HSRI Report No. UM-HSRI-79-90

COMPARISON OF EPIDURAL PRESSURE IN LIVE ANESTHETIZED AND POST-MORTEM PRIMATES

Guy S. Nusholtz
Jeffery B. Axelrod
John W. Melvin
Biomechanics Department
Highway Safety Research Institute
University of Michigan

and

Carley Ward
Civil Engineering Laboratory
Naval Construction Battalion Center
Port Hueneme, California

November 1979

ABSTRACT

The response of the head to impact in the posterior to anterior direction was investigated with live anesthetized and post-mortem primates.* The study was conducted at the Highway Safety Research Institute under the sponsorship of the Motor Vehicle Manufactures Association. 3-D motion and epidural pressures were experimentally measured. Interpretation of the results by simulating the tests using a 3-D mathematical model of the primate brain was done by Dr. Carley Ward. The results of the tests and the simulation are presented to demonstrate the differences found between live and post-mortem primate brains.

INTRODUCTION

Experimental investigations in the biomechanics of head impact response have used human cadavers and animals as surrogates of the living human. The parameters commonly used for measuring mechanical response during direct impact have been: angular and translational accelerations, angular and translational velocity, displacements, deformation, and pressures. These parameters, once obtained, can then be used in developing and and validating mathematical models of the head.

The unembalmed cadaver is chosen as an experimental model because its geometry and soft tissue distribution is similar to that of the live human. In addition, soft tissue damage can be directly related to injury patterns observed in clinical studies. The disadvantages of the cadaver include the inability to measure pathophysiological response and the susceptibility of some tissues to post-mortem degradation. Also, it had been reported (1)** that during the contact time of direct impact, the

---

*Animals cared for and handled according to AALAC guidelines.

**Numbers in parentheses indicate reference at the end of paper.

motion of the brain of the unembalmed cadaver is only partially constrained by the skull. The degree of constraint can depend on the time after death and preparation of the cadaver. This partial decoupling can have a marked effect on kinematic time histories of the head during and following impact.

Experimental impact testing of animals, in particular primates, provides basic neurophysiological information related to neuropathology. However, although the primate geometry is the most similar to man's, it is significantly different in anatomic soft tissue distribution and skull morphology. This can present severe problems when scaling test results to human levels. Ultimately these differences lead to complications in the very complex phenomena of head injury (2).

Mathematical models can be used to interpret the results from impact tests and they can provide information at locations in the brain where measurements are impossible, giving a more complete picture of the response. Models are also helpful in extrapolating the animal findings to the human and allow for a minimum use of live animal subjects.

Techniques have been developed in the past few years for accurate determination of three-dimensional motion of the head (3,4,5,6,7,8), preparation of the unembalmed cadaver (1,9,10), and creation of biodynamic finite element models (11), for use in brain injury research. This report discusses the techniques for conduction posterior to anterior head impacts with primates, while measuring three-dimensional motion and epidural pressure. In addition, the basic features of the mathematical model of the primate brain are given and the results of the simulation are used in interpreting the test results.

METHODOLOGY

Three-Dimensional Motion Determination

The HSRI method used for measuring the three-dimensional motion of the head is based on a technique used to measure the general motion of a vehicle under a simulated crash (12). In the current application, three triaxial clusters of Endevco series 2264-2000 accelerometers are affixed to a light-weight rigid magnesium plate (Fig. 1) which is then solidly attached to the skull. The nine acceleration signals are used for the computation of the three-dimensional head motion.

With this method, it is possible to take advantage of the physical and geometrical properties, as well as the site of impact, in the design of a system for measurement of 3-D motion. In the case of small primates, it is more convenient to design a specific system for each species and site of impact. A system was designed and constructed at HSRI, utilizing a light-weight magnesium plate to mount 9-accelerometers; to be used for the Macaca primates. The prominent orbital ridges and dental plate found in this genus were used to install the rigid plate. Using a multi-point attachment scheme, it is secured at a maximum distance from the point of impact.

Epidural Pressure Measurement

HSRI developed a method for obtaining epidural pressures which employs a Kulite model MCP-055-5F catheter tip pressure transducer. A Stryker bone-coring tool is used to make the hole. A special 3 mm circular bit (Fig. 2) with an adjustable set-screwed collect was machined which enabled the technicians to core into the skull in small increments, preventing a dura damaging breakthrough. The increment of the bone core is then

