ANALYTICAL BRAIN MODELS FOR HEAD IMPACT

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ABSTRACT

Newly developed finite-element brain models of a small primate, a baboon, and a human, are used to simulate animal and cadaver head impact tests. Response measures of these three-dimensional models are compared to measured brain displacements and recorded pressures. The correlation between measured and computed response is the same in both the live animal and human cadaver tests. Brain displacements are found to be small, and pressure response is quickly damped.

INTRODUCTION

Head injury continues to be the major cause of death in motor vehicle accidents. It is also the leading cause of death for the under-40 age group; yet, human tolerance to head impact has not been established. Little has been learned about the mechanism of head injury, although its tragic effects are obvious. Early experimental research relied heavily on the use of animals, but direct extrapolation of animal injury information to the human is difficult, if not impossible, because of the relative size and intracranial response differences (1). More recently, pressurized cadavers have been utilized with somewhat better correlation; the size difference is eliminated, but the difference in physiological condition must be considered and evaluated. The relationship between injuries produced in the dead brain and those in the living must be established.

Mathematical finite element brain models are utilized to provide relationships between experimental animals, human cadavers, and live human beings. Experimental head impacts and brain displacement tests are simulated on the digital computer using these models. When discrepancies between recorded information and model response occur, the model is redesigned and the simulation repeated. Using this iterative procedure, the models are revised until correlation is achieved. Thus, experimental programs have a direct impact on the design of the models.

ANALYTICAL PROCEDURE

Using three-dimensional isoparametric elements, three brain models have been developed, and are currently being refined (Figure 1-3). Two models; the baboon and small monkey, are used to simulate live animal experiments. The third model, the human, is used to simulate pressurized human cadaver tests and to study human brain response. Each model has approximately the same number of elements and the same number of degrees of freedom (1). The soft tissues and contained fluids in the cerebrum, brain stem, and cerebellum are simulated with 8 node brick elements; the partitioning internal folds of dura, the falx and tentorium, are simulated with 4 node membrane elements. The irregular external shape of each model is defined by the skull inner surface topology (Figure 4). Simplicity of design is emphasized, minimizing the number of variables, assumptions, and materials simulated.

A modified version of the structural analysis program, SAPV, is used to calculate the response. Measured head rotational and translational accelerations and rotational velocities are input to the model instead of forces (2). Since skull-fixed coordinates are used, inaccuracies due to large head displacements and rotations are avoided.

SIMULATION OF EXPERIMENTAL RESEARCH

Animal and pressurized human cadaver head impact tests are simulated and the measured responses (displacements or pressures) compared to the corresponding computed quantities (Figure 5). As more experimental results become available, the models are revised and improved.

