EVALUATING PEDIATRIC ABDOMINAL INJURIES

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ABSTRACT

Abdominal injuries, along with lumbar spine fractures, are part of a constellation of injuries referred to as "seat belt syndrome". Geometrical characteristics of the pelvis and abdomen of younger children place them at higher risk for these injuries. Efforts to design restraints that mitigate these injuries are limited as no current pediatric anthropomorphic dummy (ATD) can accurately quantify the abdominal response to belt loading. This paper describes progress on a four-phase project to address this gap involving pediatric anthropometrics, real-world abdominal injury risk, abdominal biomechanical structural response and injury tolerance from a porcine model, and development of an abdominal insert for the 6-year-old ATD based on these data.

Internal anthropometric measures consisted of radiological assessment of abdominal depth, height, and circumference at multiple horizontal planes. External measures consisted of distances, determined by digital photography, taken between skeletal markers while the child was seated on a vehicle seating apparatus with and without a booster seat.

Field investigation identified three unique kinematic patterns resulting in abdominal injury: pre-submarining where the belt is initially out of position, classic submarining where the belt starts in position and the pelvis moves under the belt with the torso reclined, and submarining/jackknifing where the pelvis slides under the belt, and the torso flexes forward.

The biomechanical studies developed age- and size-based correlations between pediatric swine and humans. Biomechanical tests performed using the most appropriately sized porcine model will be used to define the structural and injury response of the pediatric abdomen to realistic loading conditions.

INTRODUCTION

The abdomen is the second most commonly injured body region after the head/face in young children using vehicle seat belts and can be associated with significant health care costs and extended hospitalization (Durbin et al. 2001; Bergqvist et al. 1985; Tso et al. 1993; Trosseille et al, 1997). Injuries to this region, along with fractures of the lumbar spine, are part of a constellation of injuries known as seat belt syndrome (Kulowski and Rost 1956; Garrett and Braunstein 1962; Hoy and Cole 1993; Lane 1994).

Children of all ages are at risk of sustaining seat belt syndrome, but the poor fit of the belt in younger children likely places them at higher risk than older children. In a case series of 98 children with seat belt syndrome, the mean age was 7.3±2.5 years and 72% were between 5 and 9 years of age. (Gotschall et al, 1998) The exposure of children to adult seat belts is large: data from the Partners for Child Passenger Safety study, an on-going, child-focused crash surveillance system, identify the adult seatbelt as the most common form of restraint for passengers age 5 years and older. (Winston et al. 2004)

Our previous work, based on an analysis of over 200,000 children in crashes, identified key predictors of elevated abdominal injury risk in seat belt-restrained child occupants: child age, vehicle type, and seat row (Arbogast et al, 2004). Children 4-8 years of age were at the highest risk of abdominal injury: they were 24.5 times and 2.6 times more likely to sustain an AIS2+ abdominal injury than those 0-3 years and those 9-15 years, respectively. The injury risk for children 4-8 years of age was 6 and 10 times higher in passenger cars and SUVs, respectively, compared to minivans. No reduction in abdominal injury risk was seen with rear seating as compared to front row seating. The role of direction of impact on injury risk varied by child age, indicating diverse injury sources influenced by developmental differences and changes in restraint practices among the age groups. These findings provide a baseline understanding of abdominal injury patterns and suggest mechanistic hypotheses to be tested with additional in-depth data.

According to the American Academy of Pediatrics and the National Highway Traffic Safety Administration, the proper restraint for many of the children sustaining abdominal organ injuries associated with seat belt syndrome (those less than 9 years old) is a booster seat. There have been tremendous legislative, regulatory, and educational efforts to increase booster seat use in the recent past. Discussion has emphasized the need to ensure outstanding impact performance of booster seats while at the same time considering how vehicle belt systems can evolve to provide protection for this age group. In order to evaluate the safety performance of these new and emerging restraint technologies, a mechanical child surrogate that accurately assesses the risk of abdominal injuries in the motor vehicle environment is needed. Current pediatric anthropomorphic test devices (ATD) are limited in this ability.

None of the child frontal crash test dummies specified in the Code of Federal Regulations Part 572 have the ability to make any abdominal injury measurements. While several adult frontal impact dummies at the research stage have abdominal injury assessment capability (Hybrid III with Frangible Abdomen and THOR, both in mid-sized male and small female dummies), none of the child dummies have any instrumentation in the abdominal area. The Q series of dummies has taken abdominal biofidelity into account by scaling the force-deflection properties of the adult abdomen. It is not known how well this compares to the properties of real children. In addition, the dummies do not have abdominal instrumentation.

Rouhana (2002) reviewed abdominal injury criteria for various impact modes. Miller et al. (1989) and Rouhana et al. (1989) showed that given the low velocity nature of the belt to abdomen interaction, abdominal compression was well correlated to abdominal organ injury. For this reason, both the THOR dummies and the Hybrid III Frangible Abdomen dummies measure abdominal compression as the injury assessment metric.

This paper describes progress on a four-phase project to address this gap involving pediatric anthropometrics, real-world abdominal injury risk, abdominal biomechanical tolerance from a porcine model, and development of an abdominal insert for the 6-year-old ATD based on these data. The long-term objective of this 3-year research effort is to develop a modification to the current 6-year-old Hybrid III anthropometric dummy so that the risk of abdominal injury can be accurately assessed in the motor vehicle crash environment. In order to achieve this objective, the biomechanical response of the pediatric abdomen must be understood. Traditional methods used to measure the impact response of adults such as cadaver or volunteer tests are unable to be used for children. As a result, we are utilizing a multidisciplinary approach that combines 1) an assessment of the anthropometry of the pediatric abdomen, 2) analysis of an extensive database of real-world crashes involving children who sustained abdominal injury, and 3) definition of the biomechanical response of the abdomen using a well-controlled animal model.

METHODS

Anthropometry

Two methods for obtaining geometry and anthropometry were implemented: retrospective review of abdominal radiological films and prospective measure of anthropometrics and seat belt fit parameters on healthy pediatric human volunteers.

<u>Retrospective radiology</u> – With this component, we determined abdominal compartment and intra-abdominal organ measures on a representative sample of children who closely approximate the size of the 6-year-old ATD. The current 6- year- old ATD measures 48 inches in height and 52 pounds. According to the current US pediatric growth charts produced by the Centers for Disease Control and Prevention (CDC, 2000), these measures approximate a 50^{th} percentile, 7- year- old child. Intra-abdominal geometry of children was determined by examining abdominal computed tomography (CT) scans of a representative sample of children in the target age and weight range.