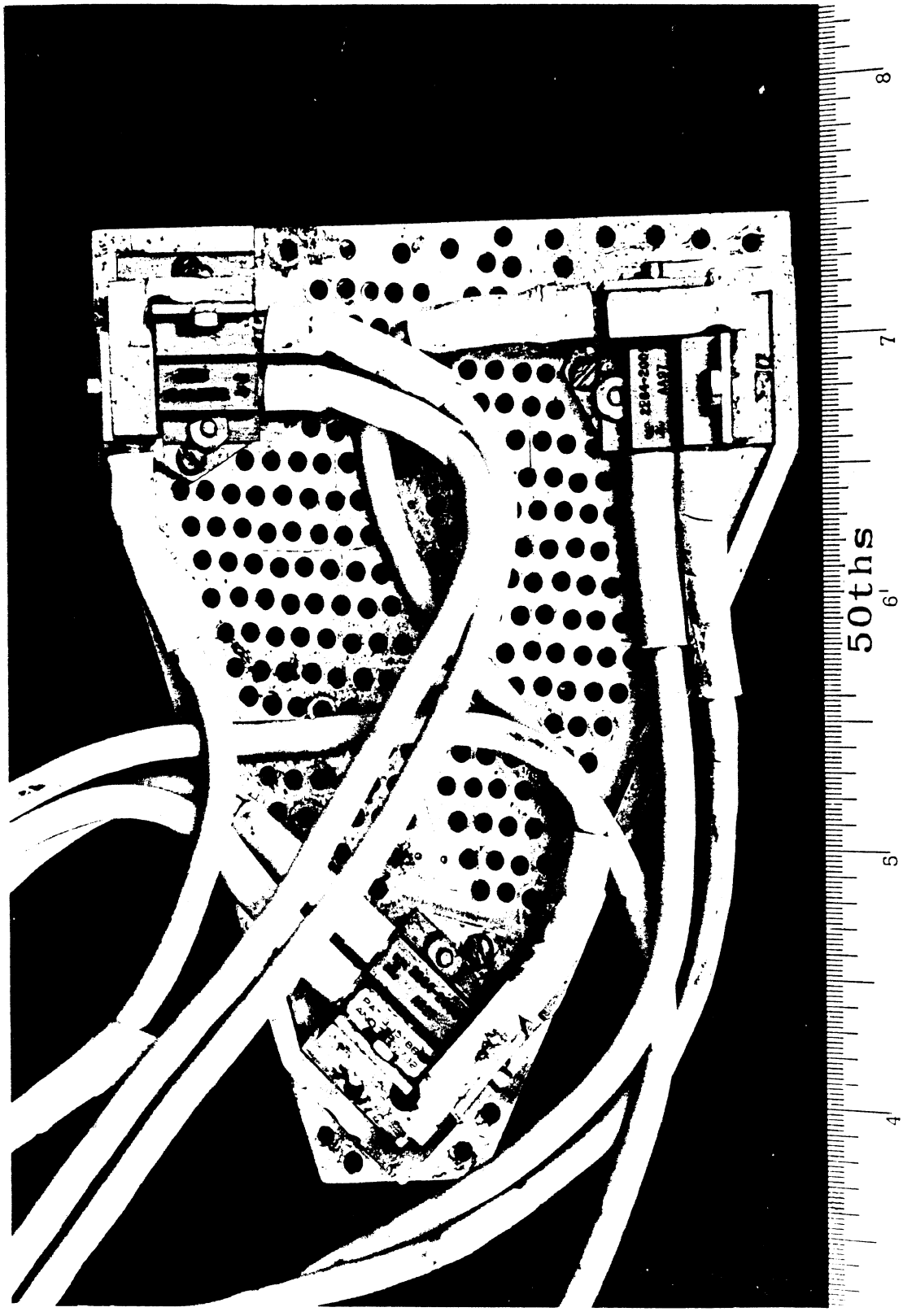


FIGURE 1. 9-Accelerometer Plate

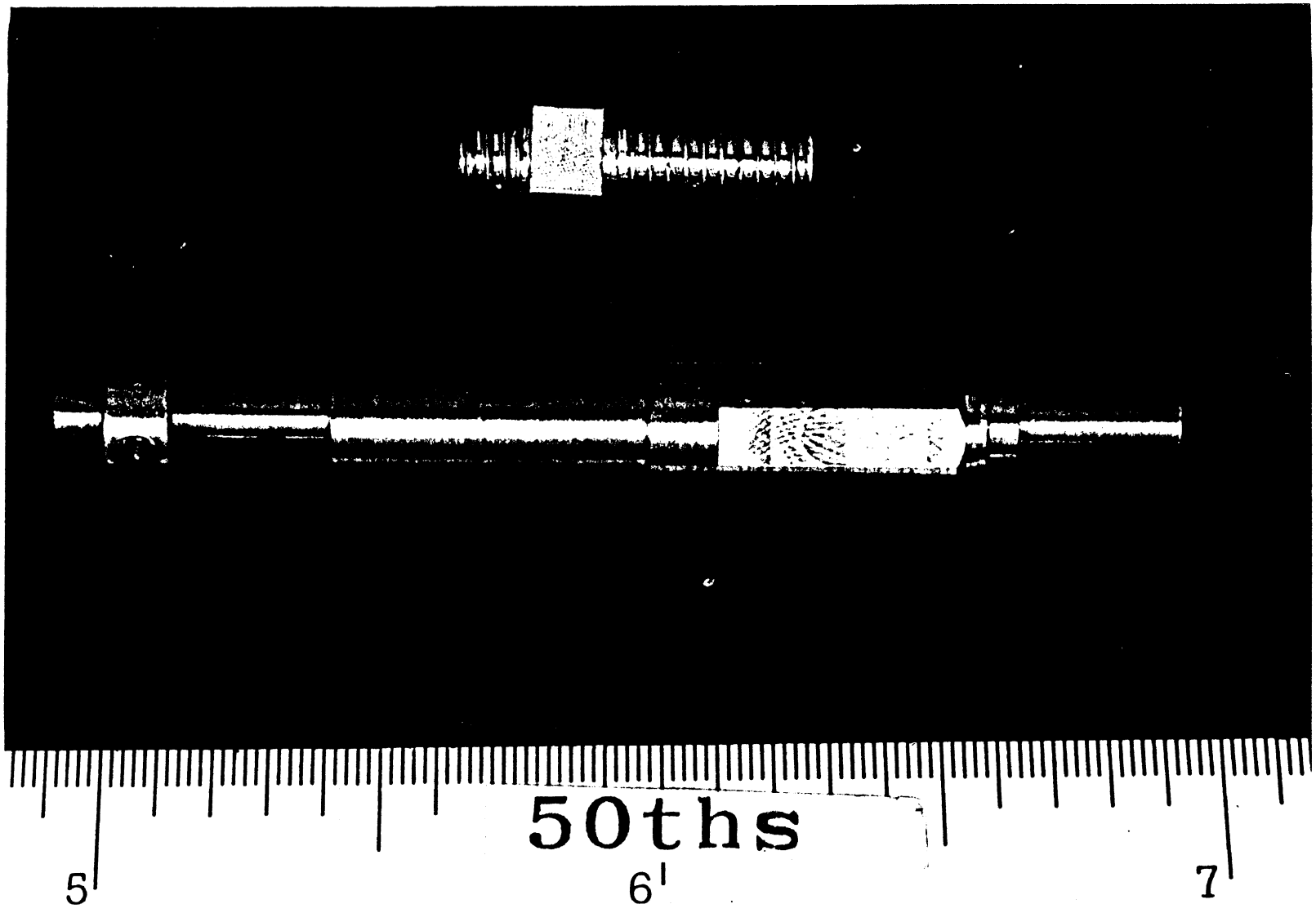


FIGURE 2. Coring Tool and Epidural Coupling Device

removed using a dental scoop. The resulting hole is then tapped.

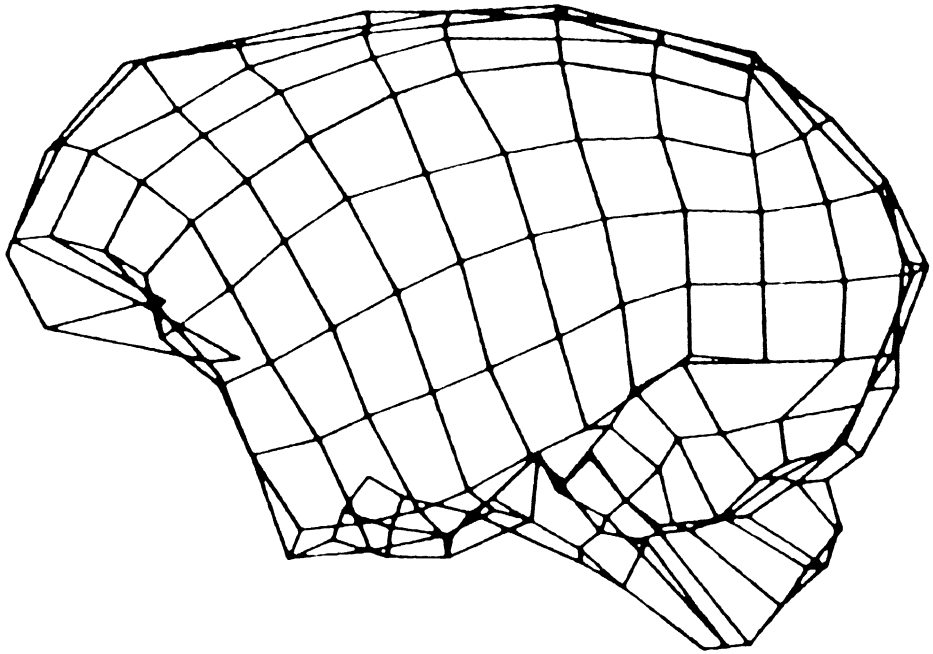
A magnesium coupling device (Fig. 2) is screwed into the cored and tapped hole. It is anchored into place using a quick-setting acrylic molded around the base. A five cm section of rubber tubing is then clamped onto the top of the device and Dow Corning dielectric gel (silicon fluid) is injected into the tubing to act as a coupling media. The Kulite pressure transducer is then inserted, and secured at proper depth.

Finite Element Models

The tests are simulated using three-dimensional mathematical models of the monkey brain. Small primate models of this type were first described in Ref.(11) and are shown in Figures 3 and 4. The soft brain tissue and fluids are modeled using isoparametric brick elements. The internal membranes, the falx and tentorium, are modeled using membrane elements. The input to the model is linear acceleration, angular acceleration, and angular velocity computed from the 9-accelerometers. In other words, the models are mathematically forced to move just as the head moved in the test. Computational improvements reported in Ref. (13) were incorporated into the models. In addition to these changes, simulation of this test series required two new modifications. A 20 cm cervical cord was added for some simulations and the Poission's ratio was varied from .499 to .4999, varying the effective compressibility of the brain. In each simulation the model was scaled to approximate the size and weight of the actual brain.

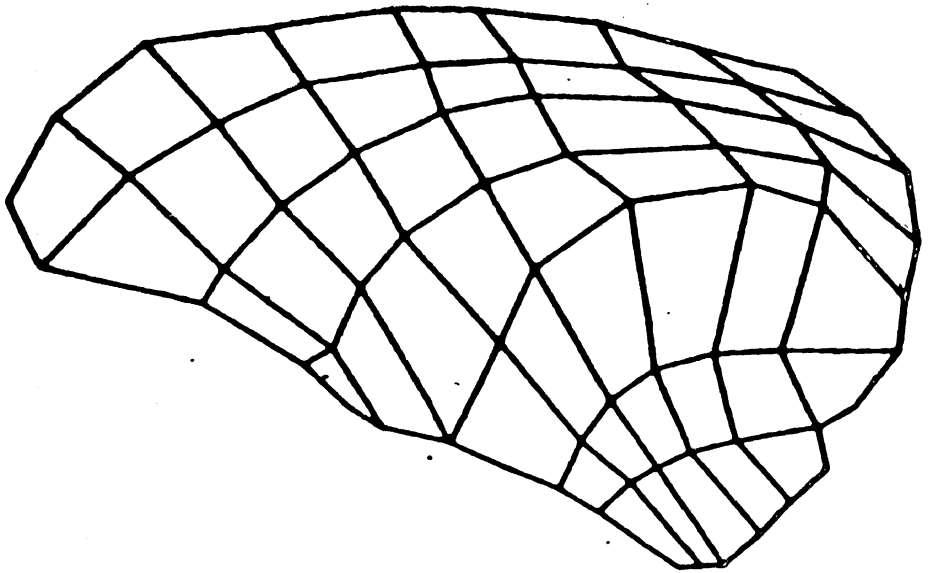
Test Subject Preparation

Five primate subjects were used in these experiments: four Macaca Mulatta and one Macaca Assamensis. These were obtained by HSRI from the



