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STRENGTH AND RESPONSE OF THE HUMAN CADAVER CERVICAL SPINE UNDER IMPACT LOADING

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16. Abstract

A test series using five unembalmed cadavers was conducted to investigate factors affecting the creation of cervical spine damage from impact to the crown of the head. It was determined that the crown impact would be accomplished by a free-fall drop of the test subject onto a load plate which would be covered with padding to vary the contact force time characteristics. The orientations of the head, cervical spine, and torso were adjusted relative to a laboratory coordinate system to investigate the effects of head and spinal configuration on the damage patterns.

Although this is a limited study of some of the important kinematic factors and cervical spine damage modes associated with crown impacts using unembalmed cadavers, in terms of damage response and force time history for subjects with similar initial conditions (impact velocity, padding, and contact surface geometry), free-fall tests do not seem to be significantly different from pendulum impacts in which a mass of 56 kg is used.

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1.0 INTRODUCTION

Cervical spine injuries have been reported extensively in the literature (1-13)* and are most frequently reviewed with respect to those injuries occurring in individual accident case histories. Approximately a dozen different types of neck fractures or fracture-dislocations have been described, and classification of the injuries and the injury mechanisms presumed to cause them are based on the inferred head/neck motion. There are four basic types of head/neck motion that occur naturally: flexion (forward bending), extension (rearward bending), lateral bending, and rotation. It is hypothesized that most fractures and/or fracture-dislocations occur when the natural motion is forced beyond the range of human tolerance.

The fracture or fracture-dislocation injuries of the cervical spine which are observed most frequently in individual case histories are commonly referred to as "flexion injuries" (14). These injuries involve fractures of the anterior aspect of the lower cervical vertebral bodies (possibly with dislocations of adjacent vertebral bodies) and/or tearing of posterior ligaments and are, therefore, hypothesized to be caused by flexion-compression motion beyond the range of human tolerance.

Few experimental studies have made an attempt to determine injury mechanisms and impact response of the cervical spine due to crown loading, which occurs frequently in numerous environments. Culver et al. (11) studied superior-inferior impacts on unembalmed cadavers. Hodgson and Thomas (12) reported on a study in which the heads of embalmed cadavers wearing protective helmets were statically and dynamically loaded in the superior-inferior direction. Most recently, Nusholtz et al. (13) have addressed the issue of neck injuries due to crown impacts. It was hypothesized that crown loading which causes the head to rotate forward beyond the range of human tolerance would result in flexion-compression injury to the lower cervical spine. To test this hypothesis cranial impacts were delivered to the cadaveric subjects in

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*Numbers in parentheses designate references at end of report.

the S-I direction using a pendulum impact device with a 56 kg free-flying mass. Some of the important conclusions from this study were:

- The initial orientation of the spine relative to the impact axis was a critical factor influencing the type of response and damage produced.
- Descriptive motion of the head relative to the torso was not a good indicator of the mechanism producing neck damage. "Flexion" damage was observed with extension motion and, "extension" damage was observed with flexion motion.
- Energy absorbing materials were effective in reducing peak impact force, but did not necessarily reduce either the amount of energy transferred to the head, neck, and torso or the damage produced in a cadaver model.

Although flexion-compression damages were observed in the upper thoracic spine, only one subject sustained this type of damage in the cervical spine. The majority of cervical spine damage observed in this study was of the extension-compression variety and not the flexion-compression damage pattern that was hypothesized.

The initial phase of the work performed under the current contract is to attempt to produce flexion-type fracture or fracture-dislocation damage in the cervical spine of human cadavers using a different type of crown impact environment. Impacts to the head in the superior-inferior direction are to be produced by a free-fall drop of the test subject onto a rigid structure to which padding may be added. This study will investigate the effects of drop height, padding at the contact interface, initial postural configuration on the force-time history, kinematic motion, and damage response of human cadavers subjected to head impacts under free-fall conditions.

2.0 EXPERIMENTAL DESIGN DEVELOPMENT

The initial technical meeting in connection with this program was held on April 21, 1982 at University of Michigan Transportation Research Institute (UMTRI). H. J. Mertz and G. W. Nyquist of General Motors Engineering Staff met with G. S. Nusholtz of UMTRI to discuss and decide upon the initial testing parameters. The following is a summary and brief discussion of the points decided upon at that meeting.

It was hypothesized that flexion damage was not observed in studies in which the pendulum impact device was used for the following two reasons. First, the impact mass was not sufficiently large to represent the "infinite" mass of a wall or ground surface; and second, the subject was not continuously accelerated, which occurs under free-fall conditions. It was believed that free-fall conditions would result in a lower contact velocity to produce a given damage. In addition, it was believed that the force-time history would increase in duration in free-fall impacts since the body mass would have to be decelerated through the head/neck structure.

It was planned that impact to the head would be accomplished by a free-fall drop of the test subject onto a load plate. A load plate using four force transducers was decided upon as opposed to a single force transducer to minimize the effects of off-axis loading and to obtain forces normal to the impact direction.

A space-frame with a seating arrangement would position the subject and guide it during the fall (Figure 1). The frame was to be released from the subject and brought to rest prior to contact of the subject's head with the load plate. Foam padding would be placed around the area of contact such that no artifactual damages would occur (e.g., skull fracture from contacting the floor). No force aside from that of gravity would be used to accelerate the subject to impact speed.

Instrumentation was to consist of a nine-accelerometer array to record head motion and triaxial accelerometer arrays affixed to various thoracic vertebrae to record thorax motion. In addition, high-speed

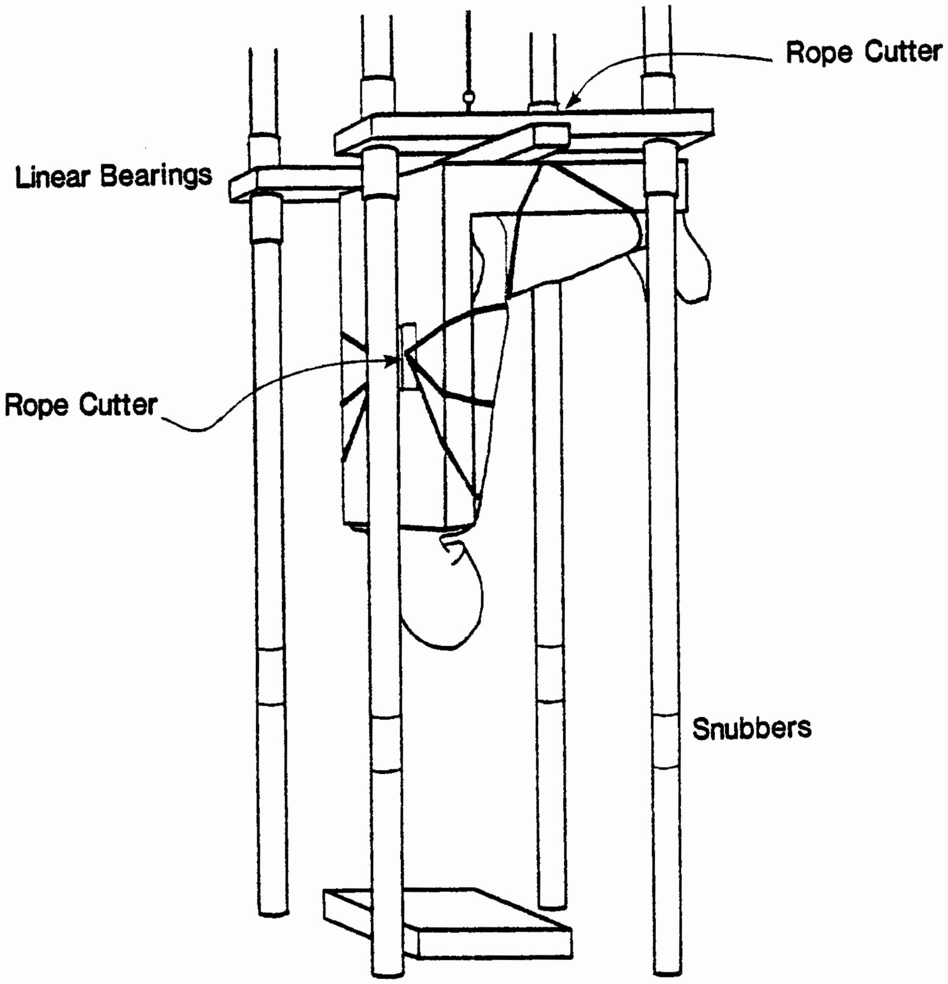

FIGURE 1. Proposed Subject Restraint Design

movies of two orthogonal views would be taken of each test so that three-dimensional motion could be documented.

It was necessary to test the initial assumption that flexion damage would occur if the subject was dropped under free-fall conditions. Rather than define a complete test matrix of impact conditions for all subjects at that time, it was decided that, in an attempt to produce the flexion-type damage, the head/neck should be pre-positioned with the chin against the chest. The subject would be positioned to simulate the seated posture of a vehicle occupant, albeit upside-down. A 25-degree seat back angle was selected.

Finally, to determine the feasibility of the protocol procedure, it was decided that several subjects over and above the ten called for in the contract would be tested without instrumentation.

3.0 PROTOCOL DEVELOPMENT AND METHODOLOGY

3.1 Subject Positioning

The initial phase of protocol development involved using a Part 572 anthropomorphic dummy to assist in determining seating, positioning, and restraining schemes.

It was originally thought that the chair would serve as a functional constraint within the space frame such that the subject would be supported for as much of the drop time as possible. Towards this end a seating apparatus was constructed (Figure 2). Upon testing this apparatus it was found that the belts which surrounded both the dummy and the chair could not be tightened sufficiently to constrain the dummy in the proper configuration. An extension was built onto the chair in an attempt to increase belt tension (Figure 3). However, constraint provided by the chair was still insufficient and the fixture became extremely difficult to manipulate. A second method involved suspending the dummy and the chair individually; however, at this point the chair provided no constraining function and was being used solely as a template for positioning the dummy (Figure 4). It was thus concluded that the dummy could be suspended solely by the belt-harness system attached to the rope cutters (Figure 5). This was not attempted initially because it was thought that inaccuracies in timing the activation of the rope cutters suspending the subject would cause the subject to rotate during the fall, resulting in the head missing the target on the load platform. Trial tests indicated that a subject constrained solely by belts could be dropped from a height of two meters and consistently fall within a 1.5 cm radius of the target point. Furthermore, high-speed film analysis showed that the rope cutters could consistently be activated within one millisecond of each other. The belt system developed to harness the subject in the desired configuration supports the shoulders, thorax, abdomen, pelvis, and knees.