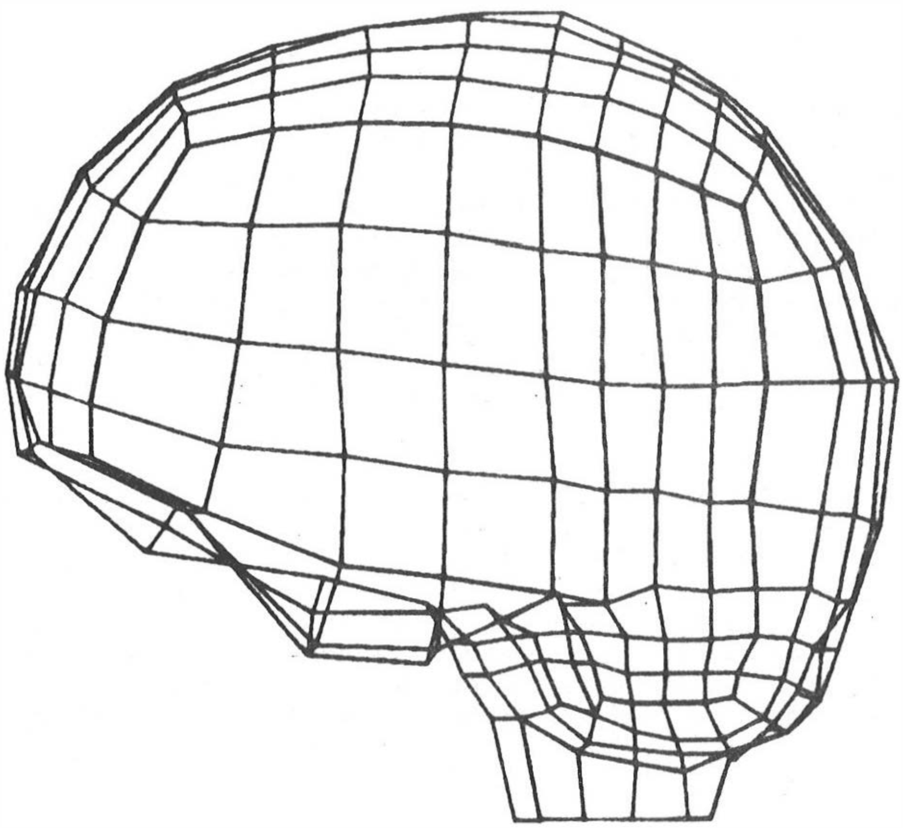

Figure 1. Finite Element Human Brain Model.

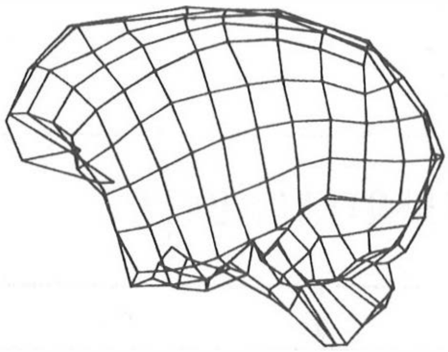

Figure 2. Finite Element Monkey Brain Model.

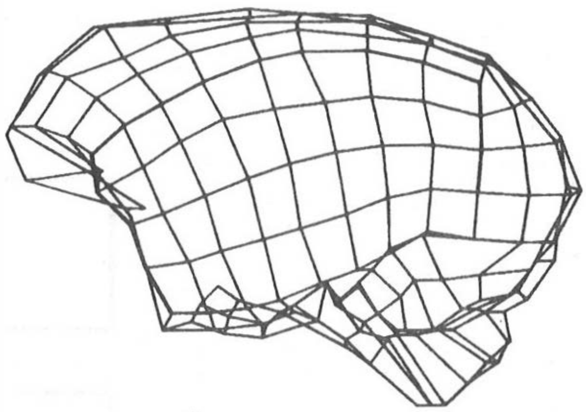

Figure 3. Finite Element Baboon Brain Model.

Brain Displacement Tests. The following dynamic brain displacement tests have been simulated:

1. Lucite-calvarium tests (3)
2. Human cadaver brain surface displacement tests
3. Live animal cinefluorograph tests (4)

In the lucite-calvarium test the skull cap overlying scalp, and underlying dura of a live monkey was removed and replaced with a lucite-calvarium. The motion of the brain relative to the calvarium was observed during impact. The calvarium test was simulated using an early version of the model, which allowed slip along the brain-skull interface (5). The gliding motion of the brain surface was reproduced by the model. However, the human pressurized cadaver tests performed later at the University of California at San Diego (UCSD), showed no measureable displacement along the brain-skull interface during head impact. In the UCSD test series, a small area on the parietal lobe surface was photographed through a plastic insert in the skull. In order to successfully correlate with the cadaver tests, the model had to be revised. Slip along the brain skull interface was eliminated. Lack of measurable displacement was also apparent in the cinefluorograph tests conducted by the Armed Forces Radiobiology Research Institute (AFRRI). In these tests, radiopaque isodense spheres, constructed of hollow lead glass approximately 2 mm in diameter, were injected into the brain. They were placed 10 mm below the outer skull on a line parallel to, and 7.5 mm lateral to the sagittal suture. Lead pellets, 2 mm in diameter, were placed along the same line in the skull to provide a reference. The head was rotated about a right-left axis central to the head. The excitation frequency ranged from 1 to 35 Hz, producing a 3 g acceleration of the pellets. A cinefluorograph system was used to monitor response. No motion of the brain relative to the skull was detected in