FINITE ELEMENT MONKEY BRAIN MODEL

FIGURE 3



MONKEY BRAIN
MID-SAGITTAL PLANE

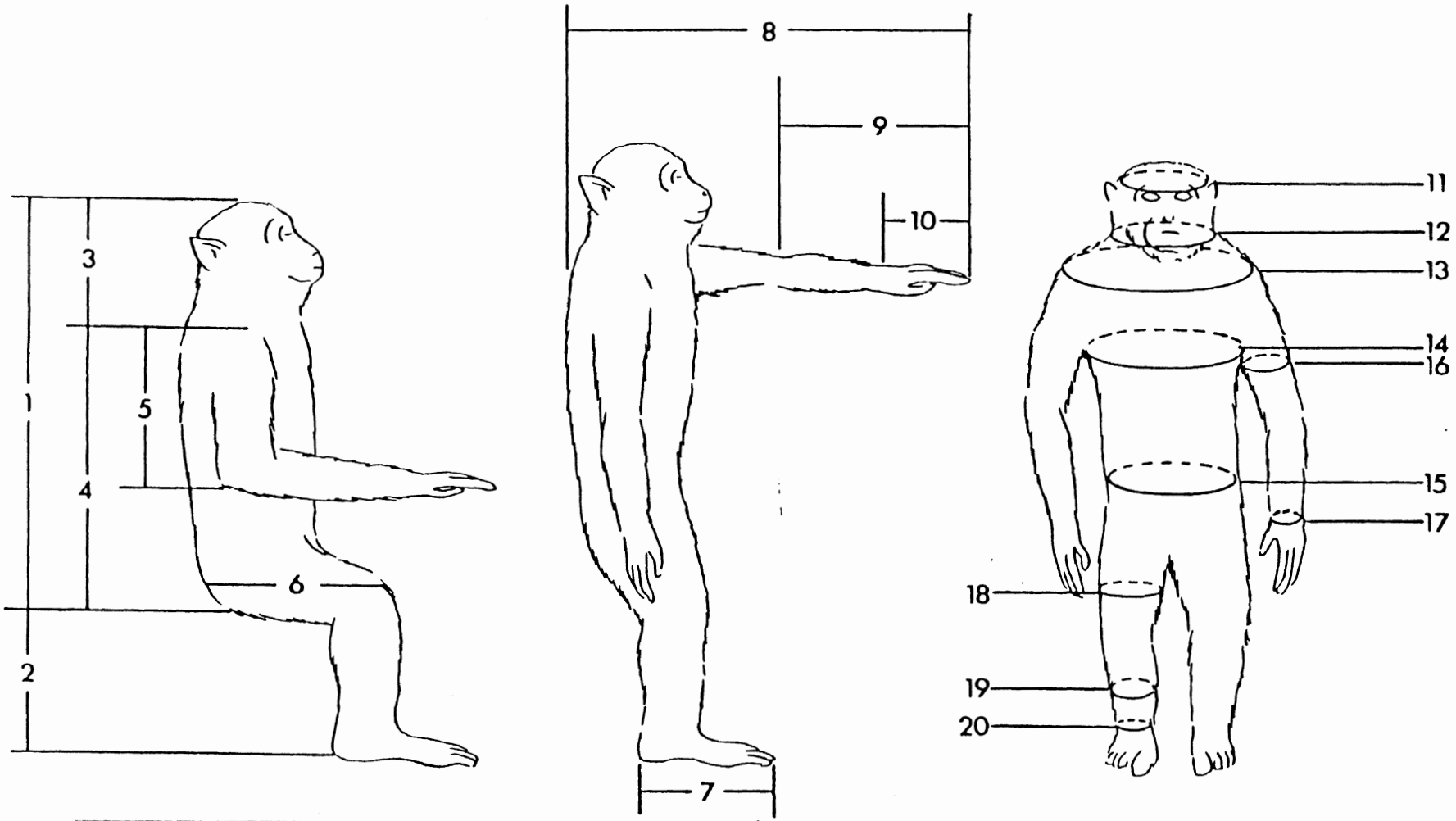
FIGURE 4

University of Michigan Unit for Laboratory Animal Medicine (ULAM). Prior to acquisition, the Macaca subjects had been used in one or more pharmacological research projects.

The impacts of three Macacas were conducted on post-mortem subjects. Upon termination, they were stored in a cooler at 4°C for 48 hours before testing. Living Macacas were used in the two final experiments. The protocol for post-mortem primates was less complex than for that of the live primates, which is outlined below.

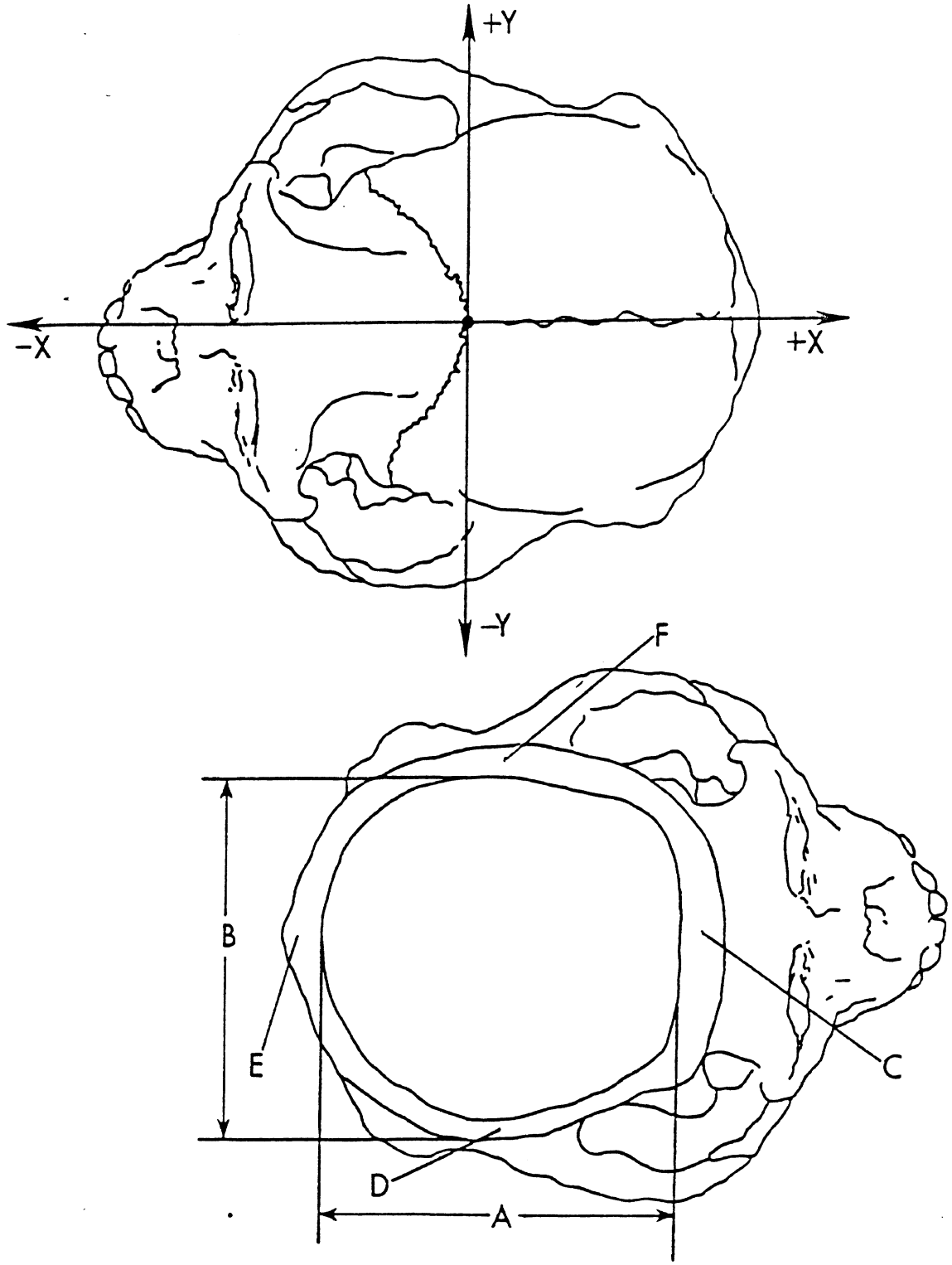
On the morning of the experiment the primate is given an intramuscular injection of ketamine (dL-2[o-chlorophenyl 1]-2-[methylamino] cyclohexanone hydrochloride) before being delivered to the HSRI Biomedical Laboratory by a ULAM technician. A catheter with a three-way valve is inserted into the saphena parva vein in the hind leg, and sodium pentobarbital injected through the valve at a dosage of 25 mg/kg, to effect, and an airway is established. The upper body is prepared and the weight and biometrical measurements are taken with a standard anthropometer, a stainless steel tape, a ruler and a Homes Model 51HH beam scale. Body measurements are illustrated in Figure 5; head measurements in Figure 6. Using a cauterizing scalpel, the scalp and muscle mass are removed from the frontal bone. The screws used to moor the nine-accelerometer plates and the epidural pressure transducer skull fitting are screwed into place. Quick-setting acylic is molded around the pressure transducer fitting and 9-accelerometer moorings. Figures 7, 8 shows the positioning of the instrumentation on the skull.

Next, eye and ear x-ray targets are positioned. The primate is trans-



LOCATION OF BODY MEASUREMENTS							
LENGTH IN CM.				CIRCUMFERENCE IN CM.			
1. BUTTOCK - CROWN		6. BUTTOCK - KNEE		11. HEAD		16. BICEPS	
2. POPLITEAL HEIGHT		7. HEEL - TOE (Foot)		12. NECK		17. WRIST	
3. TOP HEAD - TOP SHOULDER		8. TOTAL ARM REACH		13. SHOULDER		18. THIGH (Mid shaft)	
4. ACROMIAL HEIGHT		9. FOREARM - HAND		14. CHEST		19. CALF	
5. SHOULDER - ELBOW		10. HAND		15. WAIST (Hip)		20. ANKLE	
REMARKS							

