

## USE OF QUADRUPED MODELS IN THORACO- ABDOMINAL BIOMECHANICS RESEARCH

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**Abstract**—Pigs and dogs have become common models of human thoraco-abdominal impact response. This paper summarizes a comparative analysis of the dog and pig to the live human accomplished through a series of necropsies performed on pigs and dogs. The results are summarized below. Emphasis is placed on specific aspects which are felt to be important for impact biomechanics. In particular, emphasis is placed upon the effect of tethering structures because of their potential in explaining mechanisms of injury for specific types of trauma such as aortic and certain liver injuries. Some aspects of tethering in the pig and dog are significantly different from that of the live human so care should be taken when using these animals in thoraco-abdominal biomechanics experiments.

### INTRODUCTION

Injuries to the heart and the aorta and injuries to the spleen or liver and their vessels have been investigated with animal and cadaver models (Zhender, 1960; Roberts and Beckman, 1970; Kroell *et al.*, 1971; Stalnaker *et al.*, 1972). The goal in such research is to progress from a description of kinematic response to explanation and prediction of mechanisms of injury. William *et al.* (1976) provides a clear outline of how life-threatening thoraco-abdominal impact trauma affects physiological functioning. Such injuries include displacement of vertebrae and fractures to the skeleton, major cardiac or great vessel hemorrhage, perforations of lungs or heart, and avulsions or ruptures of the lungs, aorta and diaphragm. Stellate and longitudinal lesions to organs are commonly observed clinically.

A popular mechanism of aortic injury is that the descending aorta remains fixed at the posterior thoracic wall while the heart and the aortic arch displace beyond their tolerance (Viano and Haut, 1977; Shatsky, 1973; Cammack *et al.*, 1959). Cammack *et al.* (1959) and Roberts *et al.* (1967) found that compression and displacement of the heart and twisting of the aortic arch produced tensions at the fixed isthmus and aortic root. Viano and Haut's (1977) rabbit study predominantly produced ruptures of the aortic root. They proposed a mechanism which was based upon observations made by Zhender (1960): during a head-extended blunt frontal impact where there is little head-shoulder rotation, the carotid and subclavian arteries pull superiorly while rotation and translation of the heart about the hilus pulls inferiorly. When Viano and Haut (1977) prevented head rotation, transverse tears predominated at the stretched surface of the anterior surface of the aortic root.

It seems reasonable to assume that a number of

injury mechanisms can occur in a thoraco-abdominal impact. The importance of velocity and displacement have been documented (Rouhana *et al.*, 1985; Kroell *et al.*, 1971). In addition, impact site has also been shown to be an important parameter (Viano *et al.*, 1977).

Injuries on the opposite side to force input, such as liver hilus injuries observed in the cadaver model steering wheel assembly impact experiments of Nusholtz *et al.* (1985b), seem to be best explained as the organ and its tissues having been stressed by compression and/or displacement beyond their tolerance. This compression/displacement only occurred for specific impact sites. Because the position of the liver in the abdominal cavity is determined by its tethers, tethering seems to be an important aspect for certain types of liver injuries, and potentially may be important for injuries of other thoraco-abdominal organs. In the UMTRI dissections, significant tethering differences between the pig or dog and the human were noted.

### DISCUSSION

The primary result from this dissection study as an addition to other pertinent impact experiments (Nusholtz *et al.*, 1980, 1983, 1985a, b) was that certain anatomical differences among the currently popular biomechanical human surrogates (i.e. the canine, porcine, repressurized human cadaver) were significant in terms of mechanisms of injury. The important results from the dissections performed at UMTRI are summarized in the Appendix. Discussion of these results and their relevance is included in what follows.