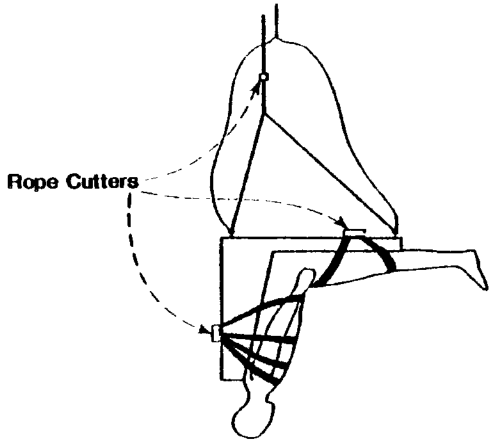

FIGURE 2. Initial Functional Restraint Design

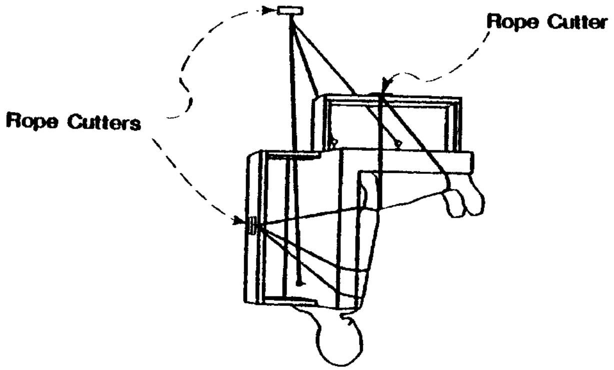

FIGURE 3. First Modification to Restraint Design

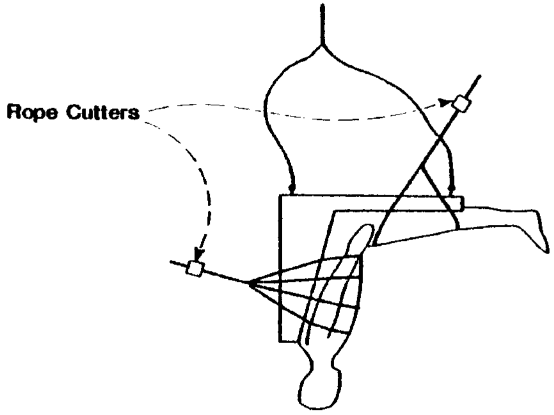

FIGURE 4. Second Modification to Restraint Design

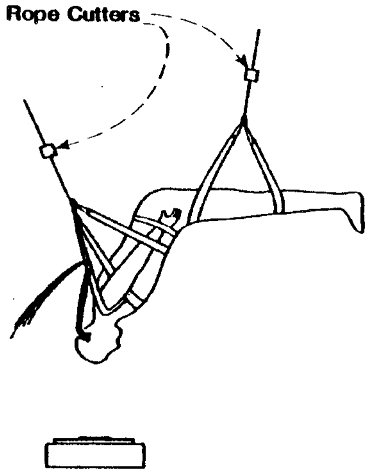

FIGURE 5. Final Restraint Design, Part 572 Dummy

3.2 Accelerometer Instrumentation

The following is a brief description of the techniques used for mounting of accelerometer hardware.

Head Nine-Accelerometer Array. Several metal self-tapping screws are threaded through small pilot holes into the parietal bone of the skull. Feet are attached to the magnesium accelerometer mounting plate (Figure 6) and positioned near the screws on the exposed skull. To insure rigidity, plastic acrylic is molded around the screws, feet, and plate, such that the plate becomes rigidly affixed to the skull. Three triaxial clusters of accelerometers are then attached to their positions on the plate.

Spine Triaxial Arrays. Incisions are made over the first, sixth, and twelfth thoracic vertebrae. The mounting platforms are screwed directly into the spinous processes of both vertebrae. Plastic acrylic is applied under and around the mounts to insure rigidity (Figure 7).

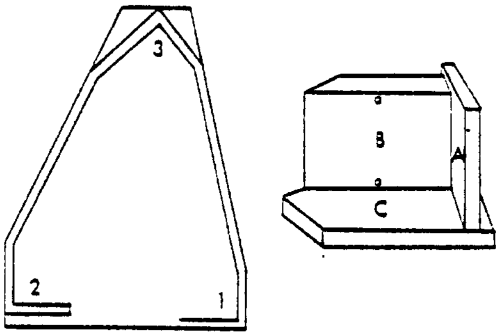

FIGURE 6. 9AX Plate (left) and Triax Mount (right)

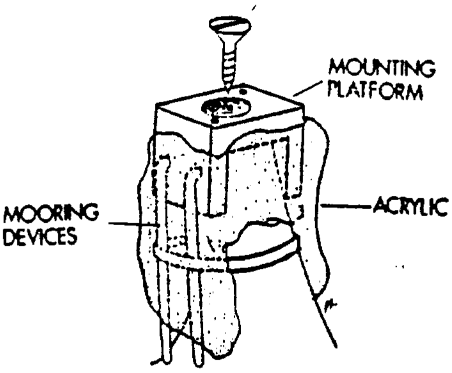

FIGURE 7. Schematic Representation of Spinal Mounting System

3.3 Load Plate

The apparatus used to measure axial and shear forces in all tests to date consists of a rectangular metal platform which rests on four piezoelectric force transducers (Figure 8). At the base of each transducer is a ball bearing which may rotate but is constrained from movement in the horizontal plane by a Plexiglas template. The output signals from the transducers undergo a series of processing steps prior to being recorded. Charge couplers first convert the signal information from charge to voltage, after which a series of range capacitors are necessary to decrease the voltage output per pound force. The two axial force signals are then added together as are the two shear force signals, and these two resultant signals are inverted such that their voltage is positive. Amplifiers increase the signal gain as necessary before the signals are recorded on analog tape.

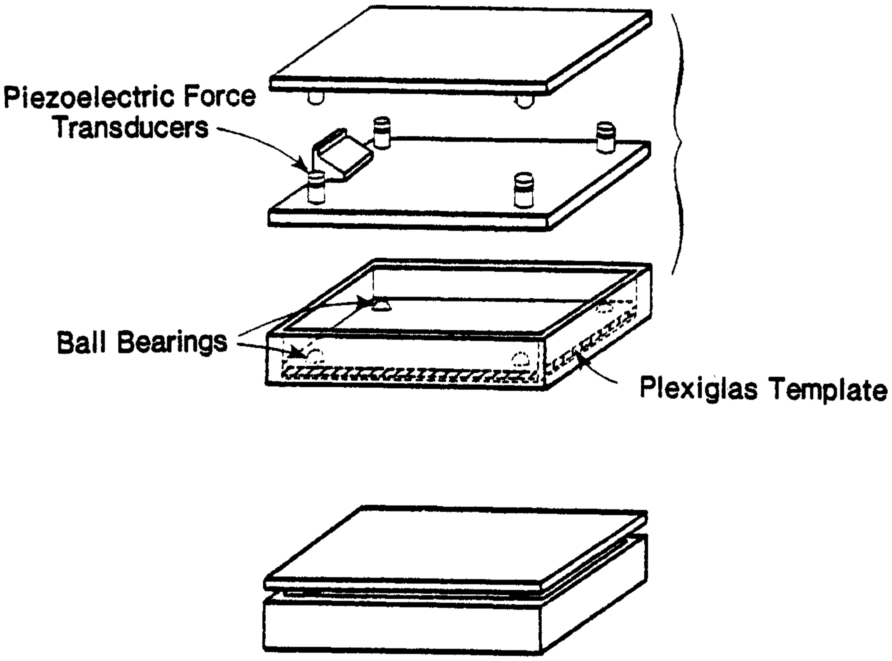

FIGURE 8. Load Plate

The present load plate system provides accurate axial and shear force readings for impacts of relatively long duration (100 to 300 ms) and low frequency content and for impacts which are associated with excessive motion of the subject on the surface of the plate.

However, when the impact is of a localized nature and the signal is of a high frequency content and short duration (10 to 30 ms), the load plate system fails to yield accurate results due to the fact that the natural frequency of the top plate is approximately the same as certain frequencies contained in the force signal, and oscillation of the plate may result. While it is ultimately possible to compensate for the inertial loading effect of the plate by either attaching accelerometers to the load cells and subtracting the resulting acceleration signals from the force signal, or to mathematically model the plate oscillation and compensate the signal after digitization, these are not considered to be acceptable alternatives for two reasons. First, it is felt that the additional effort necessary to modify the design of the load plate or develop the necessary software techniques is not justified given the nature of the study. Second, since most of the impacts are of a short duration and high frequency nature, it will be possible to use one load cell with a single compensating accelerometer and eliminate the load plate entirely in subsequent tests.

3.4 Overhead Hoist System

When positioned for the impact, the subject is suspended by two primary harness systems, each of which is ultimately connected to the ceiling by a single rope which is passed through a rope cutter (Figure 9). At first these two ropes were suspended from pulley systems attached at fixed points to the ceiling. When it became necessary for the subject to be positioned with various head/neck/thorax angles as described below, an overhead hoist system had to be developed which would allow for increased relative motion between these two harness systems. Consequently, the system shown in Figure 9 was constructed. It consists of two power hoists which move linearly in tracks oriented perpendicularly to the long axis of the subject. These tracks in turn move linearly parallel to the long axis of the subject, such that each hoist can be positioned accurately anywhere within the horizontal plane.