FIGURE 5. Identification of Body Measurements



Skull Inside Length A _____ Skull Thickness at Pt. D _____

Skull Inside Width B _____ Skull Thickness at Pt. E _____

Skull Thickness at Pt. C _____ Skull Thickness at Pt. F _____

FIGURE 6. Identification of Head Measurements

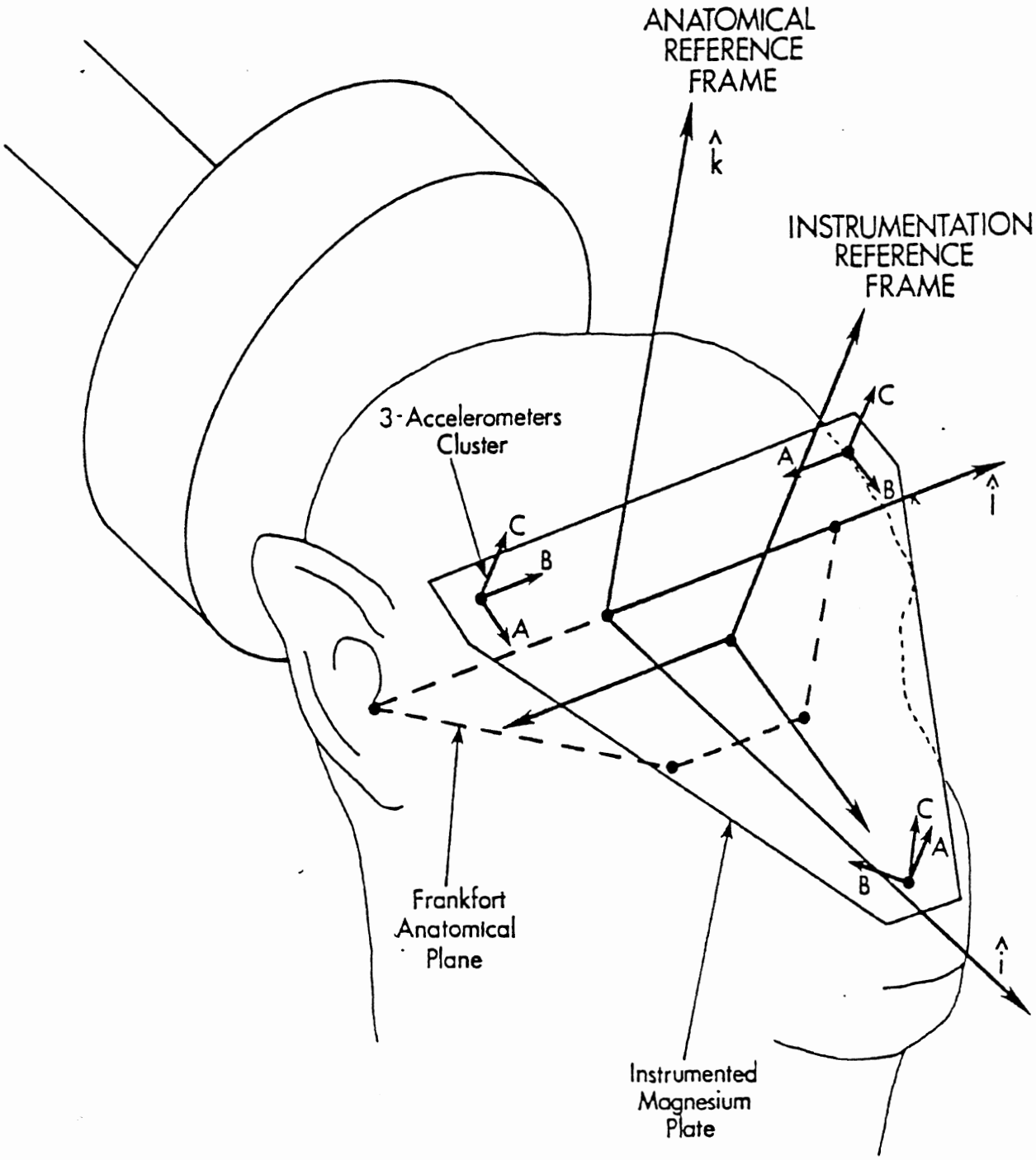


FIGURE 7. Instrumentation Reference Frame and Location of the Three Triaxial Accelerometer

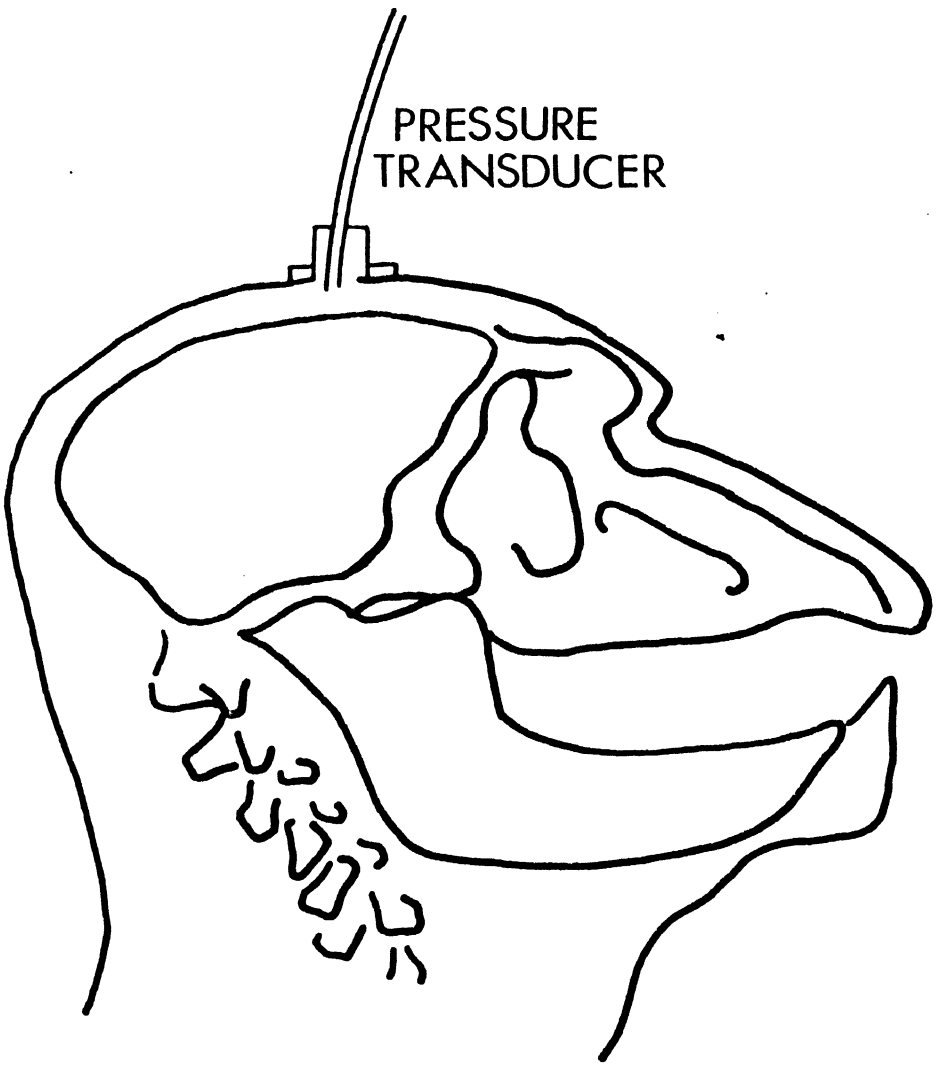


FIGURE 8

ported to the x-ray room where two head x-rays (x-z and y-z views) are taken. The distance between each of the eight targets and the surface of the x-ray table is measured and recorded.

The primate is then taken to the impact laboratory and placed in the impact chair. Three triaxial units are fastened to the nine-accelerometer plate. Silicon fluid is injected into the pressure coupler, thus removing all air, and the pressure transducer is inserted. The primate is positioned in front of the impactor with paper tape. All of the transducer wires are then connected and cabled, and the transducers checked for continuity and function. The test is now run with all data recorded on analogue tape.

Results

Two live animal and three post-mortem animal tests were simulated. Stress (or pressure) and displacements are computed versus time throughout the brain. Stresses at the transducer locations are plotted in Figure 9-15: (stress is equal to pressure but opposite in sign). When two computed traces are shown on one curve, the transducer location is between two elements. In Figures 9-15 the measured pressures are converted to stress and plotted for comparison with the computed values. The results show the following: To simulate the live animal response (Figures 9 and 10) the model must have a Poisson's ratio of .4999 and a 20 cm cervical cord. To simulate the post-mortem animal response, Figure 11-13, the model must have a lower Poisson's ratio (ν=.499) and no cervical cord. When a cervical cord is added in this post-mortem animal simulation, higher negative stresses result, and the correlation degrades as shown in Figure 14. When a value of