Subjects were identified via a retrospective review of abdominal/pelvic CT scans performed at The Children's Hospital of Philadelphia. An initial review of the Department of Radiology database at CHOP identified all children from 6-8 years of age who underwent abdominal CT scans. The most common indications for abdominal CT scanning in children include the evaluation of blunt abdominal trauma and the evaluation of abdominal pain suggesting appendicitis. In order to select a sample of CT scans that best approximates the intra-abdominal anatomy of otherwise healthy children, only CT scans performed for suspected acute appendicitis or trauma evaluation which demonstrate no significant intra-abdominal injury were selected. Children with intra-abdominal free fluid, or solid organ injuries or pathology were excluded. Scans from 35 children were included in the study.

Specific inclusion criteria were children age 6-8 years of age who weigh between 20.4-27.3 Kg (+10% of the Hybrid III 6 year old ATD's weight). All CT scans included were reviewed by a single radiologist, board certified in pediatric radiology and experienced in the interpretation of pediatric abdominal CT scans.

All radiographs were taken with the children in a supine position (on their backs). Using scout views, axial and sagittal reconstructions, the following measures were obtained on all scans:

1. Abdominal depth and circumference at level of umbilicus and at level of last appearance of the anterior ribs.
2. Transverse width of the abdomen at the level of the iliac crests and at the level of the largest anterior-posterior diameter of the pelvis.
3. Vertical distance between the end of the 11^{th} false rib and the top of the iliac crests.
4. Abdominal height from diaphragm insertion to pubic symphysis, both anteriorly and posteriorly.
5. Vertical dimension of the pelvis as measured from the top of the iliac crests to the most inferior point on the ischial tuberosity.
6. Pelvic inlet – distance from the sacral promontory at S1 to the superior aspect of the pubic symphysis in the midline sagittal plane

Examples of these dimensions are contained in the appendix. Means and standard deviations were calculated.

<u>Prospective anthropometrics</u> - The specific aim of this component of the research study was to describe a variety of external anthropometric measures on a representative sample of target age children taken on a stylized vehicle seat with and without a booster seat.

Children eligible for the study were those from 5-9 years of age presenting to the Primary Care Clinic of The Children's Hospital of Philadelphia. Effort was made to enroll subjects between 43-47 inches in height, and weighing 16-27 kg so that the findings were most applicable to the 6-year-old ATD. Any child with an existing neurologic, orthopedic, genetic, or neuromuscular condition was excluded. 60 children were enrolled in the study.

On each child, several skeletal landmarks were palpated by a research nurse and marked with a small bright sticker. The child wore bike shorts and a tight fitting T-shirt to facilitate the identification of anatomic landmarks and optimize the accuracy of the measurements. The skeletal landmarks included:

1. ASIS (anterior superior iliac spines) - the anterior most portion of the iliac crest of the pelvis
2. AIIS (anterior inferior iliac spine) - AIIS is found immediately below the ASIS and is a bony prominence on the lower part of the anterior margin of the iliac bone of the pelvis between the ASIS and the acetabulum.
3. Greater trochanter - the lateral most protrusion of the proximal femur bone
4. PSIS (posterior superior iliac spine) - PSIS is the upper protrusion on the posterior border of the ileum; a readily apparent dimple occurs in the skin overlying the PSIS
5. End of 11th false rib - the end of the bottom most rib (11^{th}) on the lateral aspect.
6. Shoulder joint - right lateral greater tubercle of the proximal end of humerus at the center of the tuberosity
7. Knee joint - right lateral epicondyle of the distal end of femur at the center of the tuberosity
8. Ankle joint - right lateral malleolus of the distal end of fibula at the center of the tuberosity
9. Xiphoid (center point of the bottom tip of sternum)
10. Manubrium (center point of the top edge of sternum)

The child was then positioned on the stylized vehicle seat in a standardized symmetrical position with their head forward and hands at their sides. (Figure 1) The research nurse re-palpated the skeletal landmarks to assure proper placement of the markers. Photographs were taken with a high-resolution digital SLR camera mounted in a standardized location for all study subjects and remotely operated from a laptop computer. Photos were taken from the front as well as the side.

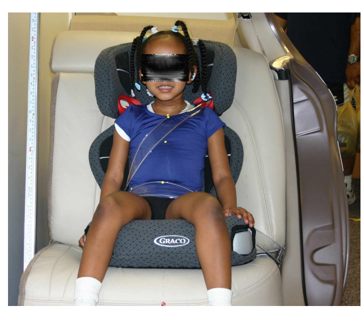


Figure 1: Subject for the prospective anthropometric study in the standard position with her head forward and hands at her side seated on the full back booster.

The stylized vehicle seat was fitted with a transparent seat belt representing the geometry of an actual rear seat 3-point seat belt. Front photographs were taken with and without the belt. The belt was applied by the research nurse and fitted snugly to the study subject. Once the belt was applied, three additional markers were placed on the subject:

1. Shoulder belt outer (lateral edge of the shoulder belt where it crosses the clavicle)
2. Shoulder belt center (bottom edge of the shoulder belt where it crosses the midline)
3. Superior edge of lap belt (top edge of the lap belt where it crosses the midline)

The entire study protocol was repeated for the vehicle seat alone and seated on two different belt-positioning booster seats: a backless booster and a fullback booster. Digital measurements from the photos were calculated using SigmaScan Pro image analysis software. Specific measures obtained were as follows (specific locations described above):

From front view photo:

- Vertical distance between the xiphoid and a horizontal line drawn between the right and left ASIS
- Distance between right and left ASIS bilaterally
- Vertical distance between a horizontal line drawn through manubrium where it intersects with the sternum to the bottom edge of shoulder belt along the midline of the body.
- Horizontal distance between a vertical line drawn through manubrium where it intersects with the sternum and the outer edge of shoulder belt at the level of the clavicle
- Vertical distance between horizontal line drawn between the right and left ASIS and superior edge of lap belt along the midline of the body
- Difference in the vertical heights of right and left ASIS relative to the seat base

From side view photo:

- Pelvic tilt (angle formed by the intersection of a vertical line and the line connecting the ASIS and PSIS)
- Pelvic angle (angle formed by the intersection of a vertical line and the line connecting the ASIS and AIIS)
- Hip angle (angle formed by the intersection of a line joining the shoulder joint and greater trochanter with a line joining the greater trochanter and the knee joint)
- Vertical distance between the ASIS and the greater trochanter.
- Knee angle (angle formed by the intersection of a line joining the greater trochanter and the knee joint with a line joining the knee and ankle joint).
- Tibia/Fibula angle (angle formed by the intersection of a vertical line and the line connecting the knee and ankle joint)

All measurements were compared across the different restraint systems and by size of child (standing height, seated height, weight and/or body mass index (BMI)). All data obtained in this study were continuous in nature. Analyses consisted of the calculation of mean, standard deviation, range, and interquartile range for each measure obtained.