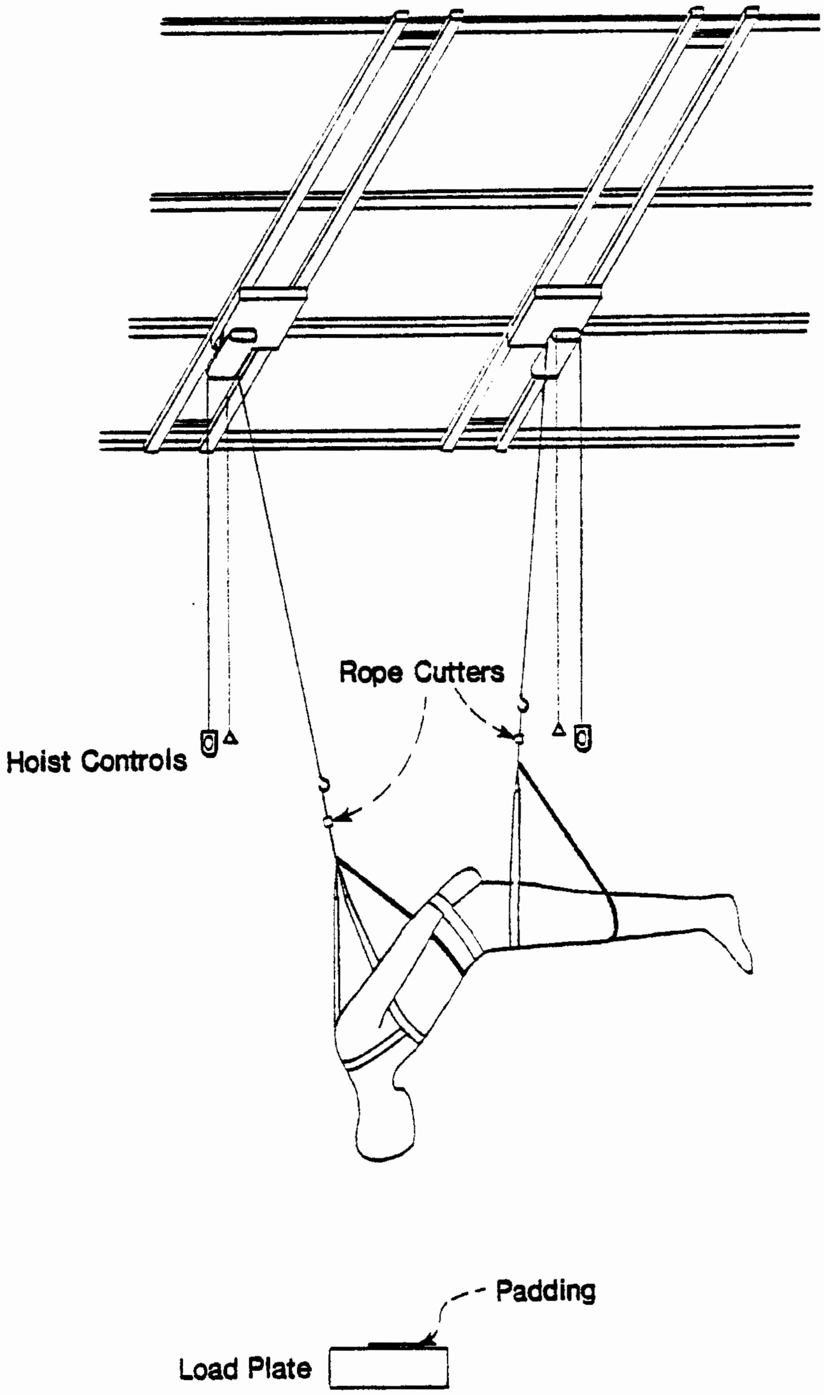

FIGURE 9. Overhead Hoist System and Restraint Configuration with Cadaveric Subject

4.0 THREE-DIMENSIONAL MOTION DOCUMENTATION

Both acceleration and photokinemetric data are used to record three-dimensional motion of the head, neck, and thorax. The methods used to obtain these data are summarized below.

4.1 Acceleration

The method used for documentation of three-dimensional motion from accelerometer data is based on a technique used to measure the general motion of a vehicle during a simulated crash (15).

For this application, three triaxial clusters of Endevco 2264-2000 accelerometers are affixed to a lightweight rigid magnesium plate which is then solidly attached to the skull. The nine acceleration signals obtained from the three triaxial clusters are used for computation of head motion using a least squares technique (16). This method takes advantage of the redundancy of nine independent acceleration measurements to minimize the effect of experimental error to produce three angular accelerations and three estimates, in the least squares sense, of the true solution.

4.2 Reference Frames

Description of the impact response of the human head requires that kinematic quantities measured experimentally be described in reference frames which vary from one instrumentation method to another. One method for comparing kinematic responses between subjects is to refer all results to a "standard" anatomical frame which is easily identified. However, it is impractical to require that the transducers be aligned with this anatomical frame since this creates physical problems which may have no satisfactory solutions. Therefore, the transducers are mounted in an arbitrary and convenient reference frame, and the transformation necessary to convert the data from this instrumentation frame to the desired anatomical frame is described. For head impacts, this is accomplished using a three-dimensional radiographic technique.

Four anatomical landmarks of the head (two superior edges of the auditory meati and two infraorbital notches) are marked with four mutually distinguishable lead pellets. The nine-accelerometer plate is marked with lead pellets at the center of mass of each triaxial accelerometer cluster and also at the plate center of mass. The head containing this instrumentation is then radiographed in two orthogonal directions (the x-z and y-z planes). On each of the two radiographs the optical center and the laboratory vertical z-axis are simultaneously x-rayed. Distances between the plane of the radiographic film and each lead target are recorded for each view. The subsequent computations reconstruct the laboratory coordinates of each of the lead targets. The Frankfort plane is determined and the anatomical reference frame is reconstructed from the four anatomical points. The instrumentation frame and its origin are determined from the three triaxial accelerometer centers. Finally, the transformation matrix between the instrumentation frame and the anatomical frame is obtained.

4.3 Initial Conditions

As well as the head instrumentation and anatomical reference frames, one further frame is required to document the initial position and potentially the three-dimensional motion of the head and provide a method of comparison for responses between subjects. This is the laboratory reference frame, with respect to which all initial angles of the head are measured.

In addition to the anatomical reference frame of the head, reference systems must also be defined on the neck and thorax where triaxial accelerometer clusters are located, such that initial angles of these anatomical members may be defined.

Also, the angle defined as ξ in Figure 10 is measured such that some of the kinematic data may be compared with that obtained in (13). Figure 11 depicts the reference systems used and a definition of each is presented in Table 1. The Euler Angle transformations necessary to describe the reference systems of the head, neck, and thorax in terms of the laboratory reference frame are derived and presented in Appendix III.

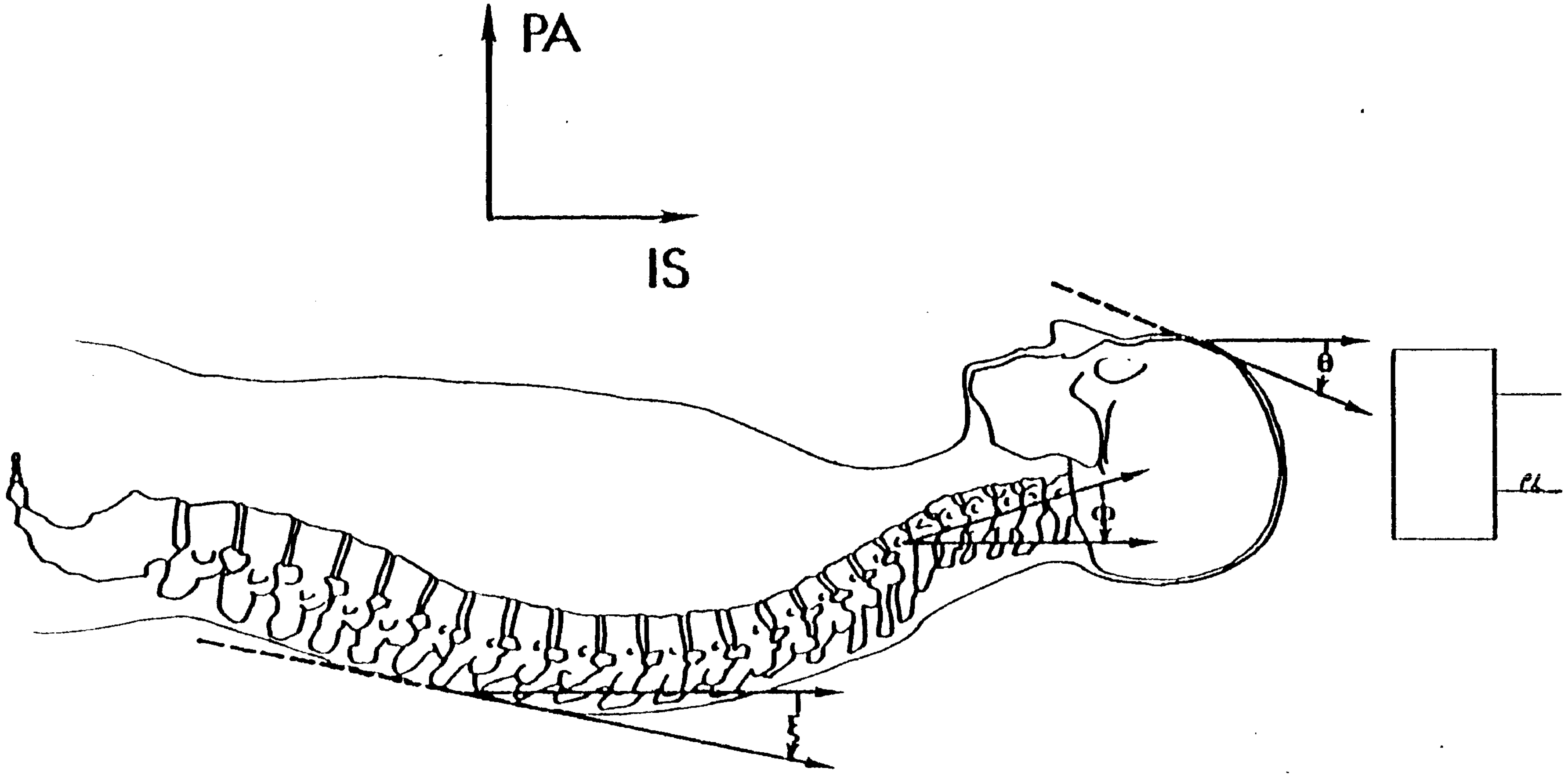

FIGURE 10. Initial Angle Definitions, 25th Stapp Car Crash Conference

TABLE 1: REFERENCE SYSTEM DESCRIPTIONS

Four reference systems were used to describe the initial configuration of each test subject. The conventional anatomical reference system for the head was used. The reference systems associated with the neck and thorax were not standard and have been defined for convenience of measurement with respect to the laboratory reference frame used. All anatomical systems were defined such that the 1 axis corresponded to the posterior-anterior direction, the 2 axis to the medial-lateral direction, and the 3 axis to the inferior-superior direction.