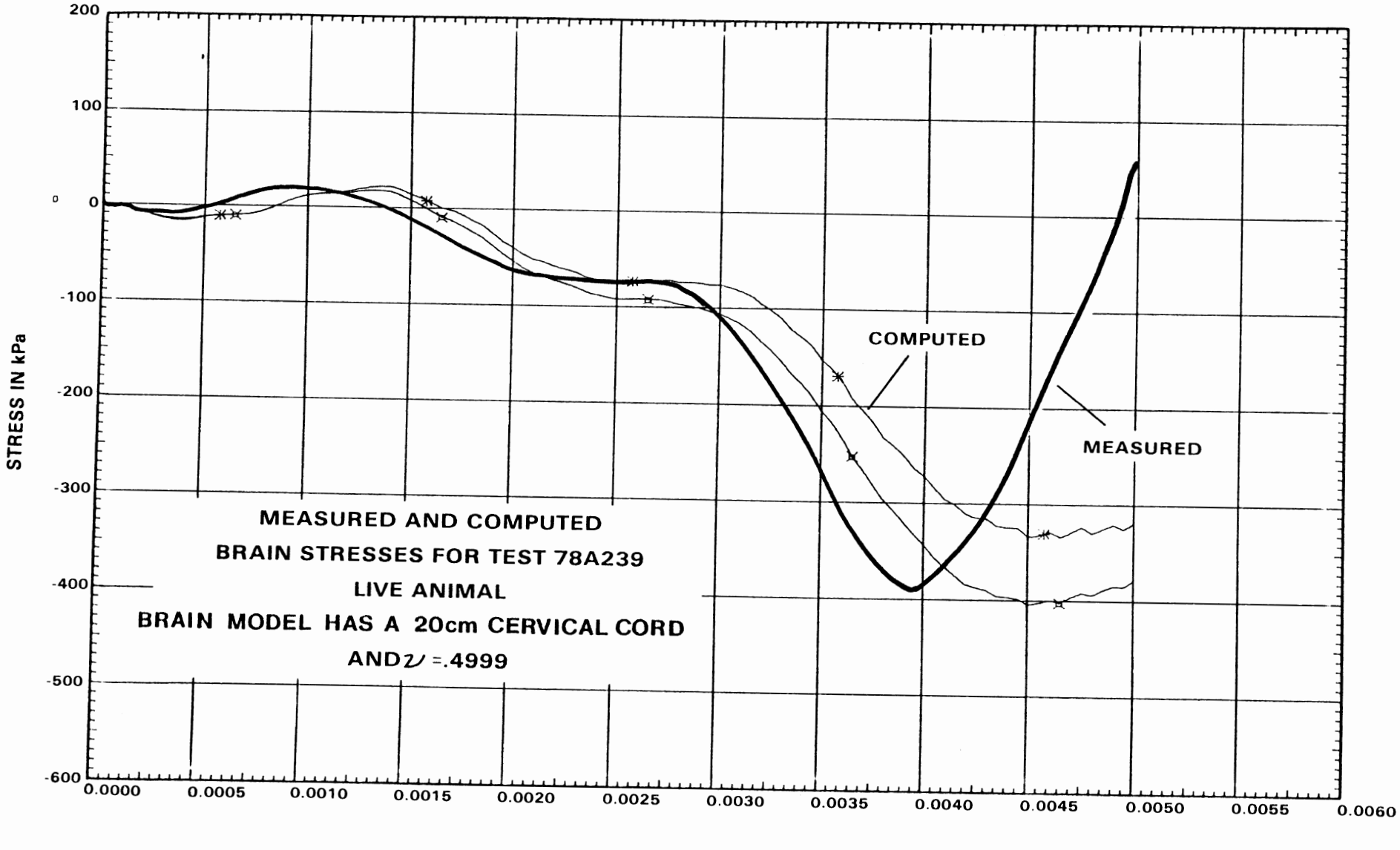

200
100
0
-100
-200
-300
-400
-500
-600
STRESS IN kPa
0.0000
0.0005
0.0010
0.0015
0.0020
0.0025
0.0030
0.0035
0.0040
0.0045
0.0050
0.0055
0.0060
TIME
COMPUTED
MEASURED
MEASURED AND COMPUTED
BRAIN STRESSES FOR TEST 78A239
LIVE ANIMAL
BRAIN MODEL HAS A 20cm CERVICAL CORD
AND ν =.4999

FIGURE 9

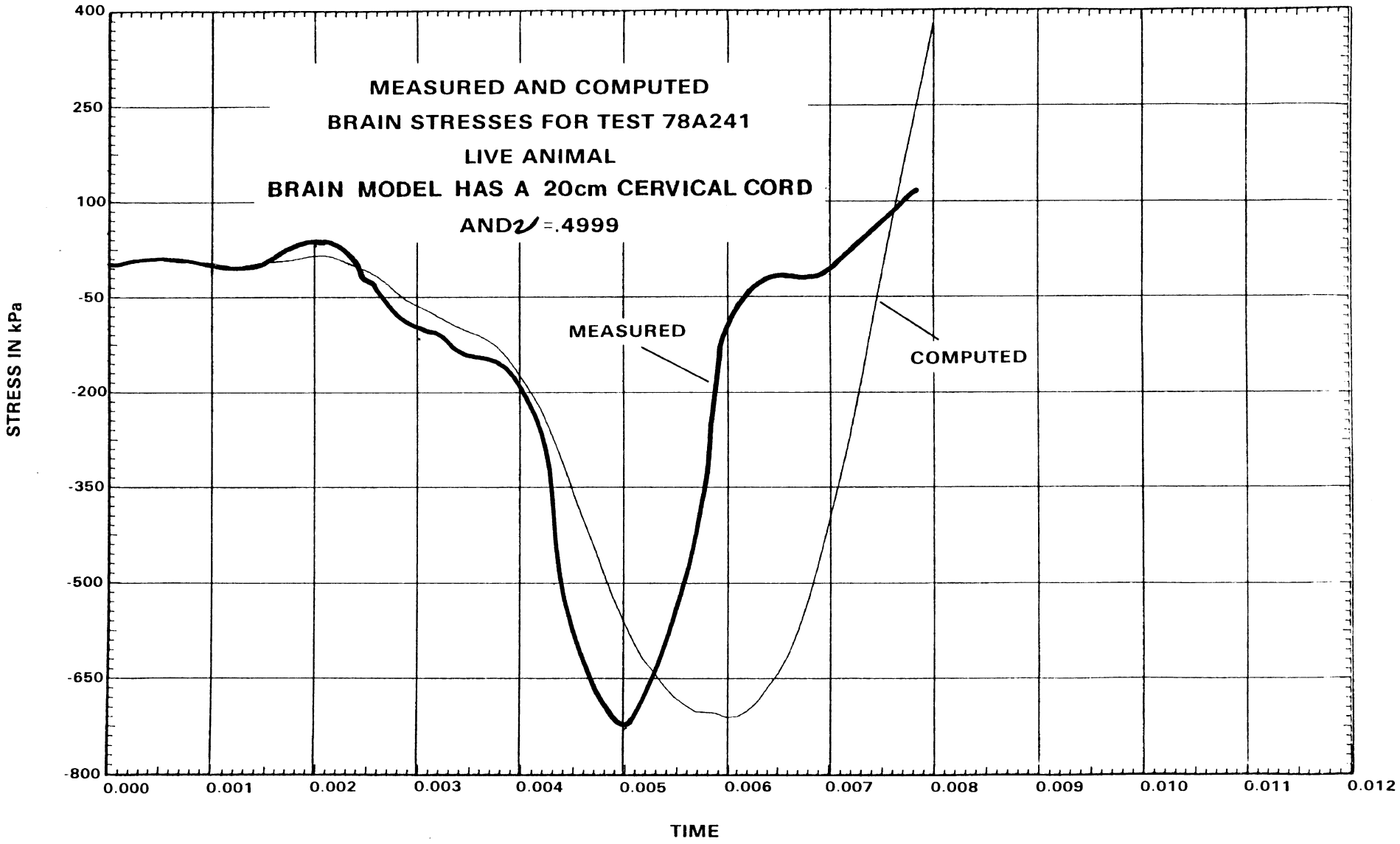

MEASURED AND COMPUTED
BRAIN STRESSES FOR TEST 78A241
LIVE ANIMAL
BRAIN MODEL HAS A 20cm CERVICAL CORD
AND ν =.4999
MEASURED
COMPUTED
STRESS IN kPa
TIME
400
250
100
-50
-200
-350
-500
-650
-800
0.000
0.001
0.002
0.003
0.004
0.005
0.006
0.007
0.008
0.009
0.010
0.011
0.012