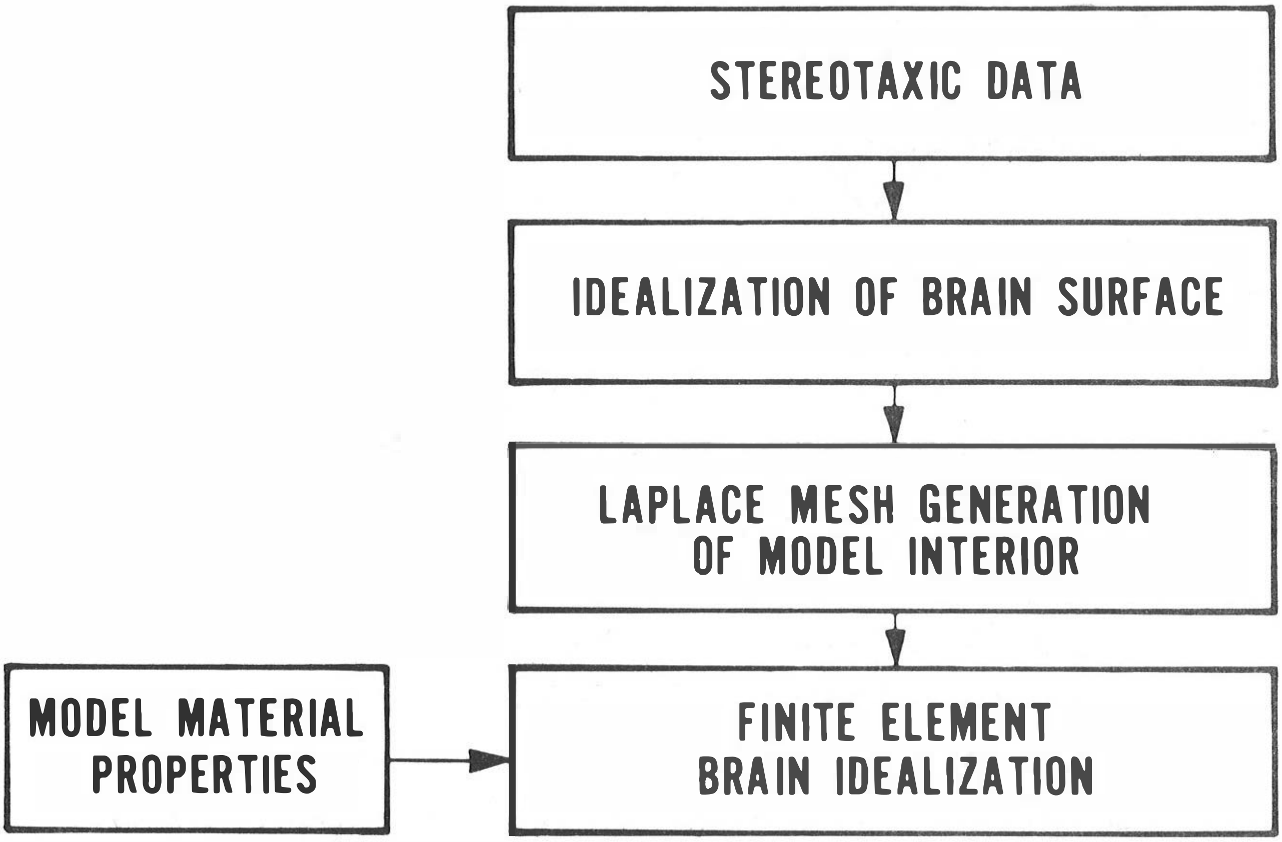

Figure 4. Analytical Program.

