IN VIVO MEASUREMENTS OF HUMAN BRAIN DISPLACEMENT

Qiliang Zhu (1), Lawrence Dougherty (2), Susan S. Margulies (1)

(1) Department of Bioengineering
University of Pennsylvania
Philadelphia, Pennsylvania

(2) Department of Radiology
University of Pennsylvania
Philadelphia, Pennsylvania

ABSTRACT

This study investigated the *in vivo* human brain relative displacement with respect to the skull using magnetic resonance imaging (MRI). High-resolution images were acquired at both neck extension and flexion from three healthy adult volunteers. Kinematic analyses clearly revealed relative displacements of the brain with respect to skull as the head position changes.

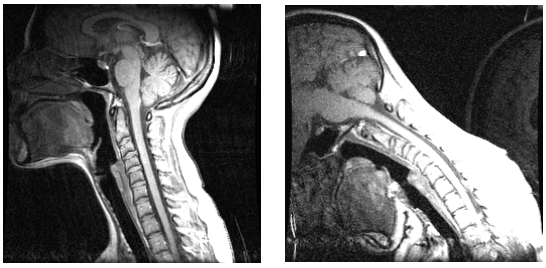
INTRODUCTION

Traumatic brain injuries (TBI) result in a high-rate of mortality and morbidity. The treatment and prevention of TBI require precise understanding of the pathology and underlying injury mechanisms. To this end, finite element method (FEM) has been widely adopted to predict the intracranial stress/strain fields corresponding to various external mechanical loading conditions. It has been long recognized [1] that the accuracy and applicability of FEM largely depend on the accuracy of (1) material property assigned to the brain tissue; and (2) interfacial boundary conditions between the brain and skull. However, while constitutive modeling of brain tissues has been the principal focus in the past, little direct, quantitative experimental data regarding the interfacial conditions was available until recently. Thus the brain/skull boundary has been assigned according to qualitative observation or in effort to match simulations with other easily measurable variables such as acceleration or intracranial pressure.

The relative brain/skull displacement due to traumatic head impact was first directly observed by replacing the convex portion of Macaque monkey skull with a transparent Lucite calvarium and using a high-speed camera [2]. This method, however, requires sophisticated surgical procedures and has been replaced by high-speed x-ray systems. For example, during impact to re-pressurized human cadaver heads [1,3], embedding neutral density accelerometers were tracked by x-ray to record brain motions, from which the brain/skull interfacial condition was deduced. However, all the previous studies required invasive surgeries, and it remains unclear whether relative brain/skull displacements were due to the intrinsic free interface or breakdown of the weak but naturally constrained interface at the time of impact. Therefore, the objective of this study was to directly measure the relative displacement at the brain/skull boundary noninvasively on living human in normal physiological conditions.

METHODS

Experiments were conducted in a conventional 1.5-T whole-body MRI system (Signa; GE Medical Systems, Milwaukee, WI) and approved by IRB of University of Pennsylvania. Three adult volunteers with no history of brain or neck injury or disease were studied. A posterior surface neck coil was used to obtain the images of the lower part of brain. Two 5-mm-thick mid-sagittal images were acquired for each subject at modest neck extension and at full flexion. A spin echo sequence was used, and the acquisition matrix was 256 × 256 with a 24 × 24 cm field of view (FOV) (0.94 mm/pixel), repetition time (TR) of 600 msec, echo time (TE) of 8 msec, and number of signal averages (NSA) of 1. Since the image quality deteriorated significantly with distance from the neck coil, we restricted the region of analysis (ROA) in the area containing brain stem, cerebellum and upper part of cervical spine cord (Figure 1).



(a) (b)

Figure 1. Mid-sagittal MR images at (a) modest extension and (b) full flexion

Image enhancement was performed on all acquired images by first reducing noise in the frequency domain and then enhancing contrast of ROA. Each pair of images at modest extension and full flexion were printed on transparencies and aligned by anatomical features. Kinematically, planar motions of the skull, brain stem and cerebellum can be completely represented by transformation of corresponding coordinate systems, which were obtained by aligning the skull, brain stem, and cerebellum, separately. To minimize the digitization error, ten readings were performed for each image pair. The relative displacements for the brain stem and cerebellum were obtained by subtracting the skull motion.

