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INJURY BIOMECHANICS RESEARCH
Proceedings of the Thirty-Fourth International Workshop

3-D Real Time CT Reconstruction: A Tool for Analyzing CIREN Data

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ABSTRACT

Previous studies have utilized three-dimensional computed tomography (CT) in the evaluation of injury. The CIREN database currently collects two-dimensional x-ray, CT, and MRI data, and 2-D snapshots of injuries, of both hard and soft tissues, are collected and stored in the database. Prior to and during case reviews CIREN centers have at their disposal three-dimensional image analysis tools. These tools are sometimes cumbersome and difficult to use and to quickly view injuries in real time can be very difficult. This is unfortunate given the tremendous insight which can be gained into injury mechanisms by looking at three-dimensional data.

This study presents the use of a combined software and hardware system for the exploration and visualization of three-dimensional CT datasets for the analysis of CIREN data. The benefit of such a system is that 3-D anatomical imagery can be manipulated in real time, and the thresholds and rendering can be adjusted based on feedback from the large number of medical and engineering experts present at case review. Examples from a subset of CIREN cases are provided for children, the elderly, the pregnant occupant, and normal adults. The reconstruction method provides insight into the location and severity of pulmonary contusion, the presence or absence of superficial soft tissue injuries due to restraint loading, or other contacts which are not always present using photographic or two-dimensional radiologic evidence. Three-dimensional visualization of internal organ injuries provides insight into potential mechanisms of soft tissue injury and the interaction of soft and hard tissues of the body during the impact. Examples of reconstructions are provided.

In short, three-dimensional medical image data from patients, particularly those involved in crashes where the crash characteristics are known, may be very valuable as an indicator of direction of impact and severity and mechanism of injury. This is demonstrated through the use of multimedia real-time analyses of injuries for a subset of CIREN cases.

INTRODUCTION

The traditional method of entering radiologic data into the Crash Injury Research and Engineering Network (CIREN) database has been to identify an x-ray or a two-dimensional slice from a CT scan. Often, this is a good way to identify injury and it is the most familiar to many radiologists and surgeons. However, modern technology has advanced to a point where hardware and software solutions are capable of three-dimensional real-time reconstruction of an injury. As CIREN transitions to collecting three-dimensional computed tomography for all CIREN case occupants in 2007-2008, more opportunities will become available to perform the types of analyses outlined in this study.

One of the cornerstones of the Crash Injury Research and Engineering (CIREN) network is the case review. During case review, questions about kinematics of the vehicle occupant, occupant/vehicle contact points, loading direction, etc often arise. In many cases insight into the injury mechanism can be gained from three-dimensional reconstruction of the cases. Looking at the crash occupant with the ability to pan, rotate, and zoom about the site of injury often provides information about the three-dimensional offset of bony fractures, the distribution of diffuse injuries in an organ, and the relative location of adjacent anatomical structures which can provide insight into the mechanism of injury. While both the medical personnel and engineers at a CIREN case review have training in injury mechanisms and anatomy and physiology of injury, the physicians' training and experience is usually more extensive and much more terminology familiar to the doctors is used to discuss anatomical proximity and location of injury, etc. The language for injury mechanisms used to discuss bony injuries can tend to be different between engineers and doctors as well. This difference in training and terminology is often semantic in nature and doesn't represent a fundamental misunderstanding by either group of experts. Often, a good three-dimensional picture of the injury can allow the engineers to agree on the nature of an injury, and is a great facilitator of communication. For the CIREN center at Wake Forest University, the use of these images and the explanations and training provided to the case review team while viewing and discussing the injuries has helped the relationship that the disparate professions have during case review.

In this study we will outline briefly, from a layman's perspective, the approach utilized in the reconstruction of computed tomography (CT) images in general, and show and discuss an image for several body regions ranging from the head to the foot. We hope to demonstrate the utility of the approach and method and to highlight its usefulness in biomechanics research.

METHODS

To understand the way three-dimensional image reconstruction works, some background on the Hounsfield unit system (Hounsfield, 1973) and some standards for attenuation of various soft tissues will be outlined. Then, different body regions will be highlighted with an example of the information to be gained from each image.