The impact and injury response of the human thorax is a complex interaction of soft and hard tissue responding to contact from an external source. The best method of understanding thoraco-abdominal response is through laboratory experiments using human surrogates. Currently there is no known 'best' model or combination of models to be used. Differences in injury patterns between canine, porcine

and repressurized human cadavers have been observed. Each model has its uses; however, considerable attention should be given to the anatomical differences between man and the surrogates used in impact experiments. Hopefully, the information obtained from the porcine and canine dissections reported here will help further understanding of the limitations of these models.

#### *Comparative impact response*

The primary problem of thoraco-abdominal impact research is to select a suitable human surrogate. Human cadavers and animals, frequently canines and porcines, have been used. The unembalmed repressurized cadaver is often chosen as an experimental model because its anatomy is most similar to that of the live human. The disadvantages of the cadaver include the inability to measure pathophysiological response and the susceptibility of some tissue to postmortem degradation which may change material properties.

The use of live subjects, such as anesthetized porcines and canines, provides basic physiological response to impact and a method of evaluating critical factors such as hypovolemic shock when tissues are damaged. However, there are significant differences in the thoraco-abdominal anatomy between man and the quadrupedal dog and pig. During the dog and pig dissections which were conducted, differences were noted in the following structures: the spleen, liver, heart, aortic arch, tethering mechanisms, and the thoracic cage. Do injuries to quadruped organ structures (such as a fourth liver lobe) that do not exist in man have usefulness in determining automotive human impact safety parameters? In the quadruped model, normal forces resulting from the mass of each anatomical structure are in the ventral-dorsal direction in contrast to humans in which these are in the anterior-posterior direction which at the very least involves a 90° shift from normal posture if the quadruped is placed in a position which imitates the bipedal posture. The effect this would have on the importance of velocity as an impact parameter is undetermined. In addition to the obvious thoracic cage differences, when the quadruped is placed upright, the heart hangs without caudal support and is suspended by the great vessels, unlike the 'cardiac unit' of man. In the upright position, the abdominal organs of the dog or pig settle down from their normal anatomical position so that the liver and spleen are relatively free to move in the abdomen, unlike man. Response data obtained from thoraco-abdominal impact experiments using the porcine (Burton, 1972; Verriest *et al.*, 1981; Viano, 1983) or canine (Life and Pince, 1968; Hanson, 1967; Moffatt *et al.*, 1966; Williams and Sargent, 1963) models may only approximate the trauma observed in the live human as a result of blunt impact. The anatomical differences between man and these surrogates may notably affect experimental determination of critical factors which relate to mechanisms of

injury or tolerance levels of biostructures in impact experiments.

Although some authorities (Englehardt, 1966; Detweiler, 1966; Douglas, 1972) imply that the pig may be nearly an all-purpose physiological biomedical experimental surrogate for living humans, this may not apply for impact studies. When using quadrupeds, impact experiments are modified to account for postural effects. Pope *et al.* (1979) investigated postural influences on thoracic impact utilizing the porcine model in a normal porcine posture (the spine oriented in a horizontal plane). They compared the results to a porcine experiment under similar impact conditions in which the porcine was placed in a seated posture with the spine in a vertical plane. There were significant differences in applied forces, thoracic acceleration, aortic overpressures, and skeletal and cardiac injuries. In addition, the unnatural positioning caused a significant amount of pre-impact stress on the subject.

Nusholtz *et al.* (1985a) impacted the thorax of canine subjects in an attempt to produce aortic trauma. Although aortic trauma could be reproducibly created, it was tearing of the ascending aorta near the superior arteries which is uncommonly clinically observed in man. They hypothesized that this was the result of the differences between the canine and live human due to tethering of the heart-aorta structures. In addition, surgical alteration of canine mediastinal tissue illustrated that the mediastinal tethering was particularly important in the injury pattern within the canine model.

Williams and Sargent's (1963) experiments, in which the dog was impacted in a seated position at low velocity, indicate that under some conditions gas- or fluid-filling (pneumointestines) protects the intestines during ventral-dorsal compression which compresses the intestines between the ventral abdominal wall and the spine. They also suggested from their observations that organ tethering plays an important role in injury response. Baxter and Williams' (1961) experiments with dogs impacted ventro-dorsally in a seated position produced more frequent injury to the liver and spleen than percentages produced by a clinically observed human population. They suggested that many minor injuries to the human liver and spleen are undiagnosed in contrast to their study which had increased diagnostic capability because of the immediate necropsy following experimentation.