W - The laboratory reference system:
W_0- *Origin,* tip of the coccyx
W_1- The projection onto the horizontal plane of the leg axis
W_2- The vector to complete the orthogonal triad
W_3- The normal to the horizontal plane in the vertical direction

θ - The anatomical reference system for the head:
θ_0 - *Origin,* the intersection of the mid-sagittal, coronal, and Frankfort planes
θ_1 - The posterior-anterior axis (the intersection of the mid-sagittal and Frankfort planes)
θ_2 - The medial-lateral axis (the intersection of the coronal and Frankfort planes)
θ_3 - The inferior-superior axis (the intersection of the mid-sagittal and coronal planes)

α - The reference system for the neck:
α_0 - *Origin,* T1
α_1 - The cross product
α_2 - The medial-lateral axis between the acromions
α_3 - The inferior-superior axis of the neck

γ - The reference system for the thoracic spine:
γ_0 - *Origin,* T4
γ_1 - The cross product
γ_2 - The medial-lateral axis between the scapulae
γ_3 - The inferior-superior tangent to the spine at T4

v - The vector originating approximately at T12 and describing the angle

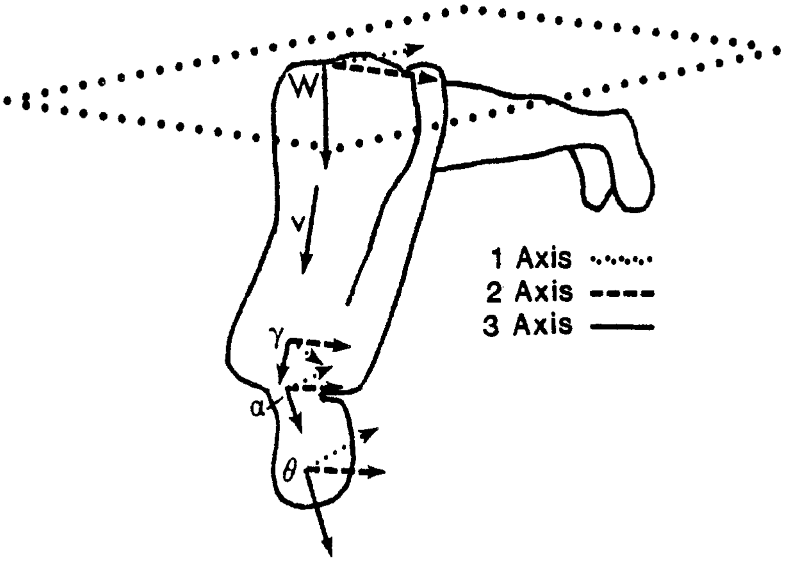

FIGURE 11. Reference System Definitions

4.4 Photokinemetrics

Photographic documentation of a test consists of two orthogonal views by high-speed movie cameras operating at 1000 frames per second. To obtain three-dimensional motion, a Direct Linear Transformation (DLT) technique may be used. The DLT method allows the spatial geometry of the image on film to be transformed by a series of linear equations such that actual three-dimensional motion of the subject in the laboratory reference frame may be reconstructed.

To accomplish this, a field of control points, each of which is accurately defined within the laboratory reference frame, is photographed in two orthogonal directions. The coordinates of the images of the control points of film are then defined relative to an image reference frame. A set of linear equations describes the transformation necessary between the reference frames, and the coefficients of the equations describing the particular transformation of interest are numerically determined by a least squares technique. A more complete discussion of the DLT technique is presented in (17).

5.0 TESTING PROCEDURE

Four groups of procedures are associated with the testing activities. They are those procedures associated with pretest preparation, surgery, impact testing, and post-test autopsy. The execution of these procedures make up a testing sequence which is coordinated through the use of a detailed protocol. A typical protocol is included in Appendix II and outlined in the following text.

5.1 Pretest Preparation

Since the arrival of a test subject usually cannot be predicted more than four hours in advance, preparation for a test series generally begins the day a subject is received. A subject requires approximately eight hours of preparation, which is also sufficient time to set up the impact lab and run trial tests. The areas requiring careful preparation are briefly described below.

Anatomy Lab. Anthropometry, surgical instrumentation, and all other pertinent subject preparation are performed in the Anatomy Lab. Tools, materials, and instrumentation equipment necessary to prepare the subject are set up in advance.

Radiology Lab. The table is positioned and a sufficient supply of film is loaded into the cassettes, such that all work in the radiology lab can be completed as necessary in the test sequence. A subject will be x-rayed twice. The subject is first x-rayed when it is received to check for skeletal integrity. Following the testing sequence, X-rays from orthogonal views are taken to define the anatomical and instrumentation reference frames.

Impact Lab. All test facilities, recording equipment, and transducers must be assembled, wired, and tested. In addition, a portable cart containing surgical instruments for mounting transducers on the subject must be prepared. Impact padding (Styrofoam and Ensolite) and the support harnesses for the subject are assembled near the overhead hoist system. The load plate, cameras, power supplies, lights, and backdrops are set up and the cameras are loaded and positioned.

Electronics Check. The input/output voltage characteristics of all analog tape channels and amplifiers are checked by calibration with a known test signal. The signal from each channel or amplifier is played back (through either the brush chart recorder or a digital voltmeter) and the playback signal is compared with the input signal.

All transducers are labeled and then wired through a patch panel into the instrumentation room. From there the signals are sent through amplifiers, if necessary, and wired to their designated channels on the analog tape recorders. The transducer excitation voltage and the proper gain is determined and set for each amplifier. A calibration test is performed on the load plate to determine its proper pretest input/output characteristics.

Trial Test. To insure that all mechanical and electronic equipment is functioning, several trial tests of the equipment are performed on the day before the test, allowing sufficient time to locate and correct system defects. Accelerometers, amplifiers, umbilical cables, tape recorders, and the load plate are tested by suspending a rubber cylinder weighing approximately 20 pounds from the overhead hoist system. All accelerometers are taped to the cylinder and a preliminary check is made to insure proper balancing and noise levels. The cylinder is then dropped onto the load plate and the output signals from the accelerometers are recorded and played back immediately. The timer box, rope cutters, lights, and strobe are tested individually. Triaxial clusters of accelerometers are then labeled for their specific point of attachment and placed in protective sleeves.

5.2 Timing of Impact Events

Three classes of operations take place before and during impact that are necessary for the documentation of the impact: events associated with photokinemetrics documentation, events associated with recording of electromechanical transducer output, and events associated with the impact itself. The event sequence is initiated by an operator-controlled manual switch and from then on controlled by signals generated by a specially constructed "timer box." The detailed relationships among the various signals or group of signals are diagrammed in Figures 12 and 13. In these diagrams, each signal or group of signals is represented by a line which has a raised section indicating the time during which the function associated with the signal was operational.

Photokinemetrics. The lights, Hycam, and Photosonics cameras must be synchronized such that all cameras are running at the correct speed and the test subject is fully illuminated at the time of impact. In addition, the cameras are sequenced such that they are operational for a minimum amount of time. This minimizes the amount of effort associated with photokinemetric documentation and allows for a smooth-running test sequence.

Electromechanical Transducers. The recording equipment must be at operational speed before the subject is released. Additional events which must be controlled are the release of the subject from the restrained position and the activation of the sequencing gate. Also, the synchronizing contact strobe which places simultaneous electrical and photographic signals on the analog tape and high-speed film, respectively, must occur near the beginning of impact.

A schematic diagram of the test equipment and a wiring diagram are included in Figures 14 and 15.

5.3 Impact Testing

Subjects are obtained from The University of Michigan, Department of Anatomy, and transported to UMTRI by Biomechanics Department personnel. Upon arrival they are weighed and pertinent information is logged in. Initial preparation is completed and pretest X-rays are taken of the head, thorax, pelvis, and femurs. If the skeletal structure is intact and no metallic implants are found, the subject is taken to the anatomy lab.

Following the procedure outlined in the protocol (Appendix II), the subject is first placed on its back and anthropometric measurements are taken. Any anatomical abnormalities are recorded and special note is