Background on Computed Tomography Data

Virtually all Level I and Level II Motor Vehicle Trauma trauma victims coming to most Level I trauma centers get a Head, Cervical Spine, Chest, Abdomen, and Pelvic CT. In some hospitals the abdomen CT includes the Chest, Abdomen, and Pelvis. In special cases of severe lower extremity injury, a CT is obtained of the leg and/or lower extremity. A standard slice thickness differs between hospitals but may be as an example 1.25 mm in slice thickness and 0.48 x 0.48 mm/pixel or 0.625 x 0.625 mm/pixel. Such a CT is taken all at once either before surgery if the patient is properly stabilized or after surgery if a patient has medical symptoms sufficient to diagnose a severe injury needing immediate repair after establishing an airway. Therefore, most CIREN patients have a CT though at the time of this paper, those CTs are not collected in the CIREN database, they exist only at the CIREN centers. During the year 2007-2008 these CTs will be collected and made available to the CIREN community.

In a very basic sense the CT works by sending a beam of x-ray radiation through the patient at a full 360 degrees around the patient and measuring attenuation. The main diagnostic portion of the CT scanner is therefore a donut shape with the x-ray beam and measurement diametrically opposed and moving at high speed as the patient moves on a table to provide z-axis (superior-inferior) slice distribution. Axial slices may be taken, where the patients' table repositions millimeters at a time and the full slice is taken, or helical slices may be taken, wherein the bed moves continuously and the beam runs continuously, allowing a quicker scan albeit usually at the expense of more artifact in the scan. Newer scanners may image 16 or 64 'slices' at a time, meaning that images can be taken very quickly, facilitating quick image acquisition, quicker diagnosis, and quicker treatment.

The CT scan results in a matrix of voxels, each voxel represented by a 2-S distance dependent on resolution in the plane of the image and a 3-D distance represented by the slice thickness. Each voxel has a unit of intensity represented by in the Hounsfield unit system (Ambrose and Hounsfield, 1973; Hounsfield, 1973). At most sites for clinical purposes the CT scanners are calibrated so that for any given scan the opacity of tissue in the scan is known with some degree of certainty. The different levels of attenuation (higher for most solid tissues such as bone and lower for most soft tissues such as fat or muscle, or particularly air) is known.

In most versions of the Hounsfield unit spectrum, the density is assigned a value in a range from -1024 to 3071, which is 4096 distinct values created by 12-bit digital sampling of the analog signal coming from the scanner. ($4096=2^{12}$). In general, the radiodensity of distilled water at standard temperature and pressure (STP) is defined as 0 Hounsfield units (HU). The radiodensity of air at STP is -1000 HU. A standard value generally considered in the range of cortical bone is 1000. A set of standards used as starting defaults in the Tera Recon system software (to be introduced in Methods) is shown in Figure 1.