There is notable variation in the thoracic and upper abdominal organs between man, dog and pig, as well as in the shape of the thoracic cavity. The subtle anatomical differences in the anatomy of the spleen, liver, heart, and tethering structures, especially in the case of the aortic arch and its tethering branches, may notably affect the range of displacement. 'Anatomical tie-downs' are also important factors, i.e. the length of the great vessels, aortic arch curvature, lack of pericardial diaphragmatic fusions, and organ thickness, all may significantly affect displacement capability and thoraco-abdominal impact response.

*Acknowledgements*—The results presented in this paper were partially funded by the University of Michigan Department of Anatomy and by discretionary funds provided by The Institute of Science and Technology.

The authors wish to acknowledge the technical assistance of Bryan R. Suggitt, Valerie A. Moses, Wendy Gould, and Shawn Cowper.

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#### APPENDIX. COMPARATIVE THORACO-ABDOMINAL ANATOMY

##### *Human anatomical considerations*

The torso, between the base of the neck and the hip joint area, includes the thorax above and the abdominal-pelvic region below. The abdomen and the pelvic cavities, although frequently described separately, are continuous, with bony landmarks used as reference points to separate the two.

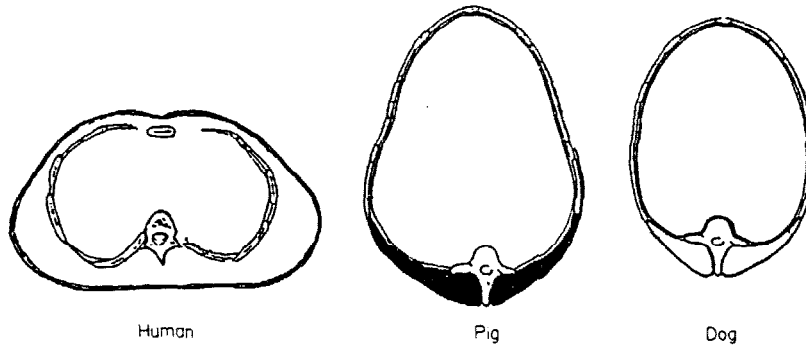


Fig. 2. Cross-section of the human, pig and dog thoraxes. Note the difference in shape between the human and quadrupeds in the anterior-posterior (ventral-dorsal) and lateral directions.

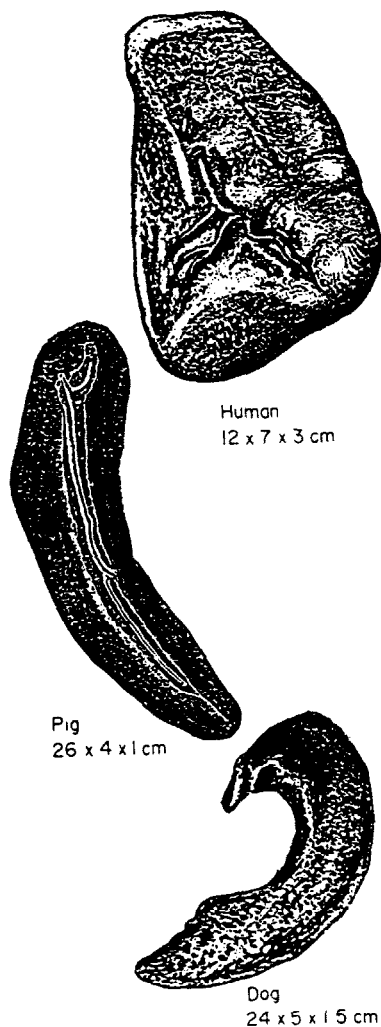


Fig. 6. Human, dog and pig spleens. Relative size between subjects is not to scale. Note the flat, elongated shape of the spleen in the dog and pig.

