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The dynamic response characteristics of traumatic brain injury

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ABSTRACT

Traumatic brain injury (TBI) continues to be a leading cause of morbidity and mortality throughout the world. Research has been undertaken in order to better understand the characteristics of the injury event and measure the risk of injury to develop more effective environmental, technological, and clinical management strategies. This research used methods that have limited applications to predicting human responses. This limits the current understanding of the mechanisms of TBI in humans. As a result, the purpose of this research was to examine the characteristics of impact and dynamic response that leads to a high risk of sustaining a TBI in a human population. Twenty TBI events collected from hospital reports and eyewitness accounts were reconstructed in the laboratory using a combination of computational mechanics models and Hybrid III anthropometric dummy systems. All cases were falls, with an average impact velocity of approximately 4.0 m/s onto hard impact surfaces. The results of the methodology were consistent with current TBI research, describing TBI to occur in the range of 335–445 g linear accelerations and 23.7–51.2 krad/s^2 angular accelerations. More significantly, this research demonstrated that lower responses in the antero-posterior direction can cause TBI, with lateral impact responses requiring larger magnitudes for the same types of brain lesions. This suggests an increased likelihood of sustaining TBI for impacts to the front or back of the head, a result that has implications affecting current understanding of the mechanisms of TBI and associated threshold parameters.

1. Introduction

Traumatic brain injury (TBI) is a significant cause of morbidity and mortality around the world. In the United States alone, 1.7 million Americans sustain some type of TBI annually, which are represented as 275,000 hospitalizations, 1.3 million emergency room visits, 52,000 deaths, and 124,000 disabilities (Rutland-Brown et al., 2006; Faul et al., 2010). These head injuries represent one of the leading causes of mortality and morbidity in adults up to the age of 45 in the United States (Centres for Disease Control and Prevention, 2011). Past research has increased the understanding of the mechanisms of injury for TBI to develop more effective environmental and clinical prevention and treatment strategies (Kleiven, 2007; Deck and Willinger, 2008).

The current understanding of the mechanisms associated with TBI is based upon research that was conducted in the 1960 s through to the 1980 s using simple physical models, cadaveric impacts, and primates (Gennarelli et al., 1971, 1972, 1979, 1981; Gennarelli, 1983; Gennarelli and Thibault, 1982; Gurdjian and Gurdjian, 1975, 1980). Much of this extensive work focused on the magnitude and duration of linear and rotational acceleration from non-impact and impact events and how they related to the mechanisms of injury for TBI. While this research provided considerable insight into TBI, it was conducted using non-human models. These non-human methods provided threshold of injury parameters for brain injury but severely limited the transferability of the results to humans (Ommaya, 1985; Doorly and Gilchrist, 2006; Yoganandan et al., 2011). In particular, any threshold parameter to predict TBI was scaled from brains much smaller than the human brain, leading to difficulties in applying the risk metrics to human populations as well, while some of the brain tissue characteristics of the animal models were similar to those of human, they were anatomically and geometrically different,

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creating uncertainties surrounding the mechanisms of injury linked to TBI. While cadaveric research provides an accurate representation of the human head and brain geometry, it suffers from limitations surrounding the methods used to characterize brain tissue and changes in human brain tissue and vasculature after death (Prange and Margulies, 2002; MacManus et al., 2014). Some researchers attempted to account for these limitations by using finite element models of the human brain to further the understanding of TBI (Huang et al., 1999; Kleiven, 2003), however these models were simulations and not reconstructions of events that occurred in reality and thus had limited application to describing TBI risk in the living human being.

While this large body of TBI research has limitations it did provide the following knowledge: a linear acceleration based threshold around 300 g would lead to skull fracture or other form of TBI (Hoshizaki and Brien, 2004; Yoganandan and Pintar, 2004). This use of a blanket threshold for all brain injuries within the category of TBI based on linear acceleration (subdural hematoma, epidural hematoma, contusion, and others) is limited as these injuries all involve different anatomical parts of the head/brain and likely have differing mechanisms of injury (Post et al., 2014a). Several researchers suggested that TBI injuries such as subdural hematoma demonstrated a directional sensitivity (Gennarelli et al., 1972; Zhou et al., 1995; Huang et al., 1999; Kleiven., 2003). Since that original research describing TBI injury thresholds and directional sensitivity, there has been no research confirming these effects on human subjects, reflecting the difficulties in obtaining real world accident data. Research investigating TBI using human subjects will provide a means for evaluating the accuracy involving existing models. The purpose of this research was to investigate the influence of event characteristics such as impact direction on the risk of TBI for reconstructions of real-world head injury events for a human population.