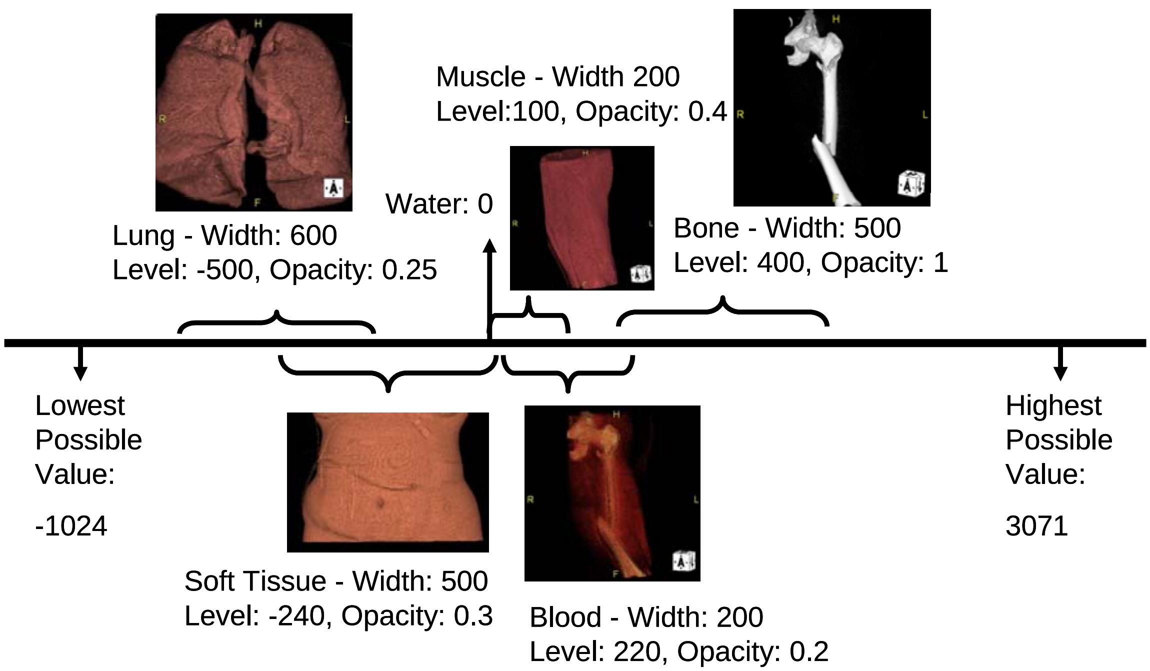


Figure 1: Example Starting Default Hounsfield Unit Range for Some Tissues of Interest.

Methods: Image Creation

In recreating the three-dimensional image, the AquariusNet viewer (Thin Client v 1.7.0.30, TeraRecon, Inc., San Mateo, CA) was employed. This viewer is run on a distributed 100 Megabit Ethernet and connects to an AquariusNet Server. Image stack manipulation occurs on the server, utilizing hardware graphics processing boards which have the capability to render the entire imageset in real time.

In creation of the three-dimensional images, mapping profiles are specified and combined which map varying degrees of color and opacity to different regions of the Hounsfield unit spectrum. Within each window width and level, a right or left recline triangle, an isosceles triangle, a right or left linear ($Opacity_{min}$ to $Opacity_{max}$), a rectangle, or a free curve are employed to apply colors and opacities across the spectrum. All of these options are selectable and various presets are employed for different anatomical features.

However, this study focuses on the end result – the three-dimensional visualization – of the injuries, which is useful for analysis and discussion of injury mechanisms.

During a case review, selections are made based on the presets and adjusted until one is looking at the injury or anatomy of interest. The remainder of this study details some of the insights that have been obtained through the use of three-dimensional real-time image analysis during CIREN case review.

RESULTS

Figures by Body Region

Head - Case Number 1 involves a three year-old male with an AIS 3 Occipital skull fracture. This case occupant has hydrocephaly, and the skull exhibits the characteristic 'beaten copper kettle' appearance that these patients can have (Figure 2a). At the time of review of the case, it was unknown that the child had hydrocephaly, and this comorbid condition helps to understand that it probably contributed to the occurrence of this injury.

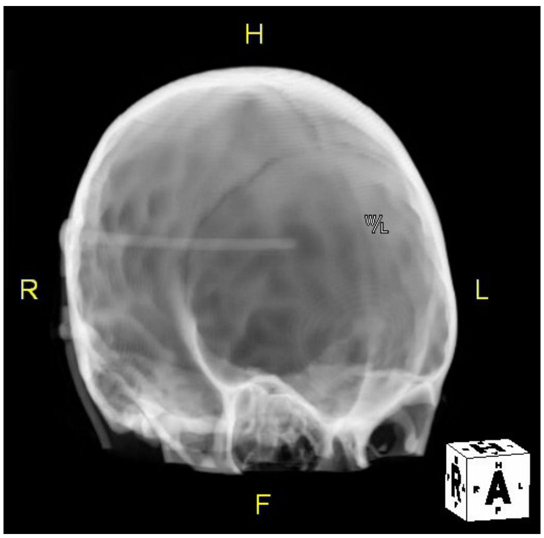


Figure 2a: Appearance of skull of three year-old with hydrocephaly.