Crash Investigation review

Cases of seat belt restrained children in motor vehicle crashes who sustained abdominal organ injury were analyzed from the Partners for Child Passenger Safety (PCPS) Study. Detailed descriptions of the study population and methods involved in data collection and analysis have been previously published (Durbin et al. 2001). PCPS consists of a large scale, child-specific crash surveillance system: insurance claims from State Farm Insurance Co. (Bloomington, IL) function as the source of subjects, with telephone survey and on-site crash investigations serving as the primary sources of data. The telephone interviews provide data for a surveillance system used to describe characteristics of the population including risk factors for injury while the crash investigations provide detailed mechanisms and sources of injury.

Crashes qualifying for inclusion in the surveillance system were those involving at least one child occupant $\leq$ 15 years of age riding in a model year 1990 or newer State Farm-insured vehicle. Qualifying crashes were limited to those that occurred in fifteen states and the District of Columbia, representing three large regions of the United States (East: NY, NJ, PA, DE, MD, VA, WV, NC, DC; Midwest: OH, MI, IN, IL; West: CA, NV, AZ). On a daily basis, data from qualifying and consenting claims were transferred electronically from all involved State Farm field offices to researchers at The Children's Hospital of Philadelphia and University of Pennsylvania (CHOP/Penn). Data in this initial transfer included contact information for the insured, the ages and genders of all child occupants, and a coded variable describing the medical treatment received by all child occupants.

In order to gain more detailed information about the kinematics of the child and the mechanisms and sources of the injury, a subset of these cases was chosen for in-depth crash investigation. Cases were screened via telephone with the policyholder to confirm the medical details of the case. Contact information from selected cases was then forwarded to a crash investigation firm and a full-scale on-site crash investigation was conducted using custom child-specific data collection forms.

Crash investigation teams were dispatched to the crash scenes within 24 hours of notification to measure and document the crash environment, damage to the vehicles involved, and occupant contact points according to a standardized protocol. The on-scene investigations were supplemented by information from witnesses, crash victims, physicians, hospital medical records, police reports, and emergency medical service personnel. From this information, reports were generated that included estimates of the vehicle dynamics and occupant kinematics during the crash and detailed descriptions of the injuries sustained in the crash by body region, type of injury, and severity of injury. Delta v (the instantaneous change in velocity) was calculated using WinSmash and crush measurements of the vehicles involved.

Medical, crash, and child characteristics of 26 cases of pediatric abdominal injuries in restrained child occupants in frontal crashes were analyzed. The mechanism of each abdominal injury was determined by an assessment of the specific location of impact and the resultant kinematics.

Development of the Porcine Model

In order to design an abdominal element for use in a dummy, it is necessary to define the structural and injury characteristics of the 6-year-old human's abdomen. The field investigations described above allow the study of meaningful clinical outcomes on real children in real crashes; however, data obtained from these analyses are limited in that the engineering input is derived rather than measured directly. An experimental model, in contrast, allows the application of an exact loading condition and documentation of specific injuries but is limited by the knowledge of the exact transfer function between the experimental model and the human.

For adults, abdominal characteristics are typically determined using human cadavers (Hardy et al. 2001). For the child, however, such data are not available. Scaling techniques may be used to estimate pediatric force-deflection characteristics based on those measured for adults, but these techniques require assumptions about age-related changes in geometry and material properties that remain largely unproven, particularly for the complex and inhomogeneous abdomen. Additionally, injury threshold values and the correlations between injury criteria and injury outcome cannot be reliably scaled from adults to children. It is necessary, therefore, to identify a surrogate that mimics to an acceptable degree the child's anatomy, size, organ development, and other characteristics and to quantify this surrogate's abdominal characteristics. The porcine model is reasonably well established for studying thoracoabdominal impact and injury response of both adults (Stalnaker et al. 1973, Trollope et al. 1973, Gogler et al. 1977, Miller 1989, Miller 1991a, Miller 1991b) and children (Aldman et al. 1980, Mertz et al. 1982, Prasad and Daniel 1984). The studies by Miller et al. focused specifically on belt loading to the abdomen, but used an adult pig. The other studies listed above focused on loading mechanisms other than abdominal belt loading (e.g., hub loading or air bag loading on an out-of-position occupant). Recent research has utilized a pediatric porcine model to evaluate the influence of active muscle tensing on the structural response of the thorax (Kent et al. 2003, 2004) and to study resuscitation of a choking child (Woods et al. 2002). This history provides the basis for selecting the pig as a reasonable representation of the human abdomen, but the porcine model has not been sufficiently developed to apply directly to the study of abdominal loading to a 6-year-old human. This study will, therefore, identify the porcine age that best correlates with the size and development of a human six year old and will characterize the abdominal structure and injury tolerance of these swine as a reasonable approximation of the human child.

This identification was accomplished via an imaging and necropsy study, which correlated the geometric and mass properties of the pig and the 6-year-old. Twenty-five pigs, age 14 days to 429 days, were included in the study. Whole-body mass ranged from 4 kg to 101 kg. Females were chosen preferentially, and only one male was included in the study. Over 30 geometric and inertial characteristics of each subject were measured and compared with similar characteristics of humans. Human data were taken from four primary sources. External body dimensions were obtained from the GEBOD database (Grunhofer 1975, McConville et al. 1980, Clauser et al. 1972, Young et al. 1983, and Snyder et al. 1977), the University of Michigan data compiled under the name "Anthrokids" (Owings et al. 1975, Snyder et al. 1977, see http://ovrt.nist.gov/projects/anthrokids/), and the data from Children's Hospital of Philadelphia collected as part of this project. In cases of apparently contradictory values, the GEBOD data were used preferentially (note that the GEBOD database and the Anthrokids database draw from overlapping sources, but are not identical). The organ masses for the pigs were compared with data compiled by Stocker and Dehner (2002), who list average organ weights for children for each year from birth through age 19 years.

Since the goal of the necropsy study was to identify the best overall representation of the 6-year-old human, two functions defining a series of characteristics were used instead of a single target to identify the most appropriate pig model. These functions included i = 1..5 external measures (f^1_i) and j = 1..4 internal organ masses (f^2_j) . The external parameters considered in f^1 were :

a. Abdominal depth (at umbilicus) (target = 15.1 cm),
b. Abdominal breadth (at umbilicus) (target = 18.5 cm),
c. Sitting height (defined for the pig as the distance from the proximal end of the tail to the cranial surface of the head, with the neck in a neutral position) (target = 64.5 cm),
d. Distance in the midsagittal plane from the cranial end of the sternum to the umbilicus along the ventral surface of the trunk (target = 25.4 cm), and
e. Trunk weight (target = 11.8 kg).