FIGURE 10

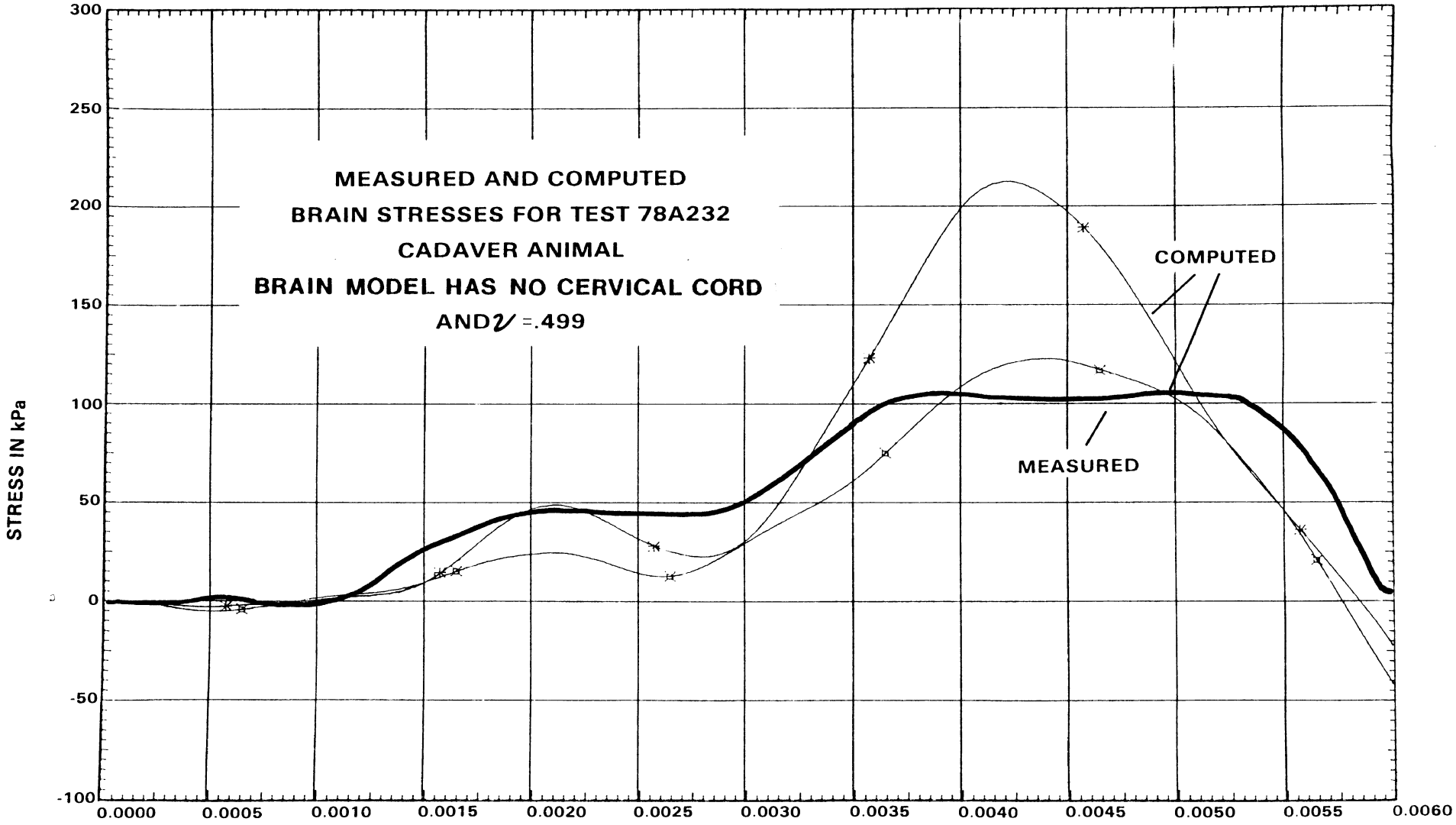

MEASURED AND COMPUTED
BRAIN STRESSES FOR TEST 78A232
CADAVER ANIMAL
BRAIN MODEL HAS NO CERVICAL CORD
AND ν =.499
COMPUTED
MEASURED
STRESS IN kPa
TIME
300
250
200
150
100
50
0
-50
-100
0.0000
0.0005
0.0010
0.0015
0.0020
0.0025
0.0030
0.0035
0.0040
0.0045
0.0050
0.0055
0.0060

FIGURE 11

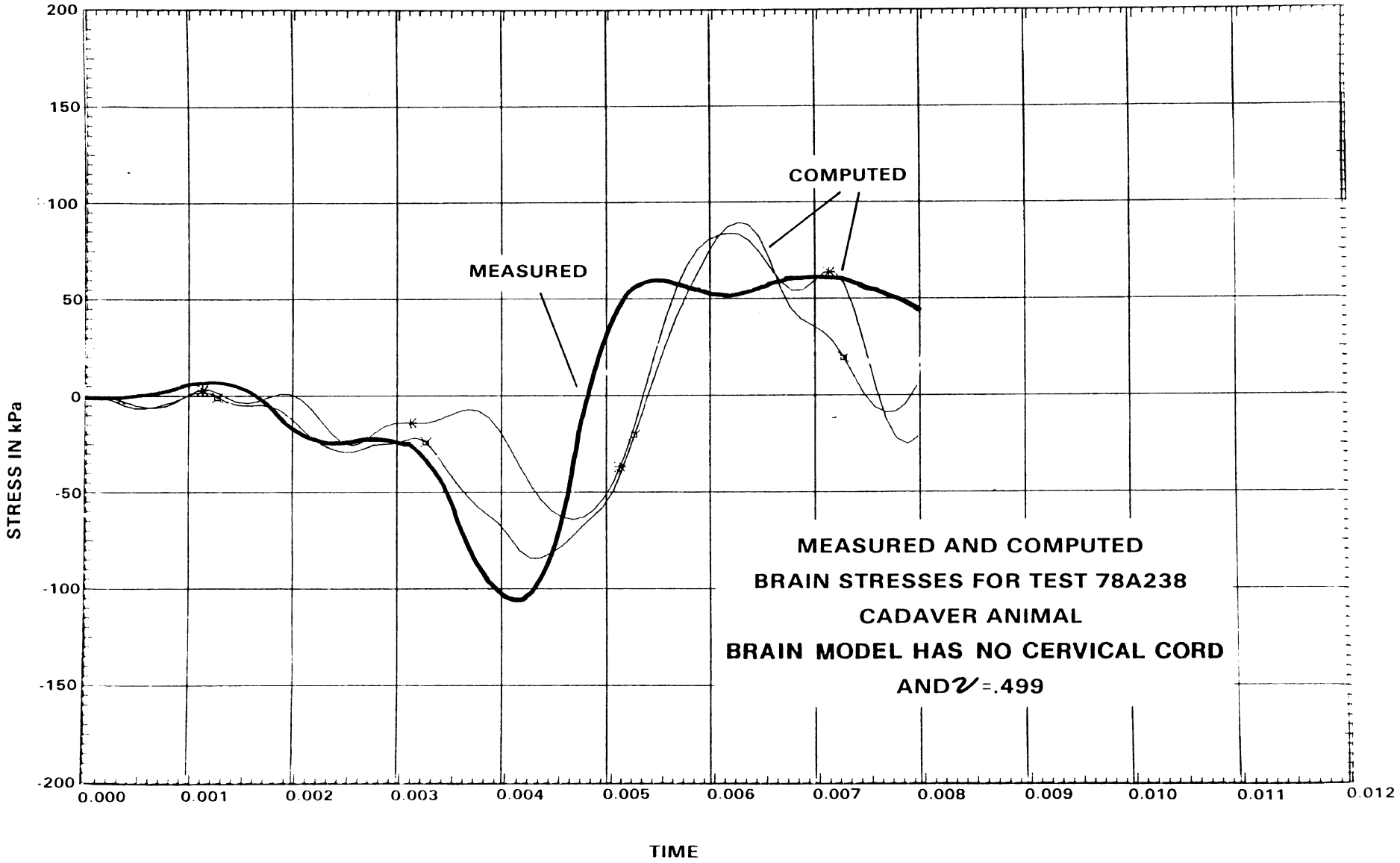

200
150
100
50
0
-50
-100
-150
-200
STRESS IN kPa
0.000
0.001
0.002
0.003
0.004
0.005
0.006
0.007
0.008
0.009
0.010
0.011
0.012
TIME
COMPUTED
MEASURED
MEASURED AND COMPUTED
BRAIN STRESSES FOR TEST 78A238
CADAVER ANIMAL
BRAIN MODEL HAS NO CERVICAL CORD
AND ν=.499

FIGURE 12

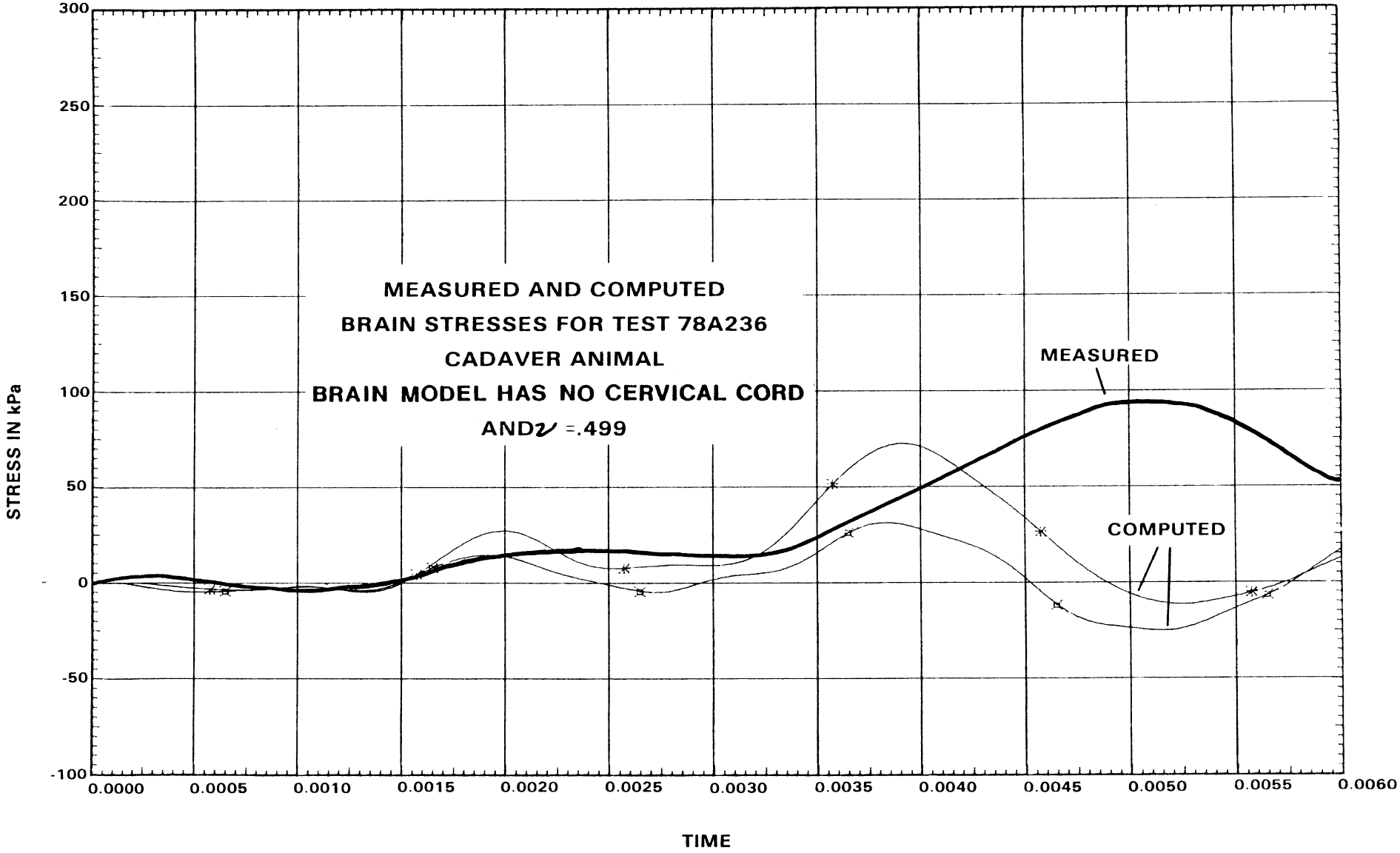

MEASURED AND COMPUTED
BRAIN STRESSES FOR TEST 78A236
CADAVER ANIMAL
BRAIN MODEL HAS NO CERVICAL CORD
AND ν =.499
MEASURED
COMPUTED
STRESS IN kPa
TIME
300
250
200
150
100
50
0
-50
-100
0.0000
0.0005
0.0010
0.0015
0.0020
0.0025
0.0030
0.0035
0.0040
0.0045
0.0050
0.0055
0.0060