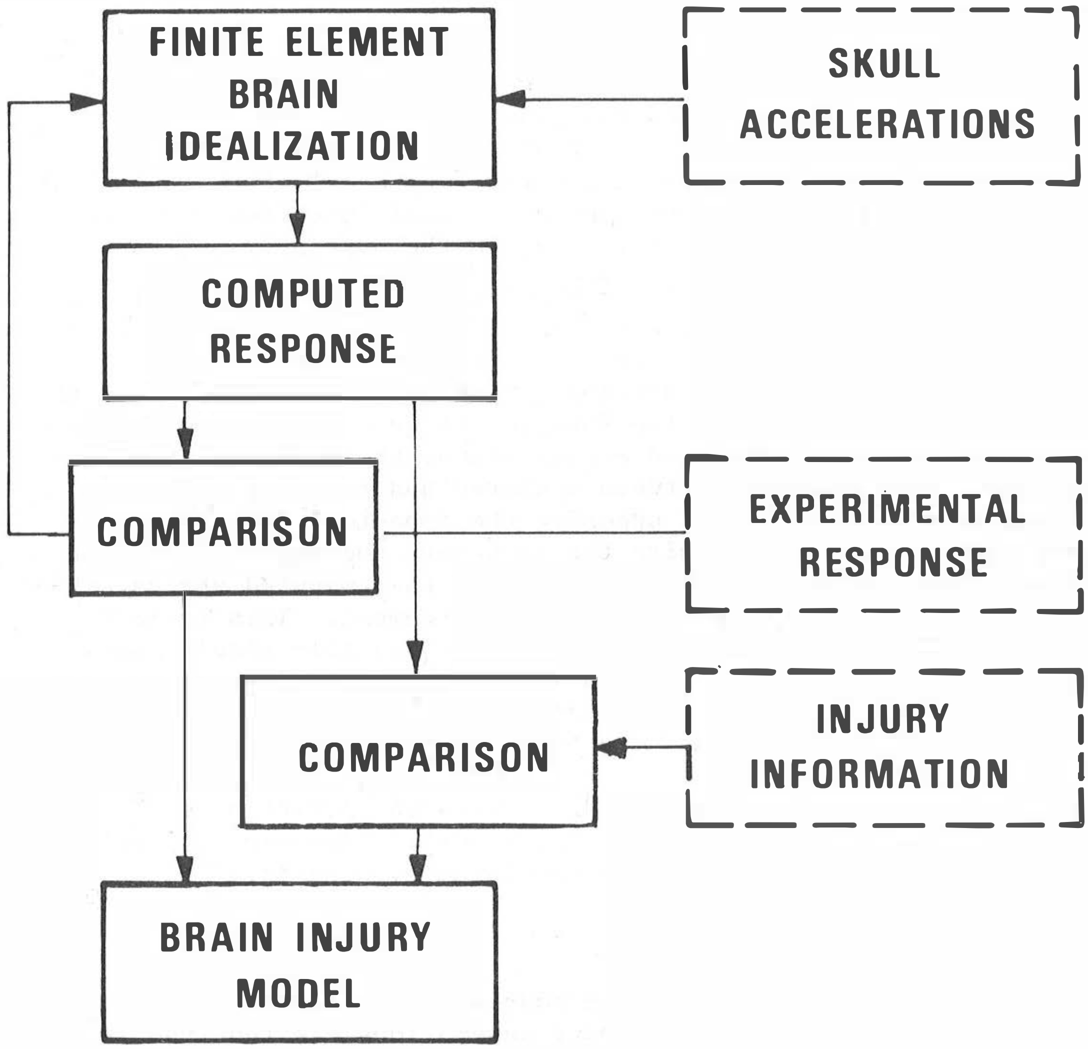

Figure 5. Simulation of Impact Experiments.

the film analysis.* Very small displacements (less than 0.01 mm) were calculated using the revised models in the test simulations. This correlates with the lack of displacement observed in the film.

The cadaver and cinefluorograph tests show that the displacement of the brain relative to the skull along and near the brain-skull interface is very small. It is hypothesized that the removal of the skull cap and connecting tissue in the calvarium test altered the structure to the degree that the response observed is not representative of the normal in vivo state. Therefore, slip along the brain-skull interface, characteristic of the calvarium test, is eliminated in the current models.

Pressure Tests. Live animal and pressurized human cadaver impact tests were simulated, and the measured and computed pressures compared. The experimental programs are outlined in Figure 6. High, short-duration intracranial pressures develop during impact, positive near the impactor, and negative opposite the impactor (Figures 7 and 8). These pressures are produced by the head motion alone; skull deformation is not simulated. The agreement between measured and computed values is good throughout the head (except opposite the impactor) in both the animal and cadaver tests. Opposite the impactor, the magnitude of the measured negative pressure is always less than the computed stress, although there is often good pulse duration agreement. This variation may be produced by a skull response not included in this simple model. The brain displacements referred to in the previous section are further substantiated by these pressure correlations, because the pressures are computed from the relative displacements of the nodes.

A limited number of simulations have revealed that high, positive, and negative pressures correlate with injury (1). More simulations are being made to investigate this injury mechanism hypothesis.

SUMMARY AND CONCLUSIONS

The advantages of integrating the modeling and experimental brain injury research efforts are clear. Many assumptions are required in modeling biological tissue, and correlation with experimental results is the primary factor in substantiating these assumptions. Modeling misconceptions are easily identified and corrected as occurred in the brain displacement tests. When new experiments demonstrated that the relative motion between the brain and skull was small, the model was revised.