The human *thorax* is bounded in back by the twelve thoracic vertebrae that interconnect the sternum in front with the paired ribs. The bony thorax is wider from side to side than it is in the anterior-posterior direction except at its very

upper portion (Fig. 1). The first rib is basically covered by the medial end of the clavicle. The inlet to the thorax (the first thoracic vertebra, the paired first ribs and the top of the sternum) is relatively circular but narrow being 5 by 8 cm in area. The outlet of the thorax is much longer and is closed by the thin muscular respiratory diaphragm which has openings for the passage of the aorta, esophagus, and the inferior vena cava.

The human thorax is divisible into three units: the right and left pleural cavities and the central group of structures called the mediastinum. The mediastinum contains the heart and the pericardial sac, the aorta, the aortic arch and its major arteries, the esophagus, the lower trachea, the primary bronchi, the thoracic duct, the azygos venous system and major autonomic nerves. The mediastinum is bounded by the vertebral bodies posteriorly, the sternum anteriorly, and by the parietal pleura laterally.

The pericardial sac, a tough fibrous membrane, completely encloses the heart and attaches to the roots of the great vessels above. The inferior portion of the pericardium is fused to the central tendinous area of the respiratory diaphragm so that the heart and pericardial sac are not noticeably displaced during forced respiration. This means that the heart is fairly well-tethered in position just by the pericardial attachments. Above are the great vessels (the ascending aorta, the aortic arch and its branches, the superior vena cava), which, along with other structures of the mediastinum, are surrounded by connective tissue plus a modicum of fat. Because the connective tissue surrounds and binds one structure to another, there is a relatively stable tether mechanism in the superior mediastinum above the heart. Posteriorly, the pulmonary vessels also secure the heart. Therefore, in terms of mechanical mobility, the human heart, pericardial sac and its diaphragmatic attachment, the ascending aorta, the arch of the aorta, the major aortic branches, the superior and inferior vena cava and associated interconnecting fibrotic tissues form a 'cardiac unit'. The arch of the aorta passes upward and, at approximately the second costal cartilage, arches to the left and posteriorly, so that the descending thoracic aorta is on the left side of the bodies of the thoracic vertebrae. Throughout its entire course, the descending aorta is very significantly tied down in its position next to the vertebrae. This tie-down tether mechanism consists of the intercostal arteries that arise from it to pass through the intercostal spaces, the dense connective tissue adjacent to the aorta, plus the overlying parietal pleura that passes from the ribs posteriorly to form the lateral mediastinal wall.

Because the descending aorta is much more rigidly attached in place by the structures mentioned above, under impact conditions the descending aorta and the 'cardiac unit' are unable to move as one. The most frequent site of a tear of the human aorta is at the junction of the arch and the descending aorta where the ligamentum arteriosum ties the aorta to the