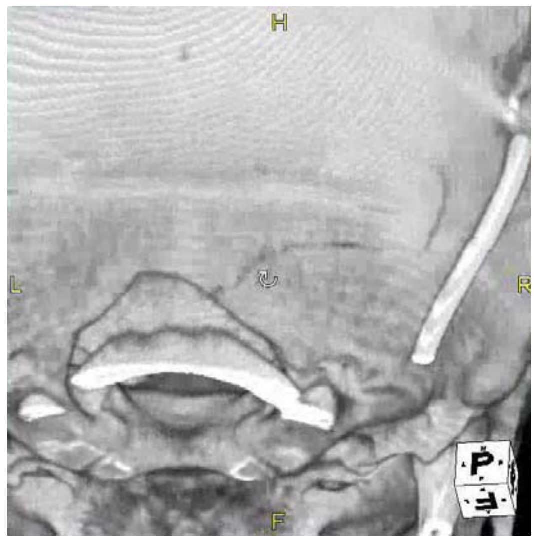


Figure 2b: Occipital skull fx at base of posterior skull.

Neck – Case Number 2 involves a 54 year-old female with bilateral C6 lamina fractures sustained in an impact of her vehicle with a tree (Figure 3a). There was some question with this case occupant as to the location and extent of her fractures, and detailed three-dimensional analysis helped the team to determine the loading mechanism she encountered.

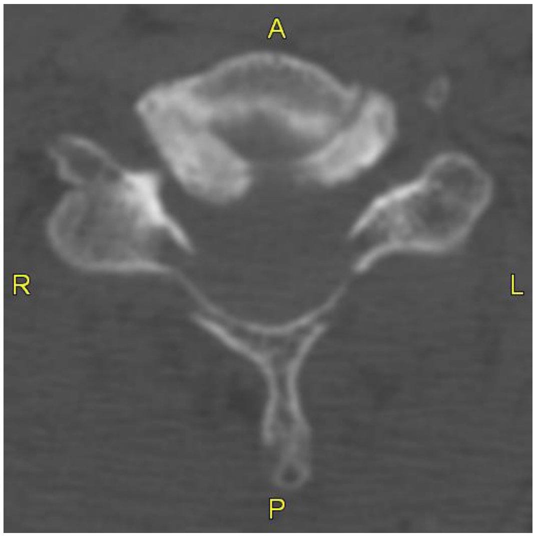


Figure 3a: Appearance of bilateral C6 lamina fractures on transverse x-ray slice.

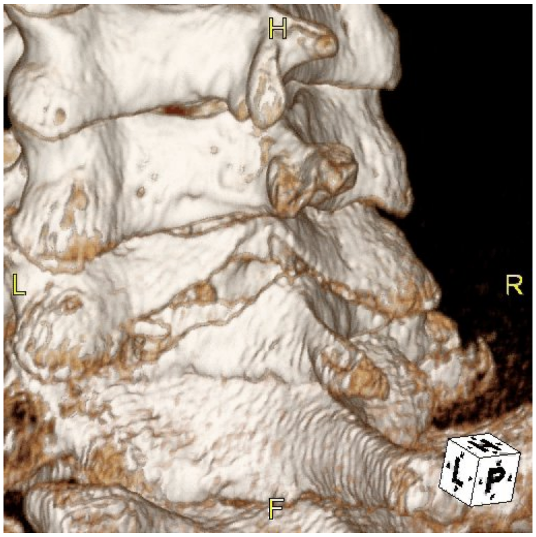


Figure 3b: 3-D appearance of the same fracture showing a V-shaped break through the lamina.

Thorax – Case Number 3 involves a 20 year-old male driver involved in a near side impact, with bilateral pulmonary contusions. Pulmonary contusions are not unusual in a younger person but this case is of interest because it highlights the presence of contusion where the lung interfaces with the internal lateral aspect of the spinal column. The bony structures seem to have influenced the location and pattern of lung injury. The 2-D slice (Figure 4a) shows the pulmonary contusion relationship to the vertebrae relatively well, but the three-dimensional reconstruction of the injury, alternating between showing the spinal column (left) and lung only (right) (Figure 4b) shows the injury pattern very well.