The extrapolation of information from one type of test to another, and to the human, is possible using brain models of the test subjects and the human. Although each test subject model has its own response frequencies, the same patterns of pressure and displacement correlation was obtained in both the small monkey and cadaver tests. A similar correlation is anticipated between head impact pressures in the live human being and in the human model.

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*In early tests, lead pellets were used in the brain (4) and displacements were obtained. Apparently, the concentrated mass of the lead pellet and the surrounding soft tissue combined to produce a localized vibration at approximately 20 to 25 Hz.

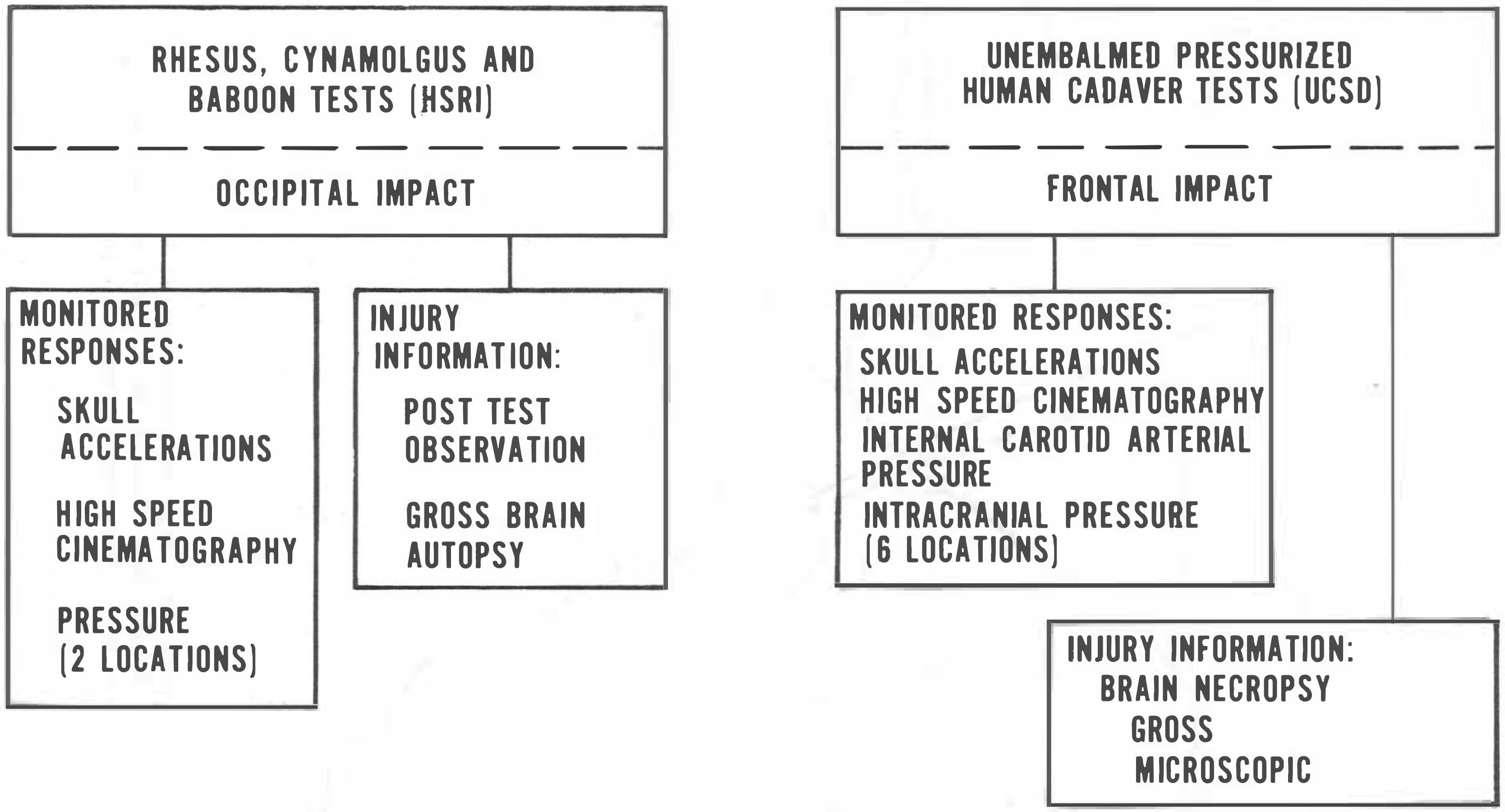

Figure 6. Experimental Program.

