>270</td>
<td>2720</td>
<td>4440</td>
</tr>
<tr>
<td><strong>Handgun Ammunition</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>.25 Remington Automatic</td>
<td>50</td>
<td>810</td>
<td>73</td>
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<tr>
<td>.32 Short Remington</td>
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<td>745</td>
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<td>.32 Automatic Remington</td>
<td>71</td>
<td>960</td>
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<td>.357 Magnum Remington</td>
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<tr>
<td>.38 Special Remington</td>
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<tr>
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<tr>
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</table>

Shotgun wounds present a different wounding potential. The muzzle velocity of this weapon is generally 1800 feet per second. However, due to air resistance acting on the spherical pellets, their velocity decreases rapidly. Deceleration also occurs rapidly after impact for the same reason, causing the maximum injury relatively superficially. The shot radiates in a conical distribution from the muzzle. With a choked or narrowed muzzle, 70% of the pellets are deposited in a 30-inch diameter circle at 40 yards. This weapon is lethal at a close range, but is relatively ineffective at greater distances. Shotgun blasts carry clothing and wadding (paper or plastic separating the powder and pellets in the shell) deep into the wound, which is a source of infection if not removed.

C. Entrance versus Exit Wounds

Caution must be exercised when commenting on whether a bullet wound represents an entrance or exit wound. The type of projectile, jacketed or unjacketed, hollow-point or ball ammunition, velocity, yaw (angle) of the projectile at the time of the strike, and the type of underlying tissue, eg, bone, all influence the appearance of a bullet wound. A bullet wound
can be identified as an entrance wound with certainty in only two instances. The first instance is when there is only one wound. The second is when there is histologic documentation of powder burns around the bullet wound. Because of the multiplicity of factors that influence the appearance of a bullet wound, statements that a wound is an entrance wound may be difficult to ascertain assuredly for legal purposes.

However, it may be very important for clinical reasons to make such a determination. Two holes may indicate two separate gunshot wounds or the entrance and exit of one bullet, pointing out the pathway the missile followed through the body. In either instance, the identification of the anatomic structures that may have been damaged and even the type of surgical procedure that needs to be done may be influenced by such information.

Weapons most commonly used in the civilian sector cause a round or oval entrance wound with a surrounding 1- to 2-mm blackened area of burn or abrasion from the spinning bullet passing through the skin. If the weapon muzzle was close to the skin, gases may have been forced into the subcutaneous tissue. A blast within a few inches of the skin leaves a visible burn on the skin. Stippling or tattooing from the burning particles of the gunpowder may be visible with a blast from four to six inches. The exit wound usually is stellate in appearance and does not have any of the other features. Like the physical examination and clinical tests, a finding that is present provides information. An absent finding is inclusive and yields no information, either positive or negative.