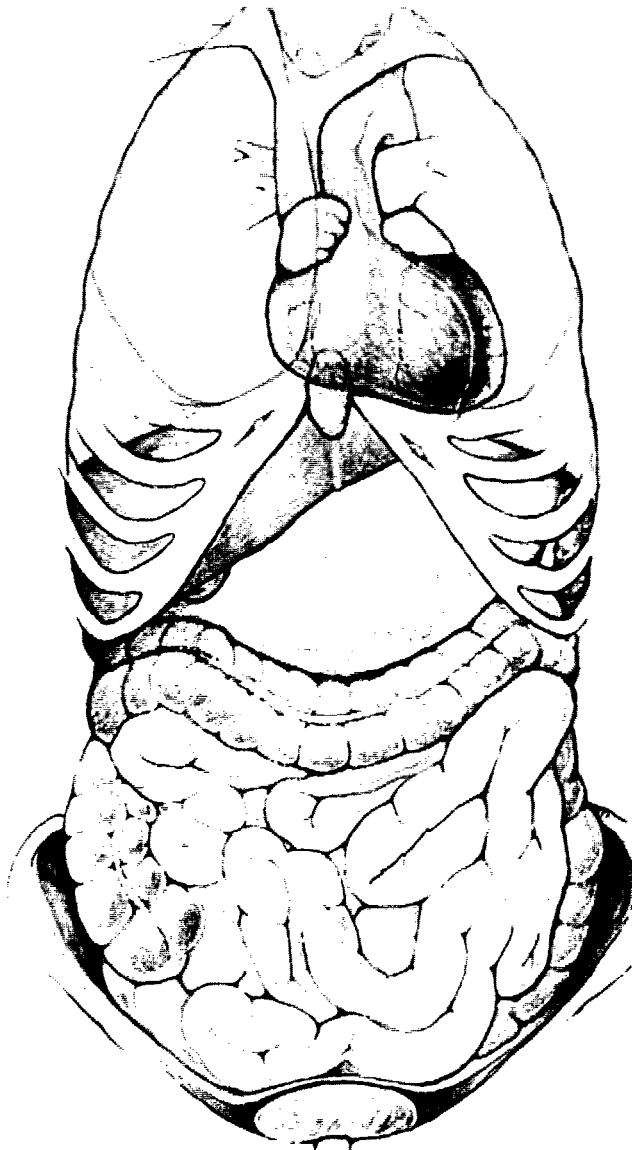


Fig. 1. Overview of the thoraco-abdominal organs in man. Note the liver and spleen are covered by the lower thoracic cage.



Fig. 3. Caudal position of the apex of the heart in the pig. Note that the heart does not sit on the diaphragm as in the human nor does the apex point to the left.



Fig. 4. The aortic arch of the pig.



Fig. 5. The multi leaf-like lobes of the porcine liver. Note that attachments to the undersurface of the diaphragm are very minimal. The liver is very free in the abdominal cavity.



pulmonary artery. It is just distal to this attachment point, where most aortic tears are found.

The human *abdomen* is separated from the thoracic cavity by the thin muscular respiratory diaphragm. The diaphragm is a double-cupula structure when seen in the anterior-posterior view. In lateral view, it is a domed structure. All of the abdominal structures are beneath the diaphragm, in front of the posterior body wall, and extend to the urogenital diaphragm at the base of the pelvis. The abdominal cavity is enclosed by muscles that surround it, and by the lumbosacral vertebral column posteriorly. The anterior abdominal wall consists chiefly of a laminated muscular wall—muscles that are sheet-like, with heavy aponeuroses. Anteriorly, there are three flat muscles—the external and internal abdominal oblique muscles, and the transverse abdominus muscle. These form the anterior, lateral, and partially, the posterior body wall. Just off the midline, anteriorly are two vertical, fairly heavy muscles, the rectus abdominus muscles.

The inner aspect of the abdominal wall is completely lined by the peritoneum. Solid and hollow organs are contained within this peritoneal sac. The hollow organs are the components of the gastrointestinal tract—the stomach, duodenum, ileum, jejunum, colon, rectum, and the anal canal (Fig. 1). In the pelvis, the urinary bladder and the uterus are also considered hollow organs. The solid organs are the pancreas, kidneys, spleen, liver, suprarenal glands, and ovaries in the pelvic cavity.

The stomach is the enlargement of the very short abdominal portion of the esophagus. It is found in the upper half of the abdomen with the spleen behind and to the left, and the liver to its right. The gastrointestinal tract, when empty, is a fairly tight muscular tube; however, when filled with food, feces, or gas, it is an extremely thin-walled structure and very vulnerable to trauma. The blood vessels to most of the gastrointestinal tract pass from the abdominal aorta, located against the anterior vertebral bodies, through the mesentery—a thin sheet-like membrane, which when significantly displaced, can easily be torn, rupturing the enclosed blood vessels.