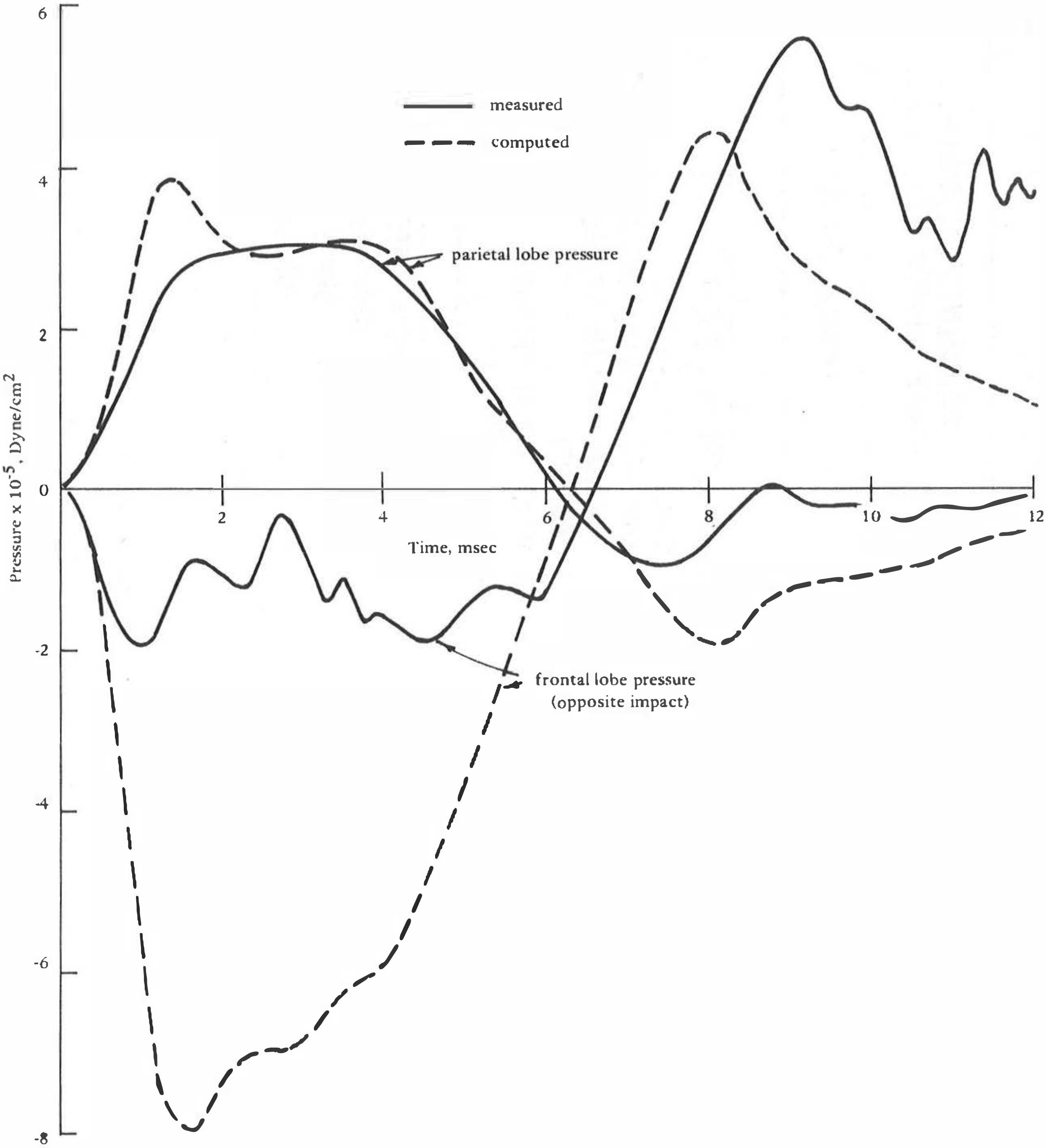

Figure 7. Measured and Computed Intracranial Pressures in Live Monkey Head Impact Test (test no. 084 performed by Highway Safety Research Institute).