The organs used for mass comparison in f^2 were the liver, kidneys, and lungs. The targets were 660 g (liver), 66 g (right kidney), 67 g (left kidney), and 328 g (both lungs).

The value of each of these parameters for each pig was defined as a percentage of the human target. The average percentage of the 5 external parameters was then defined as f^1_{avg}, and the average percentage of the organ parameters was f^2_{avg}. Regression equations were used to relate f^1_{avg} and f^2_{avg} to the pig's age, a, and mass, m:

$$f^1_{avg} = g(\mathrm{a}, \mathrm{m}) \quad [1]$$

$$f^2_{avg} = h(\mathrm{a}, \mathrm{m}) \quad [2].$$

A second-order polynomial regression was then developed defining the relationship between pig age and whole-body mass:

$$\mathrm{m} = A + Ba + Ca^2 \quad [3].$$

The pig age and mass that best represent the 6-year-old human were then determined by setting

$$f^1_{avg} = f^2_{avg} = 1 \quad [4]$$

and minimizing the error in equations [1] and [2] simultaneously subject to the constraint imposed by equation [3].

Development of Test Matrix

There are several factors that could influence abdominal force-penetration and injury response to belt loading. The goal with the experimental test matrix and fixture was to evaluate as many of these factors as practical while limiting the number of test subjects required. The six factors identified for study were:

1. The degree of belt "wrap-around" (i.e., the degree of belt-abdomen contact). The testing will involve two conditions: 105° and 160°.
2. The loading location (upper and lower abdomen). Previous research has shown that the upper abdomen (primarily solid organs) and the lower (primarily hollow organs) exhibit markedly different responses to loading (Rouhana 2002). The field data component of this project showed that most young belted children who sustain abdominal injury have those injuries in the lower abdomen, but that injuries can occur in either location.
3. The shape of the displacement wave. A ramp-hold wave will be used to define the viscous force relaxation (Kent et al. 2003), while a ramp-release wave will be used to define injury tolerance.
4. The presence of active muscle tensing (Kent et al. 2004).
5. The magnitude of abdominal compression. Tests will be performed to 25%, 50%, and 65% of the unloaded abdominal depth.
6. The peak deflection rate (3 m/s and 6 m/s). While most of the injuries identified in the field component of this study were thought to be mechanistically related to deflection magnitude, there is evidence in the literature that organs can be injured via a viscous mechanism if the rate of deformation is sufficiently great.

The conditions chosen for the testing in this project are intended to maximize the information gleaned while minimizing the number of subjects to be sacrificed. This project is designed as a multi-level parametric study with 6 parameters and multiple levels of each: belt wrap-around (2 levels), loading location (2 levels), waveform (2 levels), muscle tensing (2 levels), compression depth (3 levels), deflection rate (2 levels). Inter-specimen variability is assessed by repeated tests of all test combinations. If all possible combinations of these levels were tested, including repeated tests of each combination, a total of 2 x 2 x 2 x 2 x 3 x 2 x 2 = 192 subjects would be required. The number of required subjects can be decreased substantially if certain assumptions are made about the influence of interactions between parameters. In the proposed test plan, the following rationale is used to reduce the number of required tests.

1. The influence of muscle tensing will be assumed to be most pronounced in the maximal wrap-around condition. Since muscle activation will be either none or full tetanus, information about intermediate muscle effects is not needed.

2. The effect of muscle tensing in the upper and lower abdomen will be assumed to be similar. Muscle tensing will therefore not be stimulated in tests loading the upper abdomen.

The levels of abdominal compression chosen should generate an acceptable distribution of injury and non-injury outcomes. Multiple levels of abdominal compression are tested since many tests (both with and without injury) are required in order to develop an injury risk function using censored data. The influence of loading rate will be evaluated to a limited extent by performing the 50% compression tests with the ramp-release wave at two loading rates. Repeated tests on the same subject shall not be used, even in the case of the 25% compression tests, since some injuries may result from these tests and because the initial condition will probably be changed after even a non-injurious test. In previous UVA tests of porcine thoracic response, a long-time viscous effect and superficial soft tissue damage have made repeated tests inappropriate, even when the first test did not generate hard tissue injury (Kent et al. 2003). There is also the potential to weaken the statistical modeling if repeated tests are performed on the same subject, since clustering will have to be considered.

Test Methods

Live anesthetized porcine subjects will be intubated, ventilated, instrumented, and positioned for testing on a pneumatically driven test table similar in concept to that described by Kent et al. (2003, 2004) (Figure 2). Immediately prior to loading, the subject will be euthanized, the lungs will be inflated to maximal physiological inhalation, and the tracheal tube will be occluded. The tube will remain occluded throughout the displacement wave. The pulmonary system will therefore be assumed to be closed during the loading and the effects of airflow from the lungs will be ignored.

Pressure transducers will be inserted via catheters into the abdominal aorta, the thoracic aorta, the trachea, and at other locations. For tests involving simulated muscle tension, pairs of external electrodes will be positioned bilaterally over the abdomen anterolaterally and posterolaterally. A load transducer will be positioned between the subject and the table. Load transducers will also be used to measure the applied force on the anterior abdomen. Potentiometers will measure anterior-posterior displacement of the anterior abdominal wall. Digital video of the tests will be taken and digital still images will be used to document test conditions and the necropsy findings.

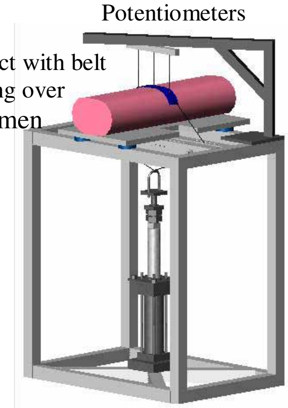


Figure 2. Schematic depiction of loading frame.

Following positioning of the subject on the table, the belt will be positioned on the abdomen. Immediately prior to the application of loading, the subject will be euthanized using a solution of pentobarbital, a barbiturate that affects the central nervous system and can therefore be assumed to have no affect on the muscles' response to an external stimulus. Immediately after death, the muscles will be stimulated when applicable and the displacement wave will be applied. In all ramp-hold tests, the displacement will be held until a nominal steady-state condition is achieved (i.e., until force relaxation is complete). Viscoelastic structural models will be developed for each ramp-hold test (Kent et al. 2003). The validity of these models will be assessed by using them to predict the measured response in all ramp-release tests. At the completion of the test, a detailed necropsy will be performed to document all macroscopic thoracoabdominal injuries.