Extending between the stomach and the liver is a very thin filamentous peritoneal layer, the gastro-hepatic ligament. At its lower free end this peritoneal sheet surrounds the blood vessels that pass to and from the liver, the associated autonomic nerves, and the biliary duct system. This portion of the gastro-hepatic ligament actually attaches to the upper portion of the duodenum and is most properly termed the 'hepto-duodenal' ligament. It extends from the hilum—the entranceway of the liver, to the right side of the vertebral column near where the duodenum is affixed to the posterior body wall.

The human liver, a solid blood-filled organ is approximately 1/40th of the total body weight. It is located in the upper-right quadrant of the abdomen and is firmly attached to the underside of the diaphragm by very short reflections of the peritoneum covering the liver—the liver capsule. These thin peritoneal attachments are less than a centimeter long, adhering directly to the under surface of the diaphragm. With the rise and fall of the right dome of the diaphragm during respiration, the liver moves in synchrony with breathing. Anteriorly, laterally, and posteriorly, the lower ribs cover the major portion of the liver.

The human spleen is a very small blood-filled organ, about the size of a fist, which lies against the posterior body wall, on the diaphragm at the ninth, tenth and eleventh rib level. It is basically free to move, having an encapsulation of a peritoneum—the splenic capsule, with all of its blood vessels entering and leaving the spleen through the hilum, which is attached to the posterior body wall.

Both the liver and spleen are anatomically considered abdominal organs. However, in anterior view, it can be seen that the liver is almost completely housed and protected by the lower ribs, as is the spleen in the lower left posterior rib area. Thus, functionally, in an impact event, the liver and spleen react as thoracic soft-tissue organs protected by the rib cage rather than as abdominal organs. Not infrequently, impacts of the lower rib cage can cause the underlying liver to rupture. Similarly, impacts to the left side, especially to the left lower posterior rib area, will rupture the spleen.

#### *Pig comparative anatomy*

The thoracic cavity of the pig is more oval anteriorly-posteriorly than the human thoracic cavity which is oval laterally (Fig. 2). The pericardium of the pig is not attached to the diaphragm as in the human, but rather it is very strongly attached to the back of the sternum. The apex of the porcine heart is pointed almost directly caudally towards the diaphragm, rather than lying to the left of the midline and on the diaphragm as in the human (Fig. 3). The porcine heart appears to have a lot of space around it, in comparison to the close proximity of the human heart to its pericardium. The arch of the aorta in the pig is much more acutely curved with the superior vessels of the porcine heart relatively longer than in the human (Fig. 4). In the human, the descending aorta runs along the left side of the vertebral column, while in the pig it runs almost directly in front of the bodies of the vertebrae, separated from them by the esophagus.

The pig's liver is multilobed, with deep fissures forming separate and discrete lobes (Fig. 5). It is not attached to the undersurface of the diaphragm and is basically free to move in the upper abdominal cavity, whereas the human liver is relatively fused to the undersurface of the diaphragm and during respiration moves up and down with it. Also, the spleen of the pig is unlike that of the human. The human spleen is approximately the size of a small fist and is located in the upper left posterior area protected by the lower ribs. The pig spleen is tongue-like in nature, being very long and narrow with its long axis almost in a ventral-dorsal direction (Fig. 6). The porcine spleen is curved to fit the greater curvature of the stomach (Getty, 1975; Bustad *et al.*, 1966).

#### *Dog comparative anatomy*

The pericardial sac of the dog is loosely attached to the sternum and diaphragm by almost transparent delicate tissue. The arch between the ascending and descending portions of the aorta occurs within 2 cm of its root. The dog liver is attached to the diaphragm at the caval opening and is free from any other significant moorings. The dog's spleen is long, narrow and flat like that of the pig and is loosely attached to the body wall. It lies in the anterior-posterior direction with the dorsal end being close to the first lumbar vertebra near the end of the last rib (Miller, 1964).