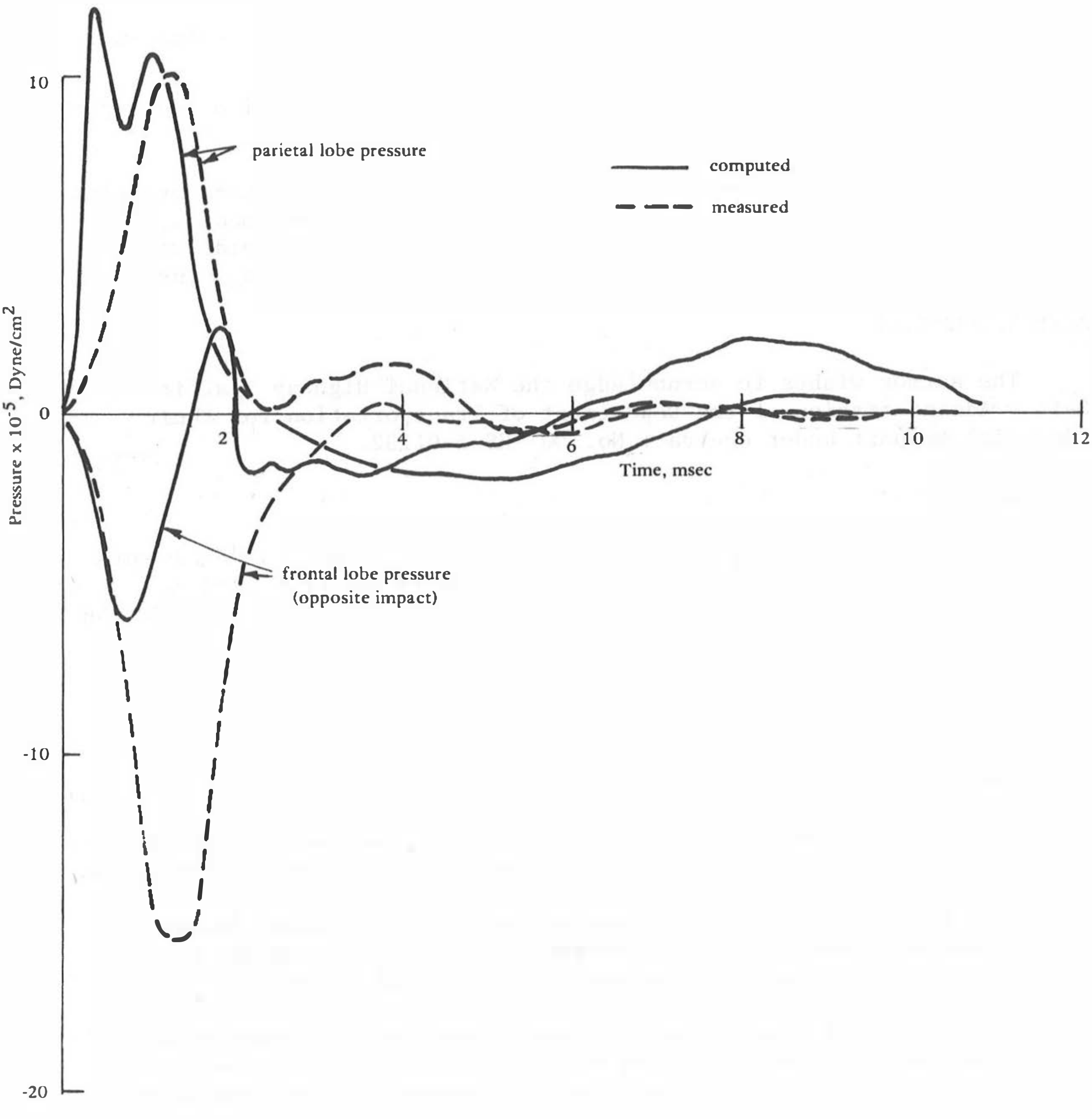

Figure 8. Measured and Computed Intracranial Pressures in Live Monkey Head Impact Test (test no. 085 performed by Highway Safety Research Institute).

The correlation of head impact experimental and computed intracranial responses reveals the following:

1. Displacements of the brain relative to the skull are small on and near the external brain surface.

2. High positive and negative pressures develop in the cerebrum and cerebellum due to head motion.

3. The intracranial pressures are of short-time duration and are quickly damped.

New information has been revealed about the dynamic characteristics of the brain during impact. This study has shown that the models, combined with experimental tests, have the potential to provide valuable data, and to contribute to the future understanding of brain injury.

ACKNOWLEDGMENTS

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