The Institutional Review Boards and Institutional Animal Care and Use Committees of The Children's Hospital of Philadelphia, The University of Pennsylvania School of Medicine, and The University of Virginia approved the conduct of relevant components of this project. All testing will be overseen by personnel from the UVa Center of Comparative Medicine and Department of Emergency Medicine. All procedures comply with the guidelines of the Animal Welfare Act and Public

Health Policy on the Humane Care and Use of Laboratory Animals. All subjects will be euthanized prior to any biomechanical testing.

RESULTS

Anthropometrics

Retrospective radiology – Radiology films from 35 study subjects, 18 females and 17 males, were analyzed to determine the geometrical measures. The average age and weight were 6.9±0.8 years and 24.4±1.7 kg, respectively. [1]

Table 1: Results from the retrospective radiology study of 35 subjects. Figures showing these dimensions are contained in the Appendix.

Measure	Average (cm)	Std. Dev.
Abdominal depth at umbilicus	13.6	1.3
Circumference at umbilicus	51.6	4.0
Abdominal depth at lower ribs	15.0	1.2
Circumference at lower ribs	54.8	3.5
Inner distance between iliac crests at first appearance	9.0	1.9
Outer distance between iliac crests at first appearance	16.0	1.2
Transverse dimension of abd. at iliac crest first appearance	20.2	1.4
Inner distance between iliac crests at largest AP diameter	7.2	1.1
Transverse dimension of abdomen at largest AP diameter	21.4	1.6
Right lowest rib to iliac crest	6.5	0.9
Left lowest rib to iliac crest	6.8	1.0
Right iliac crest to ischial tuberosity	13.9	0.7
Left iliac crest to ischial tuberosity	13.8	0.8
Lower border of the lung to the pubis - anteriorly	24.7	1.6
Lower border of the lung to the pubis - posteriorly	23.1	1.8
Pelvic inlet	9.0	0.8

Prospective anthropometrics – Anthropometric measures from 60 study subjects, 29 females and 31 males, were obtained. The average age and weight were 6.2±1.3 years and 23.7±5.2 kg, respectively. Preliminary analysis is complete on 30 subjects and several representative measures are shown below.

[1] This data was presented at the May 2005 Annual Meeting of the Society of Pediatric Radiology.

Figure 3 shows the angle made by the right fibula/tibia relative to a vertical line in space. In general, this angle is largest for those children seated directly on the vehicle seat followed by those on a back less booster, then those on a full back booster. A smaller value corresponds to a more comfortable position.

The distance between the lateral edge of the neck to the lateral edge of the shoulder belt along the line of the clavicle is shown in Figure 4. Again the role of the restraint is evident with the backless booster providing a vertical "boost" to the child and making his stature more adult like. The shoulder belt guide on the full back booster moves the belt even farther off the neck.

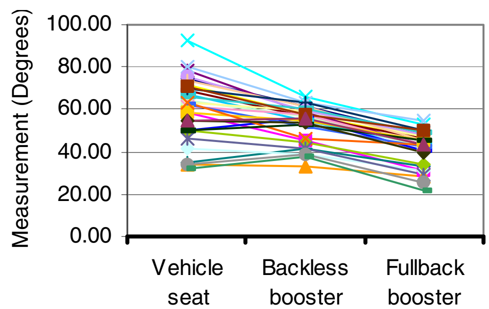


Figure 3: Right tibia/fibula angle (relative to vertical)

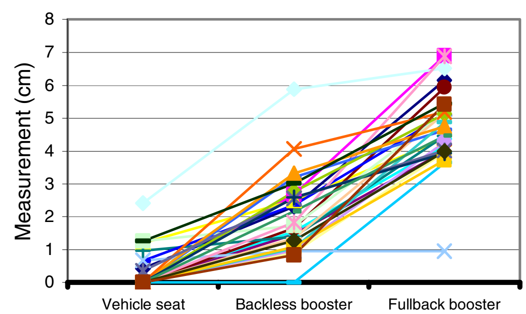


Figure 4: Distance from lateral edge of the neck to lateral edge of shoulder belt at the level of the clavicle.

Crash Investigation

Twenty-six cases meeting the following selection criteria were reviewed and analyzed: seat belt restrained child occupant age 4-11 who sustained an AIS 2+ abdominal injury in a frontal crash. Specific observations from the cases were as follows:

- Hollow organ injuries (stomach/intestine) were associated with higher delta v (47 kph) than those injuries to the solid organs (spleen/liver/pancreas/kidney) (26 kph)
- Belt compression was the primary mechanism of injury however the compression derived from both the lap and the shoulder belt.

- Belt misuse or older designs were predominant in those with injury; for example, children with the shoulder belt behind the back, automatic shoulder belts, and single manual lap belts.

The case review identified three unique kinematic patterns that resulted in abdominal injury: pre-submarining where the belt is initially out of position, classic submarining where the belt starts in position and the pelvis moves under the belt with the torso reclined, and submarining/jackknifing where the pelvis slides under the belt, and the torso flexes forward. Three cases are described here for illustration.

Case 1 - The case vehicle (1995 Honda Civic) was traveling north, vehicle 2 (1996 Mazda MPV) directly ahead of the case vehicle. Vehicle 3 (1996 Mercury Villager) was also traveling north in the lane to the right of the case vehicle and vehicle 2. Vehicle 3 lost control on the wet pavement and entered the path of vehicle 2. Vehicle 2 hit Vehicle 3 on the left side. Vehicle 2 was rear ended by the case vehicle. The PDOF was 0° and the delta v was calculated to be 20 kph. A 7-year-old male was seated in the left rear seat restrained by the lap and shoulder belt with the shoulder portion of the belt behind his back.

AIS 2+ injuries:
- Hematoma of the small bowl mesentery (AIS2)

AIS 1 injuries:
- Horizontal abrasion to the lower abdomen
- 2 cm forehead laceration

Proposed injury source:
- Submarining with jackknifing - lap belt loading

MAIS other occupants:
- Adult restrained driver (AIS 1)
- Adult restrained right front passenger (AIS 1)
- 3 year old - booster seat in right rear (none)

Figure 5: Photo of case vehicle damage from Case 1.

Case 2 - Vehicle 2 (1993 Pontiac Sunbird) was traveling north on inside lane and rear-ended vehicle 3 (1997 Honda Accord), traveled over the yellow line into oncoming traffic and struck the front of the case vehicle (1994 Mercury Grand Marquis). Vehicle 4 (1992 Jeep Wrangler) was traveling behind the case vehicle and struck it in the rear. The case vehicle struck a roadside sign with its rear plane before coming to a rest. The PDOF was 330° for the frontal impact and the delta v was calculated to be 37 kph. A 4-year-old male was seated in the center rear seat restrained by the lap belt.