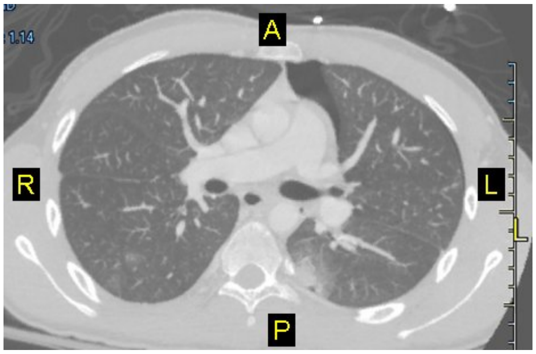


Figure 4a: Appearance of pulmonary contusions in 2-D x-ray slice.

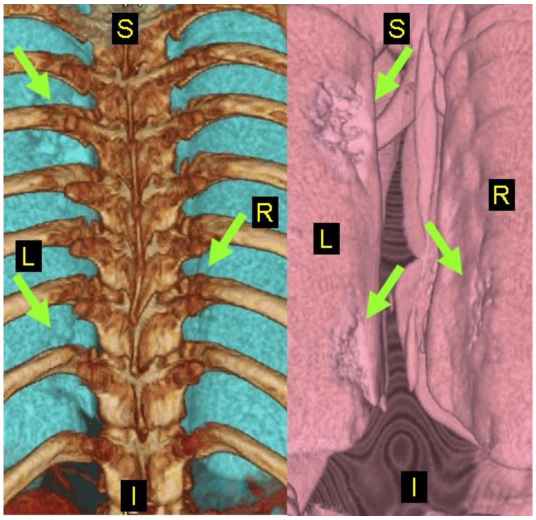
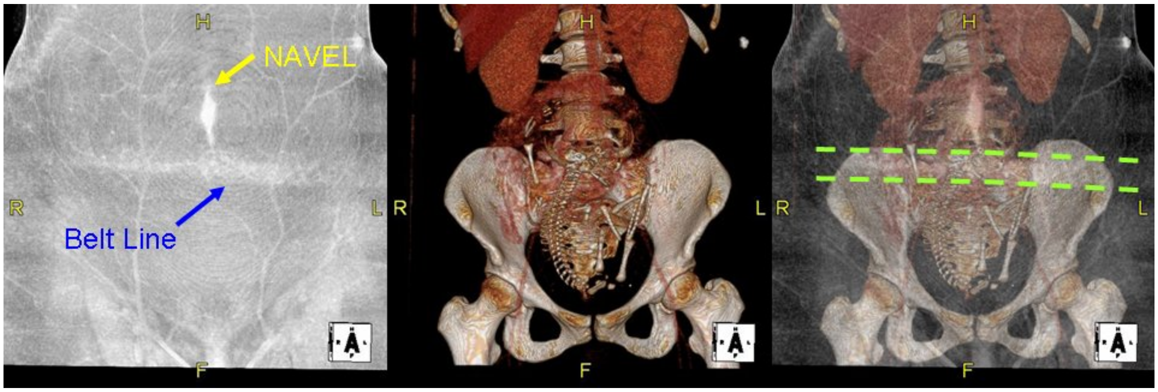


Figure 4b: 3-D appearance of the same pulmonary contusions with and without the spinal column highlighted.

Abdomen – Case Number 4 involves a 26 year-old female driver involved in a frontal impact with a tree, who sustained a left breast contusion (belt), a right lateral 11th rib fracture and left anterior 6th rib fracture, and a right talus fracture. Of interest in this case was the fact that the driver was 27 weeks pregnant at the time of the crash. This case highlights the ability, with three-dimensional reconstruction techniques, to highlight the contusions and soft tissue evidence related to belt use (Figure 5a). It also demonstrates the ability to ascertain the position of the fetus, at least at the time of the CT scan in the trauma center (Figure

5b). Additionally an image overlay visually allows one to approximate the relative location of the belt to the position of the fetus (Figure 5c). Such tools will potentially be helpful in recommending belt use standards for pregnant women.



A — Figure 5a: Appearance of the belt line (subcutaneous tissue opacity) below the navel in a 27 week pregnant occupant.