FIGURE 13

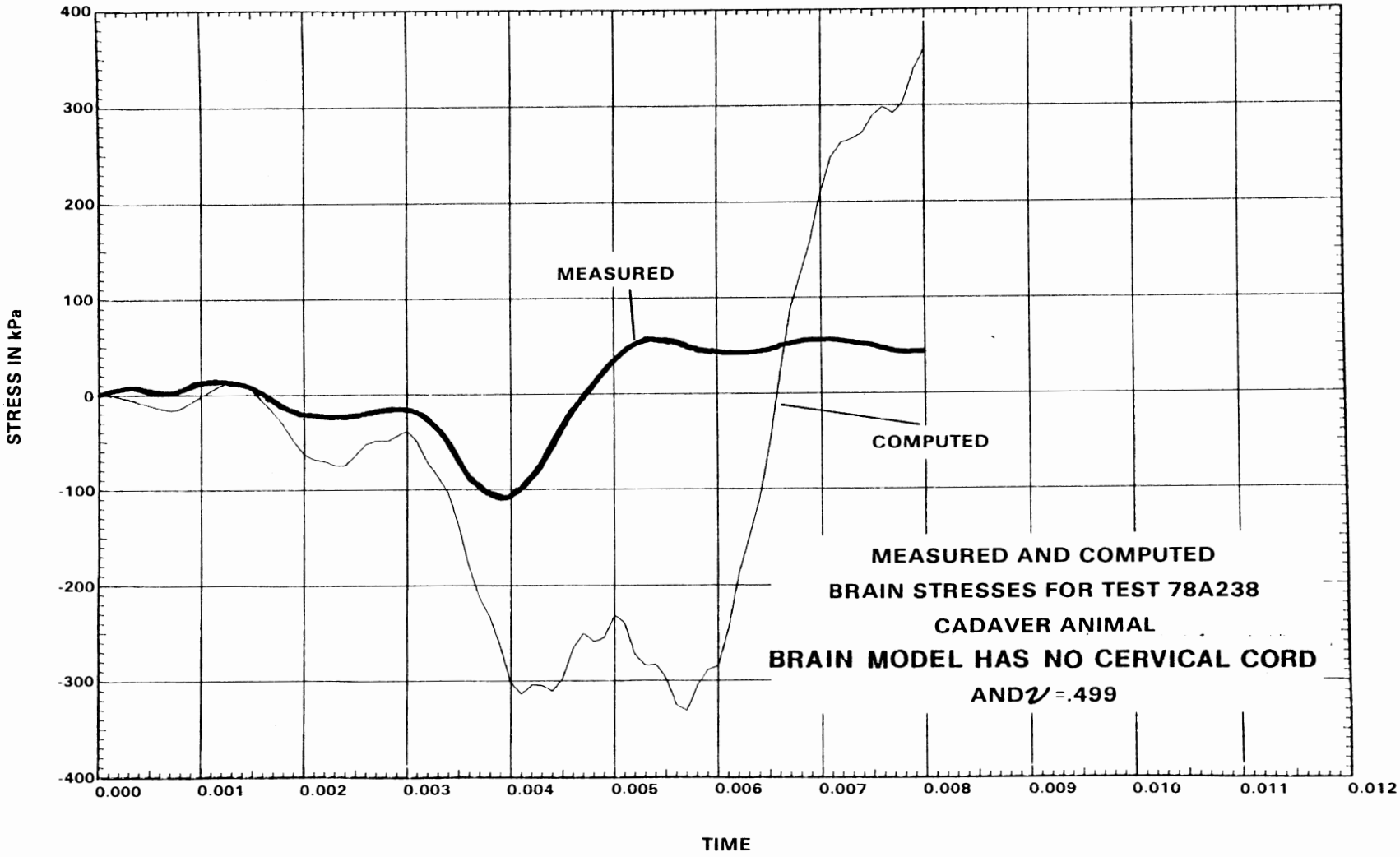

400
300
200
100
0
-100
-200
-300
-400
STRESS IN kPa
MEASURED
COMPUTED
MEASURED AND COMPUTED
BRAIN STRESSES FOR TEST 78A238
CADAVER ANIMAL
BRAIN MODEL HAS NO CERVICAL CORD
AND ν =.499
0.000
0.001
0.002
0.003
0.004
0.005
0.006
0.007
0.008
0.009
0.010
0.011
0.012
TIME

FIGURE 14

.4999 is used for ν (value for live animal) in the post-mortem animal simulations, the measured response tends to lag the computed values. Even when .499 is used, the measured value lags the computed value, Figures 12 and 13. When .499 (value for the post-mortem animal) is used for ν in the live animal simulation, the computed response lags the measured response as shown in Figure 15. If the cord is removed in the live simulations, the computed stresses are much too low (Figure 16). The maximum computed stress in Figure 16 is - 110 kPa and the measured stress is - 430 kPa (Figure 9). There is a factor of 4 difference between the measured and computed values when the cord is eliminated. Even when the cord is included, the computed results lag the measured stresses (Figures 9 and 10). This delay is a limitation of the existing model. The model does not simulate neck compression, it only simulates the inertial motion of the cord. If neck compression were included in the model, the stress initiated by the cord would be shifted in time.

Discussion

The response of the post-mortem brain is slower and more damped than that of the live brain. The post-mortem is in effect more compressible than that of the live brain and pressures (stress) in the post-mortem brain are lower than in the live brain. This is possibly due to post-mortem degradation and the fact that fluid is easily expelled out of the brain into the unpressurized arteries and into the CSF space surrounding the cervical cord. The unpressurized cervical canal and flaccid neck in the post-mortem animal may uncouple the cervical cord from the brain response. The results show that the cord can increase the pressures in the brain by a factor of 4. The difference is greatest when the head undergoes S-I acceleration because the effect of the cervical cord is lacking in the post-mortem animal.

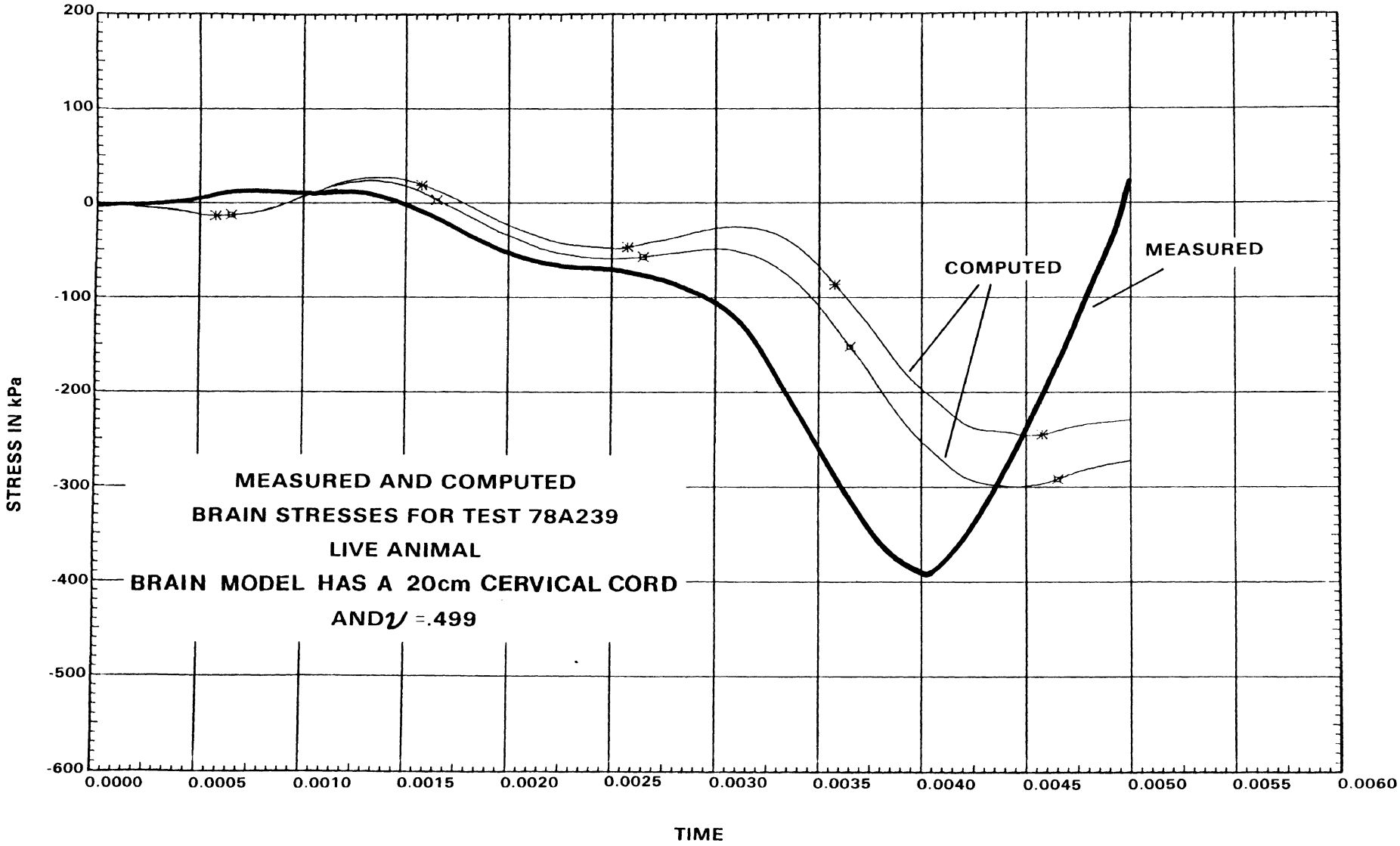

200
100
0
-100
-200
-300
-400
-500
-600
0.0000
0.0005
0.0010
0.0015
0.0020
0.0025
0.0030
0.0035
0.0040
0.0045
0.0050
0.0055
0.0060
STRESS IN kPa
TIME
COMPUTED
MEASURED
MEASURED AND COMPUTED
BRAIN STRESSES FOR TEST 78A239
LIVE ANIMAL
BRAIN MODEL HAS A 20cm CERVICAL CORD
AND ν =.499