AIS 2+ injuries:
- Proximal ileal serosa tear of the distal jejunum
- Several mesenteric hematomas
- Grade 1 liver laceration.

AIS 1 injuries:
- Contusion/ abrasion to forehead
- Contusion to lower abdominal area
- Laceration over the right eye.

Proposed injury source:
- Pre submarining with lap belt loading

MAIS other occupants:
- Adult restrained driver (AIS 2)
- 2 year old in child restraint in left rear (AIS 1)

Figure 6: Photo of case vehicle damage from Case 2.

Case 3 - The case vehicle (1994 Nissan Sentra) was traveling eastbound behind a non-contact vehicle. Vehicle 2 (1997 Honda Accord) was traveling westbound at about 65mph, when vehicle 2 lost control due to hydroplaning after hitting a water spot on the road. Vehicle 2 skid sideways into the traveling path of eastbound traffic. The non-contact vehicle in front of the case vehicle steered to the right. The front of the case vehicle was struck by the right side of vehicle 2. The PDOF was 330° and the delta v was calculated to be 43 kph. A 7-year-old female was seated in the right front seat restrained by the automatic shoulder belt and manual lap belt.

AIS 2+ injuries:
- Lacerated spleen
- Small liver laceration
- Epidural bleeding along the skull base
- Fractured left ribs #9 and #10.
- Contused right lung

AIS 1 injuries:
- Contused right abdominal area

- Abdominal abrasion, left side

Proposed injury source:

- Classic submarining - lap/shoulder belt loading

MAIS other occupants:

- Adult restrained driver (AIS 1)

Figure 7: Photo of case vehicle damage from Case 3.

Necropsy Study

The multiple linear regressions described in Equations [1] and [2] were both significant, though the age term was not significant in Equation [1]. This term was therefore dropped and the forms of Equation [1] and [2] used for the subject identification were

$$f^1_{avg} = 1 = 0.217 + 0.0327m \qquad [5]$$

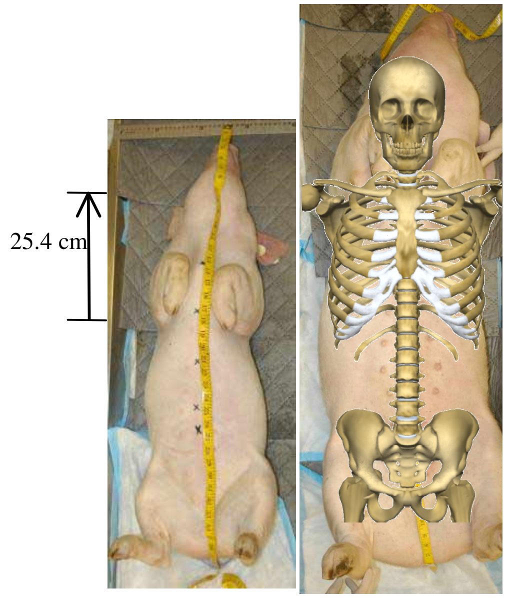
and

$$f^2_{avg} = 1 = 0.536 + 0.00266a + 0.0179m \qquad [6]$$

where

$$m = -2.5239 + 0.1812a + 0.0017a^2 \qquad [7].$$

Minimizing the error in [5] and [6] subject to the constraint imposed by Equation [7] results in a pig age and mass of 76.7 days and 21.4 kg as the best representation of a 6-year-old human based on the external dimensions and masses, and organ masses, described earlier. As shown in Figure B.1 in the Appendix, the constraint imposed by Equation [7] makes it impossible for the pig to match all characteristics of the 6-year-old human. The age and mass chosen, however, do result in a very good representation of the set of characteristics chosen for comparison (see large dot in Figure B.1). A visual comparison of a to-scale adult human skeleton, a 73.4 kg pig, and a 21.2 kg pig (i.e., the best representation of a 6-year-old) is shown in Figure 8.



Best representation of 6-year-old

Adult pig with 50th male human skeleton overlaid

Figure 8. Visual comparison of adult human, adult pig, and chosen pig model (77 days old).

DISCUSSION AND CONCLUSIONS

Abdominal injuries, along with lumbar spine fractures, are part of a constellation of injuries referred to in the medical literature as "seat belt syndrome". Geometrical characteristics of the pelvis and abdomen of young children place them at higher risk for these injuries. Efforts to design restraints that mitigate these injuries are limited as no current pediatric anthropometric dummy (ATD) can accurately quantify the abdominal response to belt loading. This manuscript describes progress on a four-phase project to address this gap involving pediatric anthropometrics, real-world abdominal injury risk, abdominal biomechanical tolerance from a porcine model, and development of an abdominal insert for the 6-year-old ATD based on these data.

The two sources of anthropometric and geometrical data serve several purposes in the overall research project. First they facilitate the identification of the relevant porcine model and second they provide geometrical guidelines for the development of the ATD insert. Use of the measures to guide the choice of the appropriate age animal is discussed below. Although the ATD does not have many of the skeletal landmarks used in either the retrospective radiology or prospective anthropometric studies, some measures can be compared to the current ATD dimensions. All ATD measures were taken from the current Hybrid III 6 year old ATD drawing package (US DOT, 2002).

Table 2: Comparison of human measures with current Hybrid III 6 year old ATD measures taken from the ATD drawing package

Measure	ATD (cm)	Human (cm)+	Diff. (%)	ATD source*
Abdominal depth	15.7	13.6	-15%	p.70
Hip width	21.6	20.2	-7%	p.7, U
Waist circ.	57.2	51.6	-11%	p.7, Z
Sitting height	63.5	61.5	-3%	p.7, A
Stature	114.0	119.5	5%	p.7, Q
Height of pelvis	14.3	13.85	-3%	p.70, 71
Dist. between iliac crests	15.3	12.5	-23%	p.71

+From either the retrospective radiology measurements shown in Table 1 or the prospective anthropometrics study
*Page number and measurement symbol, if noted, from Hybrid III 6-year-old ATD drawing package

In addition to the project specific relevance of these measures, these data provide critical information regarding belt fit and how that improves with age and booster seat use and will be summarized in a future publication.

Review of the field data provides an understanding of the conditions in which abdominal injury occurs in seat belt restrained children. An important finding is that abdominal injuries can occur in low severity crashes with little injury to the other restrained occupants as illustrated by Case #1. The delta v in this case was 20 kph and all other restrained occupants (driver, right front passenger, booster seat restrained rear seated child) sustained either no injuries or only bruising and contusions.