B — Figure 5b: 3-D rendering of 27 week fetus in utero in this occupant.

C — Figure 5c: Image arithmetic showing belt line on top of child anatomical location.

Pelvis – Case Number 5 involves a 31 year-old female driver with a comminuted acetabular fracture, an AIS 3 injury, and left pubic symphysis diastasis, also an AIS 3 injury. Three-dimensional reconstruction of this injury along with other information helped to determine loading direction and relative ad/abduction of the femur in this case (Figure 6). The severity of the pubic symphysis diastasis was also straightforward to determine and allows the identification of a mobile segment of the pelvis and provides visual information about the direction of relative displacement of the right and left halves of the pelvis.

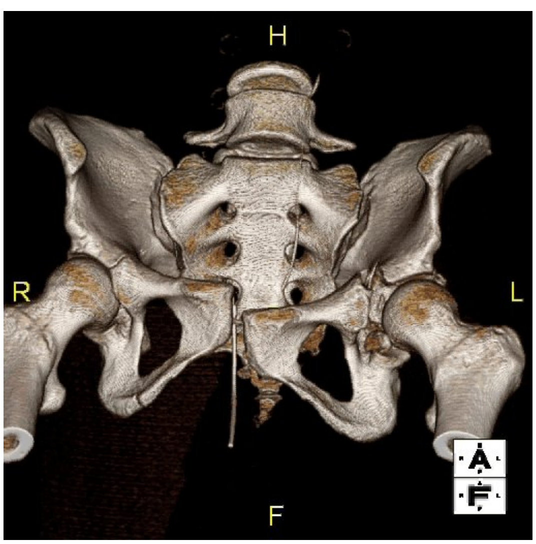


Figure 6a: Bilateral acetabular fractures, pubic symphysis diastasis and sacroiliac joint diastasis.

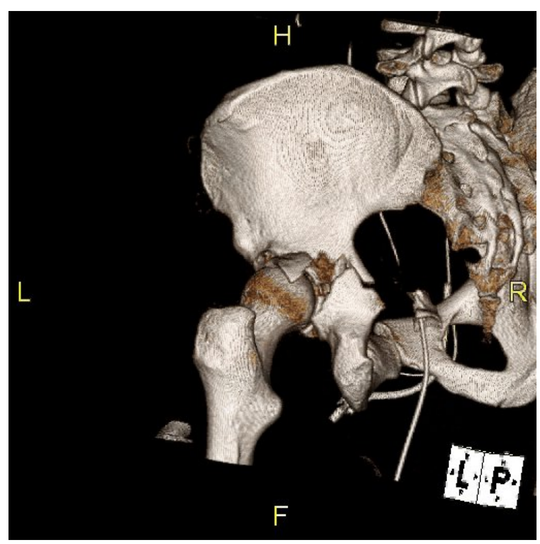
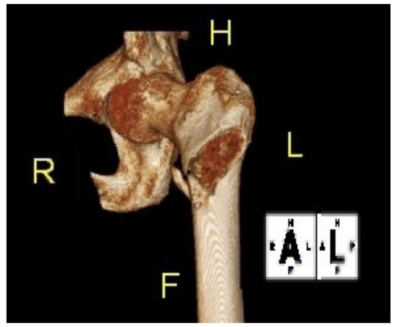


Figure 6b: Posterior view of the left acetabulum, showing comminution and posterior displacement of fragments.

Thigh – Case Number 6 involves a 71 year-old male involved in an offset frontal crash with an AIS 3 femur fracture. This fracture demonstrates two breaks due to one loading. It is a segmental intertrochanteric midshaft femur fracture (Figure 7). Being able to visualize the fracture surfaces was a key factor in determining the loading mechanism and reason for the breaks.

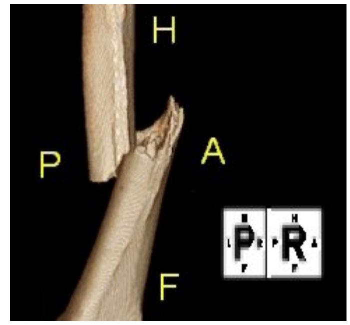
A

Figure 7a: Segmental intertrochanteric midshaft femur fracture.