2. Material and methods

Medical doctors at participating hospitals (Hull Hospital and the Ottawa General Hospital in Canada, and the National Department of Neurosurgery at Beaumont Hospital, in Ireland) identified patients who met the subject inclusion criteria for this research. Each subject was interviewed, reconstructive questionnaire completed (Post, 2013), and informed consent signed. All ethical practices for human research were followed for this study. The questionnaire recorded the characteristics of the impact event to allow for the laboratory reconstructions. As reconstruction information from eyewitness and patient recollections can be fraught with error, stringent selection criteria were applied for subject identification. The inclusion criteria that were required were: age (must be over 18 years of age), sex, mass and height of subject, description of event, impact location, surface, and presence of medical imaging. If any of these inclusion criteria was incomplete or absent, the subject was excluded from the study. There were no exclusion criteria based on sex or mass of subject and as a result male of females of any mass were included in the subject pool. If there were no details describing the impact location or surface, that subject was excluded, as this information is critical for the reconstruction. In addition, subjects must have incurred a TBI injury that was identified and confirmed by radiologist and/or neurosurgeon by computed tomography (CT) or magnetic resonance imaging (MRI) scan within 24 h of sustaining the injury. The incident in which the subject incurred the TBI must have been a fall, without complications such as being pushed or having impacted other surfaces before the head made contact with the ground. The impact location was confirmed by both contusions evident on the scalp by CT scan (Fig. 1) in addition to identification of the site on their head and recorded by physician. In total, over 700 subjects were reviewed from these hospitals and of those only 20 were found to match the selection criteria. This method of collecting reconstruction information from hospital populations has been conducted in the past and has provided results that were consistent with previous human anatomical tolerance levels (Post, 2013; Post et al., 2014a). The subject data collection yielded a variety of TBI (contusions, epidural/subdural hematoma, and subarachnoid hemorrhage), brief descriptions of the falling event and resulting TBI lesions are presented in Table 1.

The reconstructive questionnaire established the parameters used to conduct the Hybrid III laboratory reconstructions of the accidents resulting in TBI. While specifics such as impact location and vector for the impact reconstruction were determined directly from scalp contusions or CT images and recorded on the report form, the head impact velocity was determined through Mathematical Dynamic Model (MADYMO, TASS International, Livingston USA) simulations. Once the parameters including impact location, surface, surface geometry, and head velocity were determined, an instrumented 50th Hybrid III anthropometric dummy headform and neck form was attached to a monorail and used to re-create the impact (Fig. 2). The anvil at the base of the monorail was equipped with the same impact surface as described in the report forms. The Hybrid III headform drop test was repeated three times per case/impact velocity.

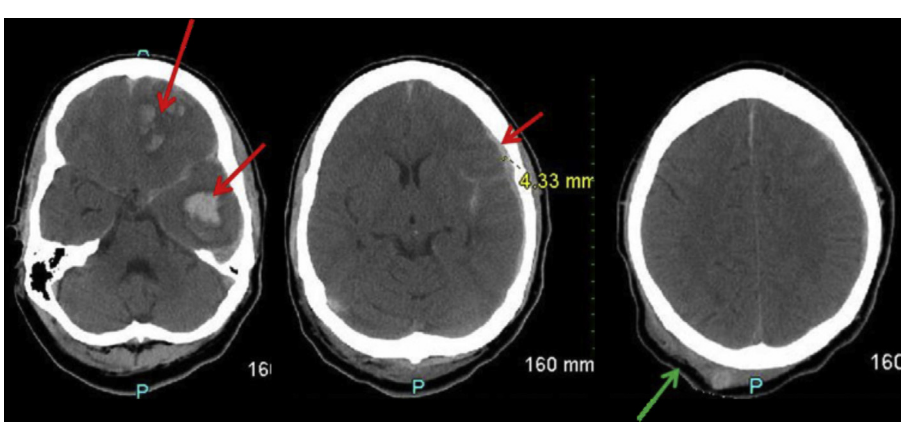

Fig. 1. Computed tomography scans indicating: (red arrows) TBI; and (green arrow) impact location on scalp. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)