From these transformations, the relative brain/skull displacements were calculated at three segments on the ventral surface of brain stem and three on the dorsal surface of cerebellum as shown in Figure 2. The motion of the mid-point of each segment was expressed in components along normal and tangential directions.

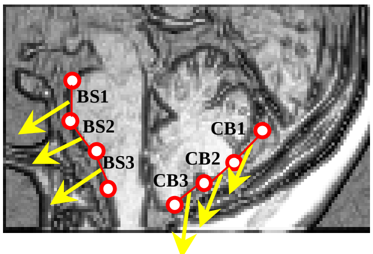


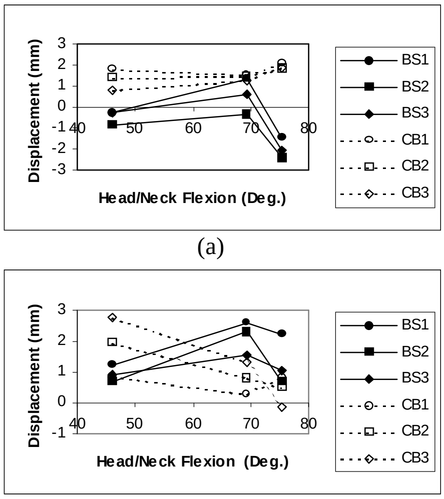
Figure 2. Relative brain/skull displacements of three segments on ventral surface of brain stem and three on dorsal surface of cerebellum were calculated (BS: brain stem; CB: cerebellum): arrows indicate displacement directions

RESULTS/DISCUSSION

It was found that brain moved relative to the skull when the head rotated from modest extension to full flexion (displacement directions indicated by arrows in Figure 2). Head rotation varied by subject, from 45º to 75º. The brain stems of all subjects moved toward the clivus surface. Along the normal direction of each segment, the average displacements of three subjects were 2.03*±0.86, 1.23*±1.10 and 1.17*±0.73 mm for segment BS1, BS2 and BS3, respectively[1]. Along tangential directions of each segment, displacements were scattered in both directions, and thus averaging -0.13±1.43, -1.19*±1.10, and -0.58±1.37 mm, which were not all statistically different from zero, but with absolute values of the displacement on the order of 1 mm. As for the cerebellum, the tangential displacements of each segments were consistently in caudal direction, averaging 1.79*±0.81, 1.57*±0.79, and 1.32*±0.87 mm for segment CB1 CB2 and CB3, respectively; the average normal displacements across subjects were 0.66*±0.59, 1.09*±0.83, and 1.32*±1.34 mm, slightly greater than zero.

The experimental finding directly and quantitatively supports the long-postulated local relative motion at brain/skull interface. Hardy et al. [3] found the relative displacements between the skull and deep brain structures were on the order of ±5mm for low-severity impacts. Since no direct measurement was made on the brain/skull interface, they used finite element method and concluded that FE simulations using a pure slip boundary condition matched the measured relative motions [1].

The relative brain/skull motion can be explained by the anatomic structures. While largely secured by cranial fossae, dura, and possibly also restrained by cranial nerves and blood vessels, human brain is indeed floating inside the pressurized cerebrospinal fluid (CSF)-filled space. While there is only a potential subdural space, the subarachnoid space is real and significant [4]. There are locations known as subarachnoid cisterns, where the arachnoid and pia matters are widely separated. Most significantly, ventral and dorsal surfaces of the brain stem are enclosed by the extensive pontine cistern and the cerebellomedullary cistern. While CSF provides effective damping against sudden intracranial brain motions during head impact [2], the damping effect diminishes when the head undergoes slow motion. With mass density of the brain tissue (1.04 kg/m^3) slightly greater than that of CSF (1.007 kg/m^3), the brain tends to sink in the intracranial space along the direction of gravity, as revealed directly by our experimental findings.



(b)

Figure 3. (a) Tangential brain/skull displacement (positive direction along caudal direction); and (b) Normal brain/skull displacement (positive direction towards the skull)

CONCLUSION

Kinematic analyses of *in vivo* human brain MRI revealed relative brain/skull displacements on the order of 1~2 mm when the head position changes voluntarily. These displacements over the normal range of head/neck flexion suggest free interfacial conditions between the brain and skull.

ACKNOWLEDGEMENT

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[1] * indicates significantly different from zero (p<0.01).