FIGURE 15

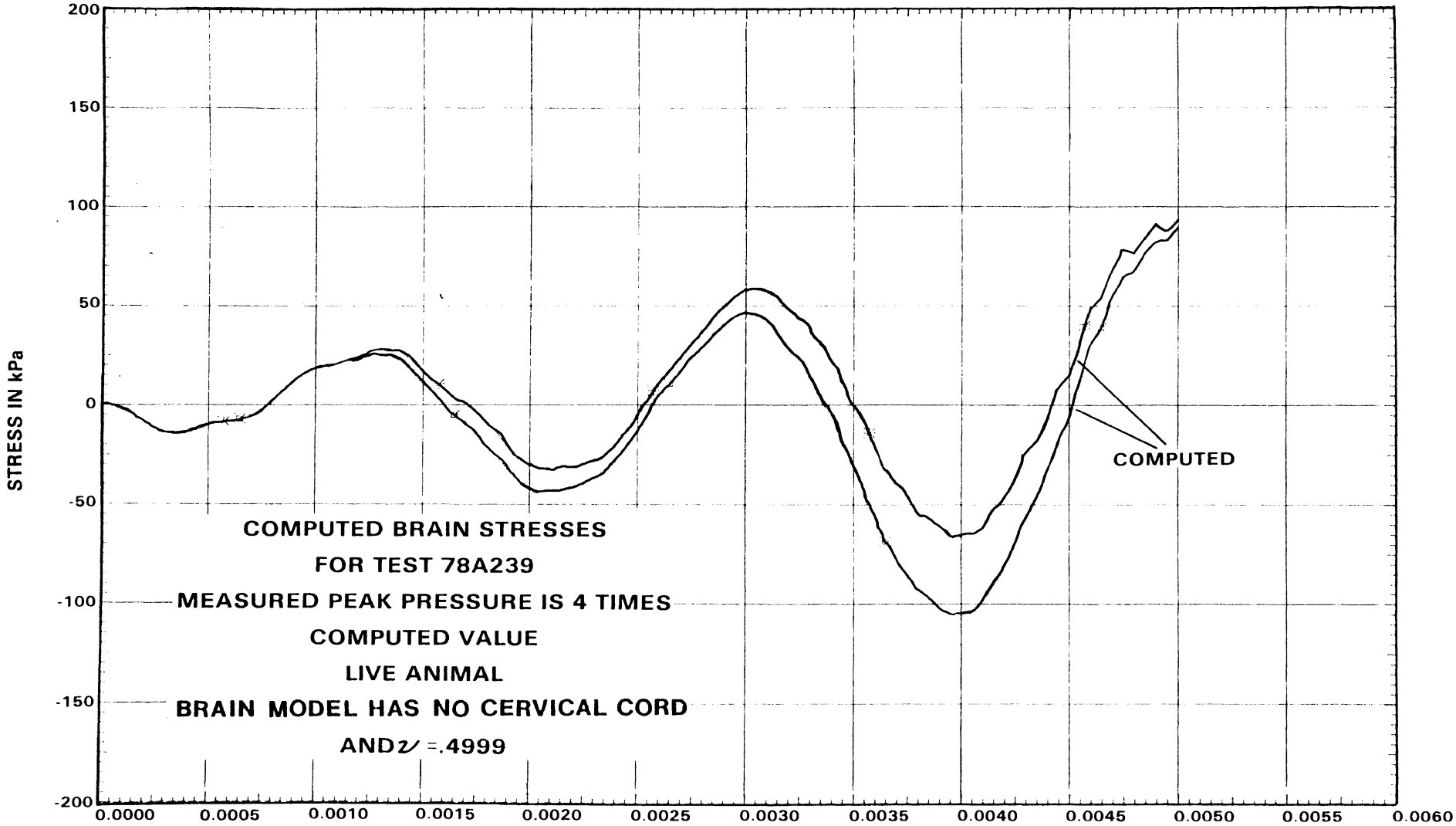

200
150
100
50
0
-50
-100
-150
-200
STRESS IN kPa
0.0000
0.0005
0.0010
0.0015
0.0020
0.0025
0.0030
0.0035
0.0040
0.0045
0.0050
0.0055
0.0060
TIME
COMPUTED
COMPUTED BRAIN STRESSES
FOR TEST 78A239
MEASURED PEAK PRESSURE IS 4 TIMES
COMPUTED VALUE
LIVE ANIMAL
BRAIN MODEL HAS NO CERVICAL CORD
AND ν =.4999

FIGURE 16

To investigate the effects of fluid in the arteries and CSF system, a third type of test is needed. Similar tests on pressurized (CSF and arterial pressurization) post-mortem animals should be simulated, and compared to the results in this report.

Summary

The dynamic responses of live and post-mortem brains in situ are different. These differences are summarized in the following table:

	Live Animal Brain	Post-Mortem Animal Brain
Response Time	faster	slower
Damping	less	more
Effective Compressibility	less	more
Response Magnitude for Some Head Acceleration	higher	lower
Cervical Cord and Brain Response	coupled	uncoupled
Effect of Cord in S-I Head Acceleration	increase intracranial pressure	no effect

Acknowledgments

The authors would like to acknowledge the contributions of Nabih M. Alem, Joseph Benson, Jean Brindamour, Marvin Dunlap, Garry Holstein, Dikran Kashkashian and Valerie A. Moses.

REFERENCES

1. Stalnaker, R. L., J. W. Melvin, G. S. Nusholtz, N. M. Alem and J. B. Benson, "Head Impact Response." The Twenty-first Stapp Car Crash Conference, 1977.

2. Patrick, L. M., "Head Impact Protection." Head Injury Conference Proceedings, edited by W. F. Caveness and A. E. Walker, 4:41-48, 1966.

3. Padgaonkar, A. J., K. W. Krieger, A. J. King, "Measurement of Angular Acceleration of a Rigid Body Using Linear Accelerations." ASME Preprint -75-APM3, June 1975.

4. Becker, E., G. Willems, "An Experimentally Validated 3-D Inertial Tracking Package for Application in Biodynamic Research." The 19th Stapp Car Crash Conference, 1975.

5. Ewing, C. L. et al., "The Effect of the Initial Position of the Head and Neck on the Dynamic Response of the Human Head and Neck to -Gx Impact Acceleration.", Paper 751157, Proceedings of the 19th Stapp Car Crash Conference, 1975.

6. Ewing, C.L., D. J. Thomas, "Human Head and Neck Response to Impact Acceleration." Naval Aerospace Medical Research Laboratory Detachment, New Orleans, Monograph 21, August 1972.

7. Ewing, C. L., D. J. Thomas, "Torque versus Angular Displacement Response of Human Head to -Gx Impact Acceleration." Paper 730976, Proceedings of the 17th Stapp Car Crash Conference, Society of Automotive Engineers, Inc. 1973.

8. Thomas, D. J., "Specialized Anthropometry Requirements for Protective Equipment Evaluation." AGARD Conference Proceedings No. 110, Current Status in Aerospace Medicine, Glasgow, Scotland, September 1972.

9. Fayon, A. et al., "Thorax of 3-Point Belt Wearers During a Crash (Experiments for Cadavers)." The 19th Stapp Car Crash Conference, 1975.

10. Nahum, A. M., R. W. Smith, "An Experimental Model for Closed Head Injury." The 20th Stapp Car Crash Conference, 1976.

11. Ward, C. C., Nikravesh, P.E., and Thompson, R. B.,"Biodynamic Finite Element Models Used in Brain Injury Research." Journal of Aviation, Space and Environmental Medicine, Vol. 49, No. 1, 1978.

12. Bartz, J. A., F. E. Butler, "Passenger Compartment with Six Degrees of Freedom." Auxiliary Programs to "Three Dimensional Computer Simulation of a Motor Vehicle Crash Victim," Final Technical Report for DOT Contract No. FH-11-7592, 1972.

13. Ward, C. C. , Nahum, A., "Correlation Between Brain Injury and Intracranial Pressures in Experimental Head Impact." Presented at the International Conference on Impact Trauma, Gotenburg, Sweden, September 1979 and published in proceedings. Navy Report TM No. 51-79-15