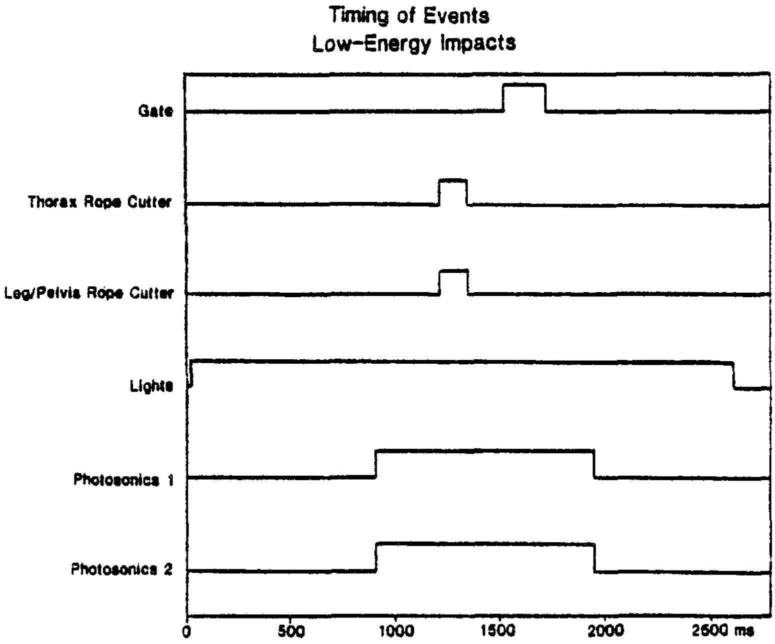

FIGURE 12. Timing of Events for Low-Energy Drops

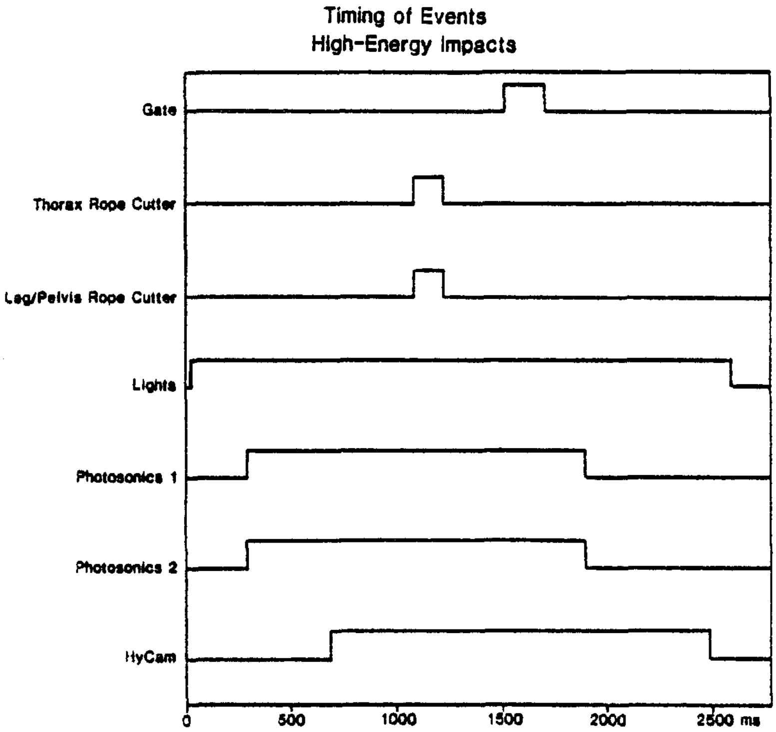

FIGURE 13. Timing of Events for High-Energy Drops

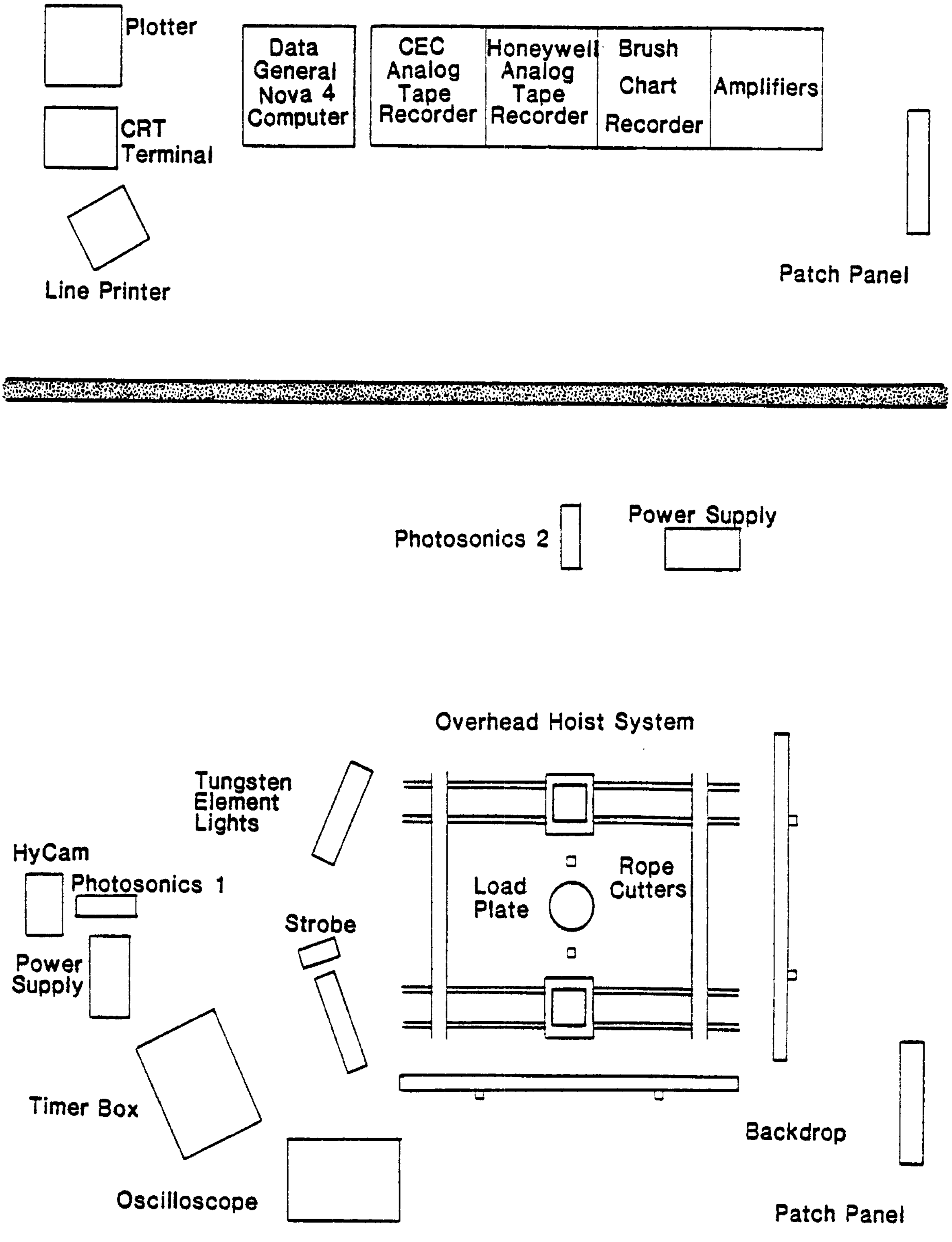

FIGURE 14. Schematic Diagram of Laboratory Setup

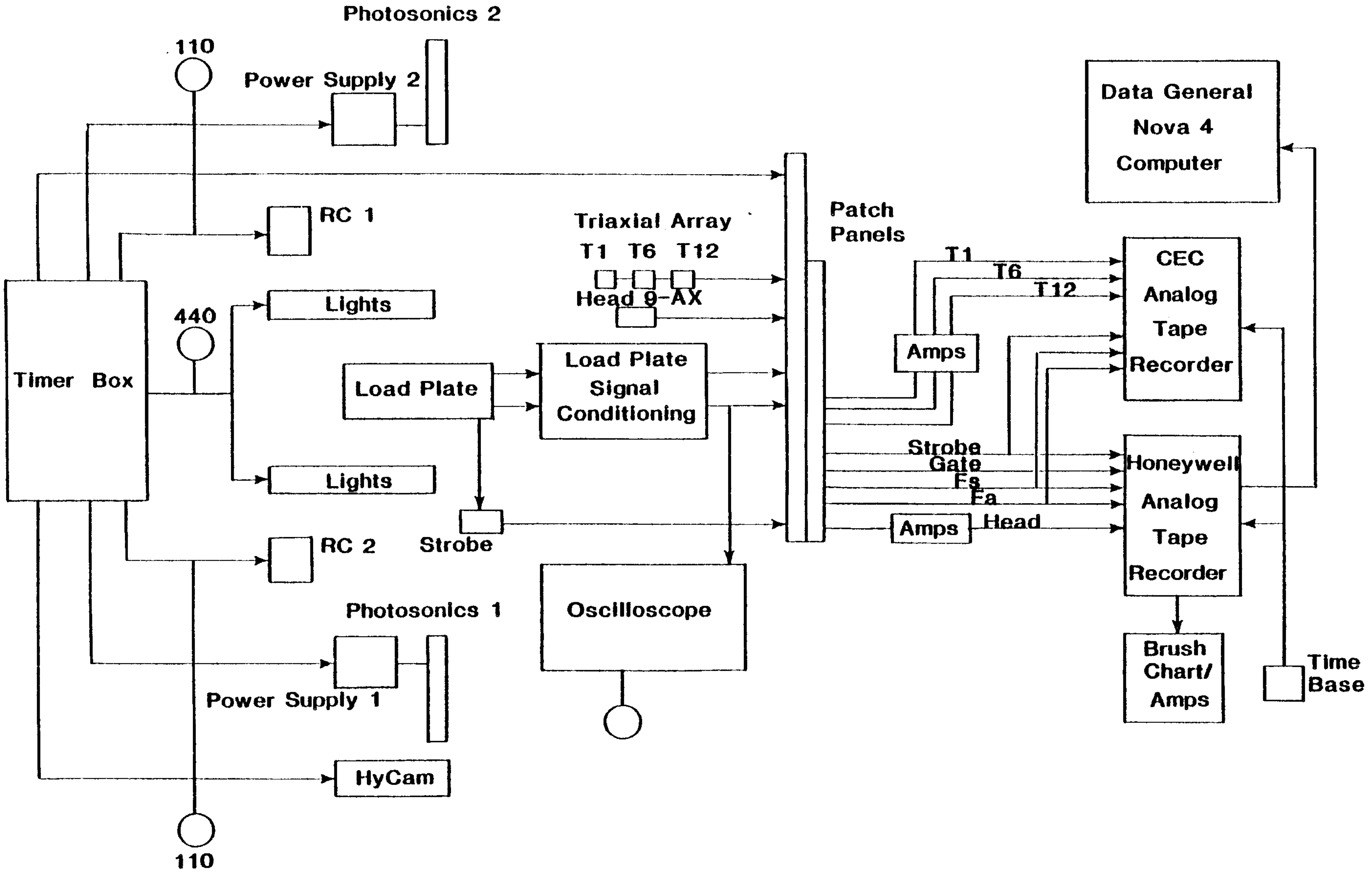

FIGURE 15. Schematic Wiring Diagram

taken if they will alter the usual instrumentation techniques. The subject is then rolled over to allow for installation of head and spinal accelerometer mounting hardware. Following completion of all mounting procedures the subject is dressed in a vinyl sweatsuit to prevent excessive leakage onto the outer set of long underwear.

The subject is transferred to the impact laboratory and all transducers are rigidly attached to the mounts. A final check of electronic equipment is made with the transducers on the subject to insure that accelerometers and amplifiers are functioning properly and that all wiring connections are secure.

The cameras are positioned orthogonally and the field of control points for the DLT calibration (as described in Section 4.4) is placed on the load plate. A brief exposure of the control field is made on the film in each camera such that they can be calibrated for their positions in this particular test series.