In almost all of the cases reviewed, the abdominal injury was due to compression by the belt. It varied whether that compression was due to the lap belt or the shoulder belt depending on the likelihood for submarining. This is illustrated in case #3 where the child was restrained by an automatic shoulder belt and manual lap belt. The position of the shoulder belt and the lap belt anchors was more aft than in a traditional manual lap and shoulder belt. Substantial submarining occurred in this case and both belts played a role in loading the upper abdomen and thorax as evidenced by the spectrum of injuries: liver and spleen lacerations, rib fractures, and a lung contusion. The role of belt compression as the mechanism of injury confirms the hypothesis highlighted in the introduction that the injury measure needed to accurately reflect abdominal injury risk for children should be deflection based, as has been suggested for adults.

Review of the possible kinematics in these cases suggested three distinct patterns of movement in the crash. Not all children sustained their abdominal injury through the jackknifing over the seat belt, the traditional view of how these injuries occur in children (Weber 2002). Although this was the suggested kinematics for some as evidenced by associated head or facial injury (Case #1), some children were injured due to poor initial belt placement (Case#2) and some were injured due to classic submarining, where the belt starts in position and the pelvis moves under the belt with the torso reclined (Case #3). In those cases with poor initial belt placement, these children were often restrained by a manual lap belt and were scooted forward on the seat causing the belt to ride high on their abdomen pre-crash. Several of these cases are being modeled using MADYMO in order to more clearly study the kinematics and relate it to the velocity and direction of belt loading, the amount of head excursion and head acceleration. The extreme stiffness of the Hybrid III 6-year-old ATD's abdomen prevents meaningful values of abdominal compression from being extracted from the models.

The necropsy component of this project identified the pig having an age of 77 days and a whole-body mass of 21 kg as the best representation of a 6-year-old human. The finding that both age and mass contributed information to a statistical model of external body dimensions indicates that pediatric pigs, like human children, are not simply scaled-down versions of adults. This supports the necessity of this type of study since scaling adult data to represent pediatric response requires the assumption of geometric similitude.

Since one of the end goals of this project is the development of an abdominal insert having the appropriate structural response, we decided that the geometry and inertial properties of the human were the most important characteristics to match. It should be noted, however, that other markers of development, such as sexual maturity or bone ossification, may not show the same age correlation between humans and pigs.

It is also important to acknowledge that, while the pig is a commonly used and reasonable model of the human for many applications, there are some important limitations for the study of abdominal response to belt loading. The most obvious are the marked differences in pelvic structure. These differences make the pig a poor model with which to study, for example, the kinematics of submarining. This study has therefore focused only on those situations where the belt is initially mis-positioned over the abdomen. There are also some abdominal anatomy differences that are significant. Some of these are discussed in detail by Huelke et al. (1986). In the case of abdominal loading using a pig model, one important factor to consider is the tethering of the abdominal contents. The quadrepedal nature of the pig results in organ tethering that reacts against gravitational forces in the dorsoventral direction, as opposed to the superior-inferior direction in a standing human. Furthermore, the subjects used in these experiments will be tested in a supine position, so the organ geometry will not be an exact match of the seated human's. Another important anatomical consideration is the spleen. In a human, the spleen is shaped somewhat like a fist, while the pig's spleen, which is long and thin, has been described as "tongue-like". The liver is also different in the pig, having many "leaf-like" lobes. Finally, the intestinal structure of the pig is different from the human, primarily in the arrangement of the ascending colon. In the pig, this structure is coiled to form a cone-shaped mass with its axis oriented dorsoventrally. The cecum is at the base of the cone.

The abdominal insert development will follow using the information provided by the aforementioned parts of the study. Specifically, a reusable, rate-sensitive abdominal insert will be developed for the Hybrid III 6-year old child dummy following the development reported by Rouhana et al. (2001). Initial prototypes will utilize equal stress equal velocity scaling for the response. The response data from the porcine tests will be used for the final design.

Based on the field data analyzed to date, the authors anticipate the measurement of abdominal deflection and/or functions of deflection will be important for the injury assessment part of the project. Therefore, initial instrumentation efforts will concentrate on deflection measurements. Data from the porcine study will also be analyzed to confirm that hypothesis and thereby, drive the injury assessment instrumentation included with the new abdomen. If the field accident data or biomechanical data indicate otherwise, the efforts will be refocused.

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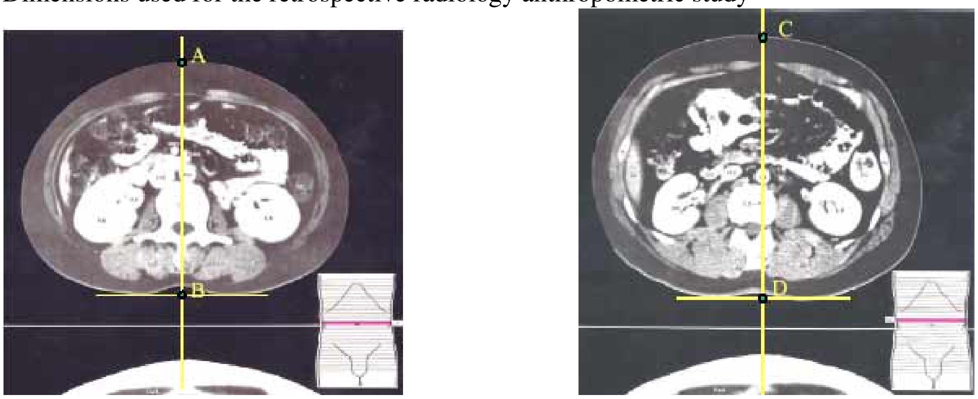
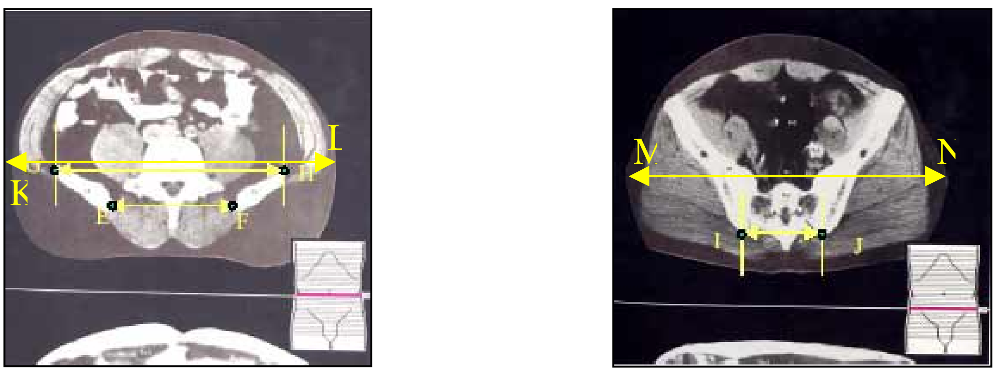
APPENDIX