B

Figure 7b: Superior portion of fracture showing shearing of broken surfaces.



C

Figure 7c. Inferior portion showing an oblique and spiral component to fracture.

CONCLUSIONS

While two-dimensional images are most often used for diagnosis of injury by a radiologist, three-dimensional images have been highly effective for visualizing the injuries in CIREN case reviews. The ability to interactively work with three-dimensional images of injuries in real time has improved communication between the doctors and engineers and other personnel in CIREN case review. Such a tool may be an ideal method to gain insight into injury causation and consequences of injury.

Limitations to three-dimensional image analysis will always exist. Three-dimensional reconstruction of images taken by CT at 3-5 millimeter spacing and greater tend not to create very good three-dimensional images, and have been less useful. This is the case for some of the scans obtained from outside Level I trauma centers, which do not perform CT scans on trauma patients as frequently. Soft tissue injuries have been more difficult to visualize in three dimensions, but this will improve with time. At the current time, the most effective method has been to use three-dimensional reconstruction of images which employ a grayscale color scheme (as used in 2-D slices). This preserves opacity of more of the HU spectrum and techniques such as slab rotation through the center of the organ can be more effective. Many types of tissues of course share similar ranges of Hounsfield units (one of the reasons contrast is used), and this makes tissues of similar radiodensity difficult to distinguish particularly when windowing and leveling is applied.

However, three-dimensional reconstruction by CT in real time has been a highly effective tool for understanding injury patterns and has provided new research questions and will continue to be something that can be used to better understand injury, and therefore better predict and prevent injury.

ACKNOWLEDGEMENTS

Work was performed for the Crash Injury Research and Engineering Network (CIREN) Project at Wake Forest University School of Medicine in cooperation with the United States Department of Transportation/National Highway Traffic Safety Administration (USDOT/NHTSA). Funding has been provided by Toyota Motor North America Inc. under Cooperative Agreement Number DTNH22-05-H-61001. Views expressed are those of the authors and do not represent the views of any of the sponsors or NHTSA.

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DISCUSSION

PAPER: **3-D Real Time CT Reconstruction: A Tool for Analyzing CIREN Data**

PRESENTER: ***Joel Stitzel, Wake Forest University School of Medicine***

QUESTION: *Hans Delye, Catholic University of Leuven, Belgium*
I have two concerns about your talk, being an M.D. and an engineer: It is true that two-dimensional images are essential actually for diagnosis and three-dimensional images really give very nice images and are better for understanding the mechanisms and all that. But, don't you think that putting every patient through a CT scan, not only of the head but also the thorax and the abdomen, will firstly increase the costs to extreme high amounts and second, to put some patients into danger of being radiated too much, for instance, a pregnant lady, which is actually not necessary for medical treatment but gives nice images for the biochemical kind of thing?

ANSWER: There's a couple things going on here. I'm not really qualified to answer that question in great medical detail. That's something that doctors debate all the time—the radiologists and surgeons debate all the time. All the patients that we get in this come in as a Level I or II trauma code. Oftentimes a Level I, they're bleeding. They need to get them stabilized, figure out if they need to have their spleen out or not, if they need to have their pancreas resected at 50% or not, and this is a life-and-death decision. So as soon as they get them scanned, they need that information.

Q: Actually, because it is a life-threatening procedure, you don't have time to go to the scan and there are far more easier--

A: And that's a clinical call that the doctors make.

Q: Yeah, it is.

A: I mean they do administer treatment as needed. But I myself am not a surgeon who could give you—or a surgeon or the ED doctor who could give you a much better answer to that question.

Q: And do you know anything about the cost?

A: I don't. I know about radiation dose to speak to that: that these are 64-slice scanners that give much less radiation for this amount of information that we get than our previous 16-slice did. The cost, I know, is billed at some rate and usually reimbursed from 20 to 15% to nothing. And often, these trauma patients have—there is no reimbursement. So, there's a lot of cost but no, no payment for it, which is fine. I mean, the system is in place to help people who are going to die.

Q: Thank you.