After the subject is fitted with the belt harnesses that will suspend it from the overhead hoist system, the subject is hoisted and positioned for a low-energy drop. The exact height and the initial angles of the head/neck/thorax are measured and recorded. Setup photos are taken and a final checklist is run through. When all initial conditions are met, a final zero of the accelerometers is made and the test is run.

This procedure is repeated three times for the low-energy drops, however, prior to running the subsequent tests all recorded signals are played back on the brush recorder. Thus, amplifier gains may be changed if a certain signal has an unexpected value and/or equipment that may have failed during the test may be either located and repaired or replaced.

Prior to the high-energy drop, the gain values of the amplifiers are changed, the subject is positioned, initial angles are recorded, and the test is run.

When the testing sequence has been completed, instrumentation is removed from the subject and an autopsy is performed.

6.0 PRELIMINARY TEST SERIES

The first three subjects in the series were tested without instrumentation to observe the damage response of the subject with respect to select initial head/neck/thorax angles (Figure 11), and also to compare the force-time histories that were measured with the load plate to those obtained in the pendulum impact study (13).

The pendulum impact study found that initial head/neck/thorax positioning was a critical factor with respect to the damage produced (as well as the force-time histories), and that the damage was almost exclusively of two types. Flexion-type damage was found to occur in the upper thoracic spine, and extension-type damage was observed in the cervical spine.

Initial conditions for the pendulum study included aligning the mid-sagittal anatomical plane of the head and neck with the AP-IS plane of the thorax in an attempt to restrict the resulting motion to two dimensions. However, three-dimensional motion was consistently observed in those tests in which flexion-type damages occurred.

Similarly, for the three preliminary tests performed in the present study, the head was pulled with tape such that the chin was tucked into the chest and the mid-sagittal plane of the head was aligned with the AP-IS plane of the chest initially and for the duration of the fall (Figure 9). In these three tests, the thorax was angled at 20, 25, and 25 degrees relative to the horizontal (Figure 11), and drop heights were 1.0 m, 1.8 m, and 1.5 m, respectively.

Based on this limited number of preliminary tests, a trend exists indicating that there is no gross difference between pendulum impacts and free-fall impacts in terms of damage response and force-time history. As in the pendulum impacts, both cervical spine extension-type damages and thoracic spine flexion-type damages were observed. One cervical spine flexion-type damage was observed in the second subject, although it must be considered that this subject was extremely osteoporotic and sustained many damages not produced in those subjects which were more structurally intact. With respect to forces recorded, the peaks and durations were similar to those in the pendulum impact tests, and the shear force recorded by the load plate was negligible. In addition, the head motion obtained from the dual camera system was similar to that observed in the pendulum tests.

For the pendulum impact tests, thoracic spine flexion-type damages were always associated with three-dimensional motion of the head after impact. Therefore, it appears that the possibility of obtaining cervical spine flexion-type damages is small when the mid-sagittal anatomical plane of the head is initially constrained in the AP-IS plane of the thorax (with resulting motion primarily in the mid-sagittal plane). Additionally, it is unlikely that the head/neck motion of vehicle occupants in which cervical spine flexion-type damages are common follows such a two-dimensional path during the impact event due to randomly oriented initial positioning.

Some observations based on this extremely limited number of preliminary tests are the following:

- Free-fall tests are not significantly different from the 56 kg pendulum impact tests in terms of damage response and force-time history for subjects with similar initial conditions.
- The damages associated with flexion-compression motion of the head for subjects with the mid-sagittal plane of the head initially aligned with the AP-IS plane of the thorax are primarily cervical spine extension-type damages and not flexion-type damages as was originally thought.

It is hypothesized that the initial conditions for a free-fall test which may result in cervical spine flexion-type damage should take into account the six degrees of freedom for each of the head, neck, and thorax, and the associated constraints. With this requirement comes an extreme increase in the complexity of the test matrix. An initial attempt will be made to reduce the number of test subjects needed by performing a series of low energy (sub-injurious) drops with varying head/neck/thorax angles on each cadaver. It is anticipated that recorded kinematic motion from these tests may be correlated with the type of damage sustained, thereby making up for the increased complexity of the initial positioning factor. To allow for the head/neck/thorax angles to be varied as necessary, the overhead hoist system as described above was developed.

7.0 PRELIMINARY INSTRUMENTED TESTS

Following the uninstrumented test series, two fully instrumented subjects have been tested. The main difference with respect to initial configuration between the uninstrumented and instrumented test series is that for the uninstrumented series the mid-sagittal plane of the head was aligned with the AP-IS plane of the thorax, and for the instrumented series the heads of the subjects were rotated not only about the lateral axis, but also about the AP and IS axes as well. Also, in the instrumented series, the thorax was twisted about its IS axis. The first subject (series 82L487 to 82L489) underwent two low energy drops with different head/neck/torso initial positions and a high energy drop from 1.5 meters. The second subject (series 82L490 through 82L494) underwent four low energy drops and a high energy drop from 1.1 meters.

Post-test autopsies showed that cervical spine flexion-type damages occurred in both subjects. In the first subject a flexion-dislocation damage of C5 was observed, as well as fractures of the first and second cervical vertebrae. These latter damages are proposed to have been caused by overdriving the system and therefore the drop height was reduced for the next test from 1.5 m to 1.1 m to alleviate this problem. The second subject sustained a flexion wedge fracture in the C6-C7 region.

8.0 RESULTS

The raw data for all preliminary instrumented and uninstrumented tests is included in Appendix I. This kinematic data, as well as injury response data, is summarized in Tables 2 through 5. The damage patterns observed from gross autopsies are described in Table 3, where neck damage is classified according to the type of motion traditionally hypothesized to cause the injury (e.g., "extension-compression"). These categories are used only to differentiate between the types of damages observed and do not necessarily correspond to the mechanism producing the injury listed.

Table 4 summarizes the individual test conditions, where the column "Initial Conditions" describes in a broad sense the initial position of a subject's head relative to the thorax prior to the test. For the uninstrumented tests, the mid-sagittal plane of the head was constrained to lie parallel to the AP-IS plane of the thorax; however, for the instrumented tests, the head did not lie in any specific orientation relative to the thorax (see Appendix III, Figure 2).

Some important kinematic quantities obtained from the instrumented tests by the UMTRI three-dimensional motion analysis computer program are presented in Table 5.

TABLE 2. ANTHROPOMETRIC DATA

Subject	Age	Ht (cm)	Wt (kg)
82L484	60	180	67
82L485	61	177	51
82L486	61	181	55
82L487-89	70	160	50
82L490-94	69	171	67

TABLE 3. DAMAGE SUMMARY

82L484

Extension-Compression Type:
  C4/C5 - rupture of disc

Flexion-Compression Type:
  T3 - Fractured right superior articular process
  T2/T3 - Partially torn interspinous ligaments
  T3/T4 - Partially torn ligamentum flavum

82L485 (Extreme Osteoporosis)
  C1, C3, C4 - Fracture of laminae
  C2 - Fracture of dens
  C3 - Fracture of spinous process
  C4,5 - Fracture of vertebral bodies
  C4/C5 - Ruptured disc
  T1,T3,T4 - Fracture of laminae
  T2 - Fractured body
  T3 - Anterior longitudinal ligament torn

82L486

Extension-Compression Type:
  C1 - Fracture of anterior ring at dens
  C4 - Fracture vertebral body;
  C3/C4 - Fractured Spinous Processes
  C2/C3 and C4/C5 - Ruptured discs
  C2/C3, C3/C4, C4/C5 - Anterior longitudinal ligament torn
  C3 - Posterior longitudinal ligament torn

82L489

Extension-Compression Type:
  C1 - Fractures of posterior arch with single fracture of right anterior arch
  C2 - Complete fracture of dens with separation of all anterior ligaments

Flexion-Compression Type:
  C5/C6 - Subluxation of C5 over C6 with disruption of all C5/C6 ligaments, capsules and discs
  T1/T2 - Compression of superior body T2; tear of posterior disc

82L494

Flexion-Compression Type:
  C6 - Fractures of RT lamina and of anterior-superior body
  C7 - Fracture of body and of right lateral facets at base
  C6/C7 - Anterior longitudinal ligament, ligamentum flava, and posterior aspect of dura torn

TABLE 4. TEST SUMMARY

Test No.	Drop Height (m)	Peak Force (kN)	Contact Velocity (m/s)	Initial Conditions	HIC
82L484	1.0	6.7	4.4	Mid-sagittal plane of head initially aligned with AP-IS plane of thorax	--
82L485	1.8	---	5.9		--
82L486	1.5	5.9	5.4		--
82L487	0.1	0.7	1.4	Unconstrained	5
82L488	0.1	0.7	1.4	Unconstrained	7
82L489	1.5	5.4	5.4	Unconstrained	2240
82L490	0.1	1.0	1.4	Unconstrained	2
82L491	0.1	---	1.4	Unconstrained	4
82L492	0.1	0.8	1.4	Unconstrained	3
82L493	0.1	---	1.4	Unconstrained	3
82L494	1.1	5.2	4.6	Unconstrained	477

TABLE 5. SUMMARY OF KINEMATIC DATA FOR INSTRUMENTED SUBJECTS

Test No.	Linear Velocity (m/s)	Linear Acceleration (m/s^2)	Angular Velocity (rad/s)	Angular Acceleration (rad/s^2)
82L487	1.6	157	5.9	375
82L488	2.3	182	5.0	384
82L489	8.5	3400	14	3800
82L490	1.3	91	5.1	354
82L491	1.6	148	1.9	184
82L492	1.5	119	1.5	124
82L493	1.7	101	2.8	192
82L494	6.0	2280	15	10000

8.1 Preliminary Conclusion

Results from the preliminary tests suggest the following tentative conclusions:

- The critical factors associated with cervical spine flexion-type injuries common in many accidents appear to be compression of the vertebral column during impact and also the relative position (in a three-dimensional sense) of the head, neck, and thorax at the initiation of impact.
- When the head is constrained to move in the mid-sagittal plane during crown impact, flexion-type cervical spine injury appears unlikely.
- Flexion-compression type cervical injuries were produced as a result of a 1.1 m crown impact. When the heads of the unembalmed cadaver subjects were constrained to sagittal plane motion, flexion-compression cervical injuries could not be produced. Such injuries could only be produced when the head was pre-positioned to produce non-sagittal plane motion.