Dimensions used for the retrospective radiology anthropometric study



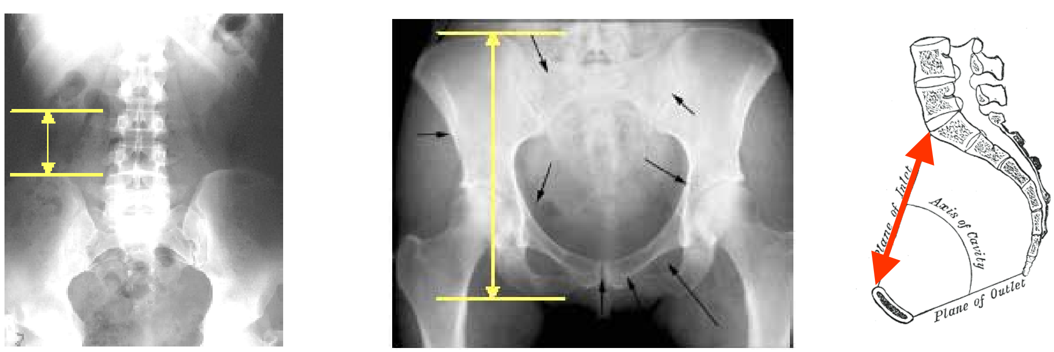
(a) *(b)*

Figure A.1 (a) Depth (AB) and circumference at the level of the umbilicus. For the circumference, continuation across the umbilicus was assumed. (b) Depth (CD) and circumference at the level where the anterior ribs last appear.



(a) *(b)*

Figure A.2 (a) At the level of the first appearance of the iliac crests, the widest transverse dimension of the abdomen (K-L), the inner dimension of the iliac crests (EF), and the outer dimension of the iliac crests (GH). (b) At the level of the largest AP diameter of pelvis, the widest transverse dimension of the abdomen (MN) and the inner dimension of the iliac crests (IJ).



(a) *(b)* *(c)*

Figure A.3 (a) From the abdominal AP film, the vertical distance from the most superior points of the iliac crest to lowest inflection point of 12th rib anteriorly measured on both the right and left side. (b) the vertical distance from the most superior point of the iliac crest to most inferior point of the ischial tuberosity measured on both the right and left side. (c) Distance from the sacral promontory at S1 to the superior aspect of the pubic symphysis in the midline sagittal plane (defined as plane of inlet in figure). Figure from <u>Anatomy of the Human Body</u>, H. Gray, 20th Edition, 2000.

Results of necropsy study

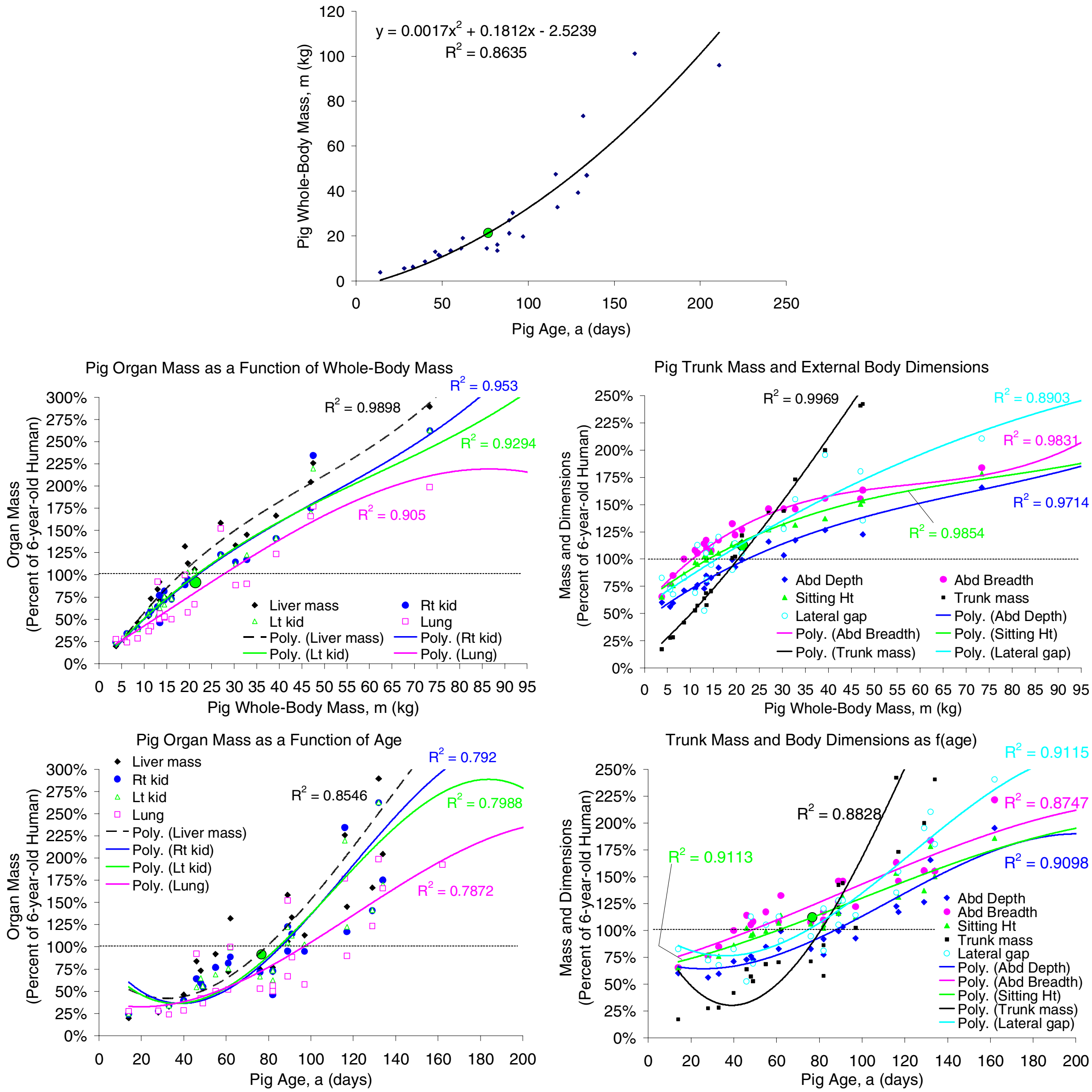


Figure B.1. Results of human-to-pig correlation. Large dot is the subject age and mass identified as the best representation of the 6-year-old human.