8.2 Recommendations for Additional Testing

Additional crown impacts should be conducted where the cadaver's head is constrained to sagittal plane motion. However, for these tests, the sagittal plane bending resistance of the neck should be made quite stiff by artificial means, such as using splints or wrapping with elastic bandages.

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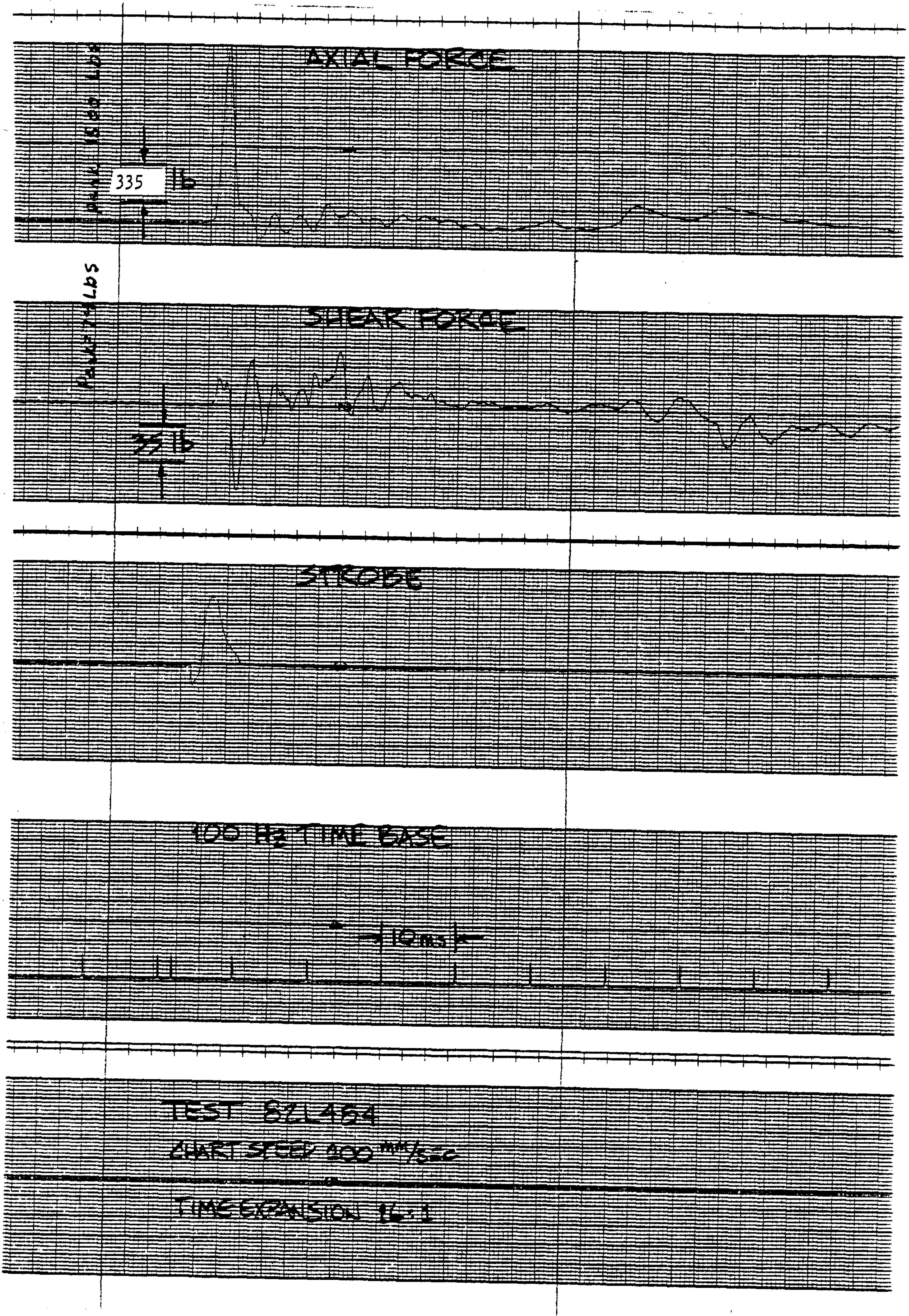
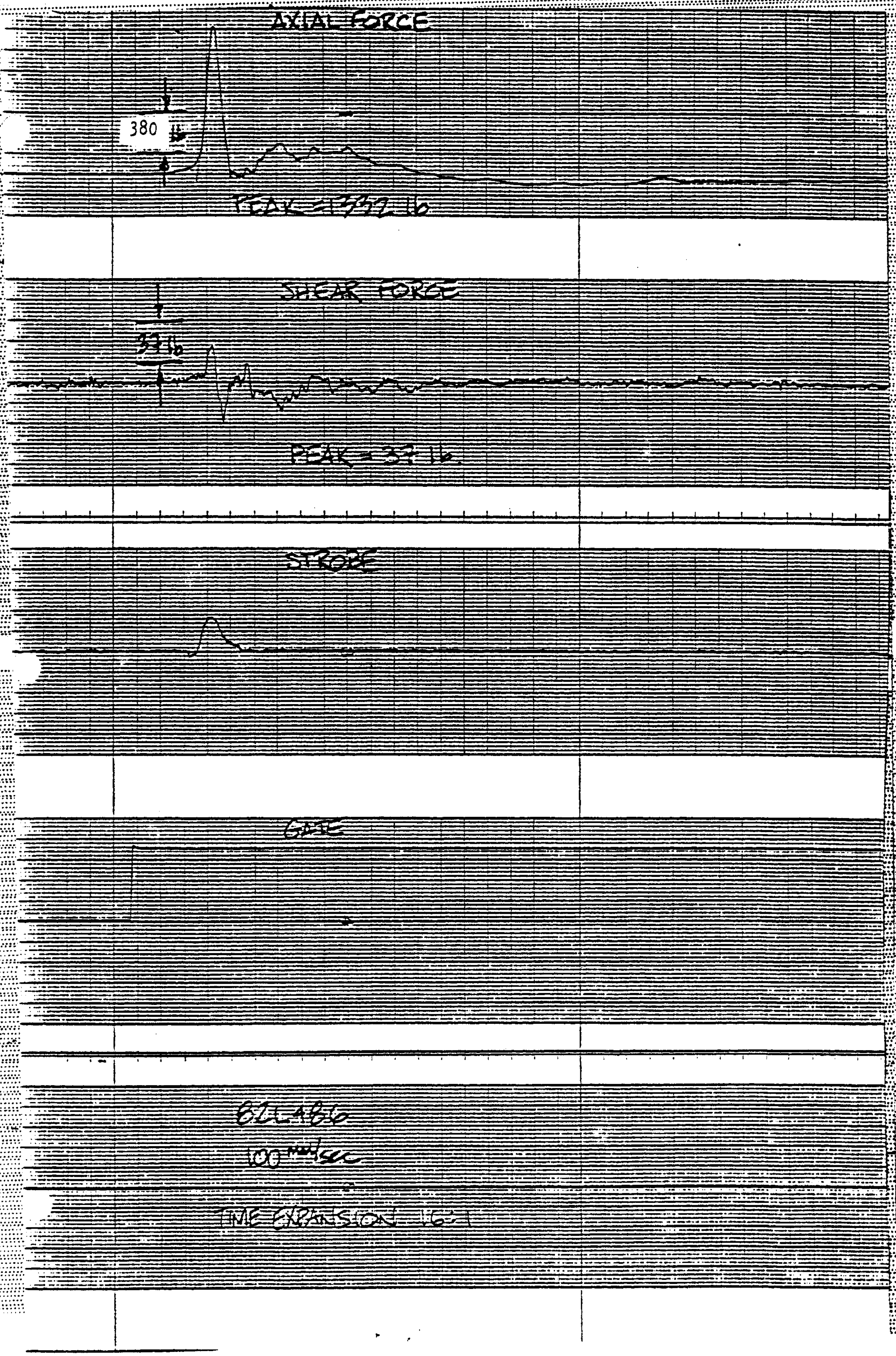
APPENDICES

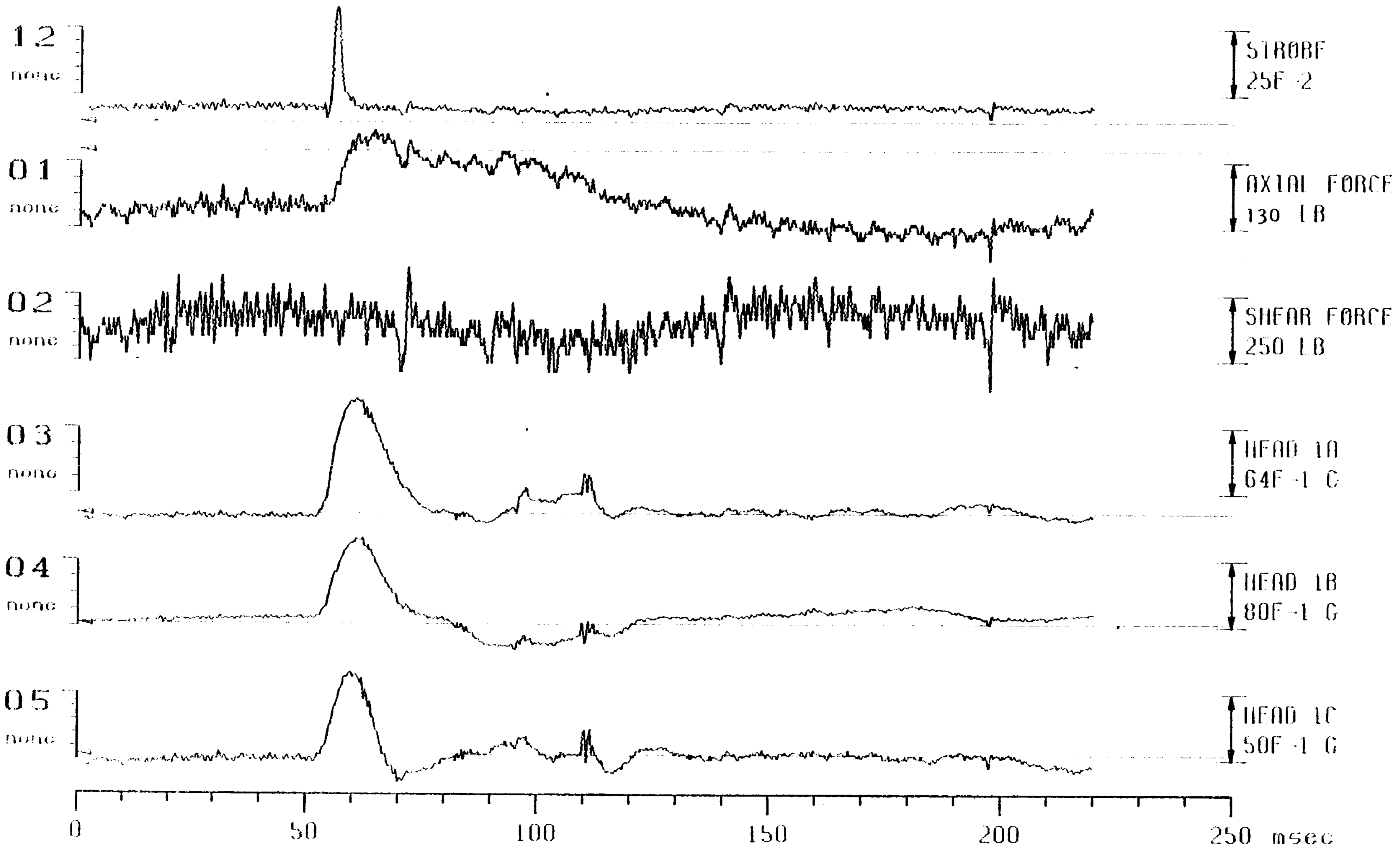
APPENDIX A

TRANSDUCER TIME HISTORIES

AXIAL FORCE
Peak 1800 Lbs
335 lb
Peak 74 Lbs
SHEAR FORCE
35 lb
STROBE
100 Hz TIME BASE
10 ms
TEST 82L464
CHART SPEED 400 mm/sec
TIME EXPANSION 16:1

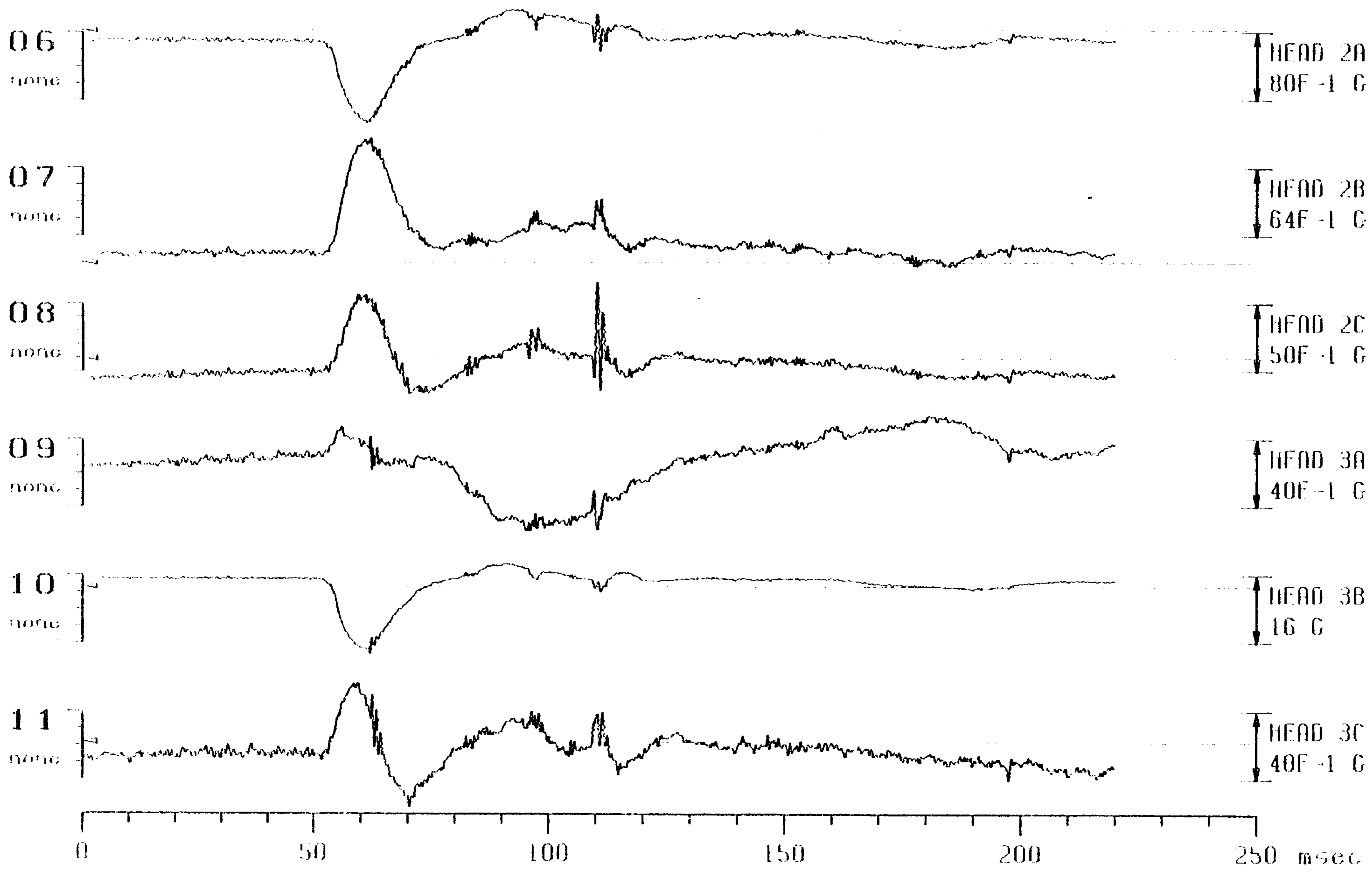

AXIAL FORCE
380 lb
PEAK = 1332 lb
SHEAR FORCE
37 lb
PEAK = 37 lb.
STROBE
GATE
62L486
100 mm/sec
TIME EXPANSION 16:1

FILE # 84 220.00 ms = 1408 Pts / 6400 Hz 14:07:50 14:11:45



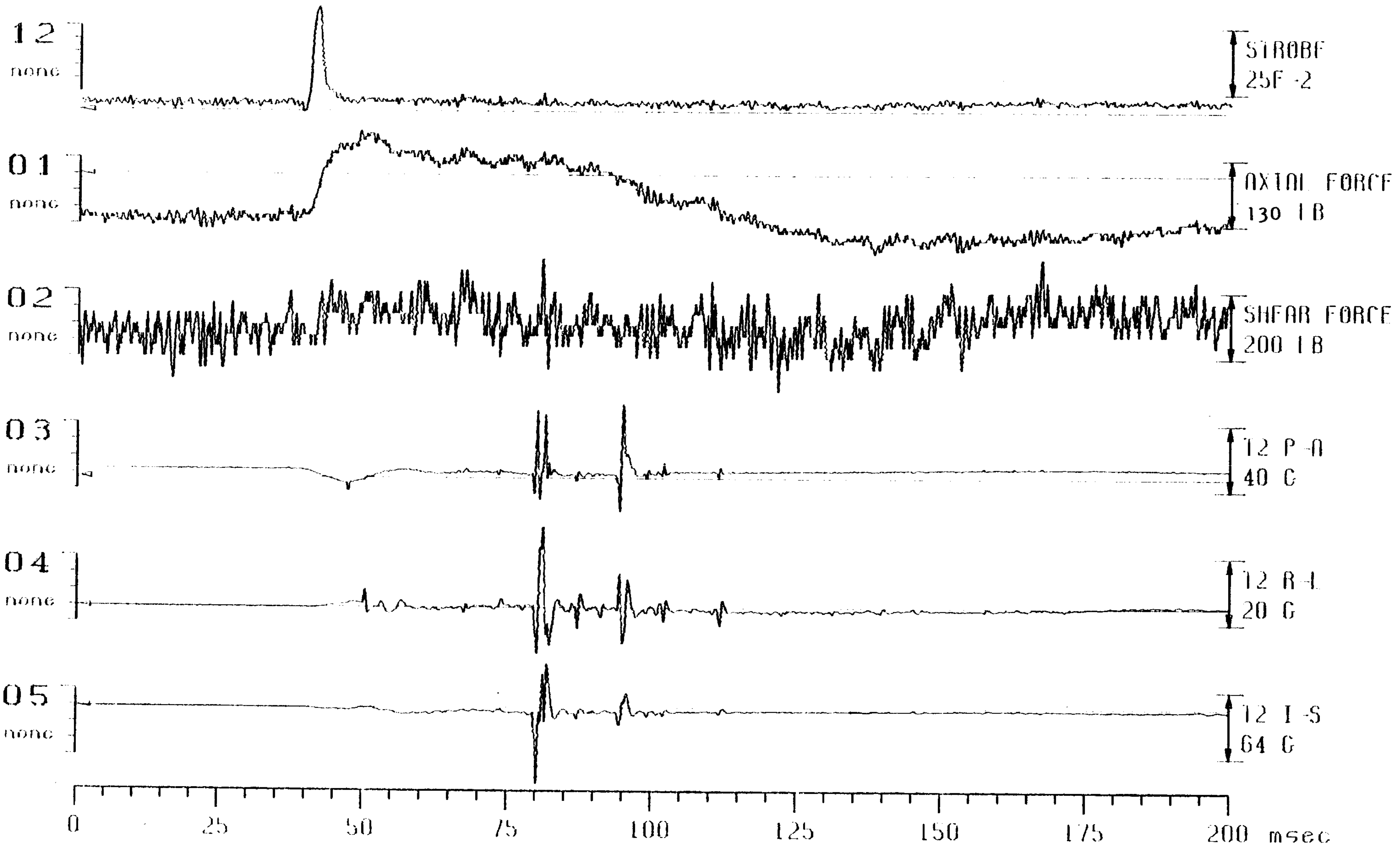
H7 : 166 ← A/D → EL-SORT 12/03/82 82L487

FILE # 84 220.00 ms : 1408 Pts / 6400 Hz 14:36:02-14:39:43



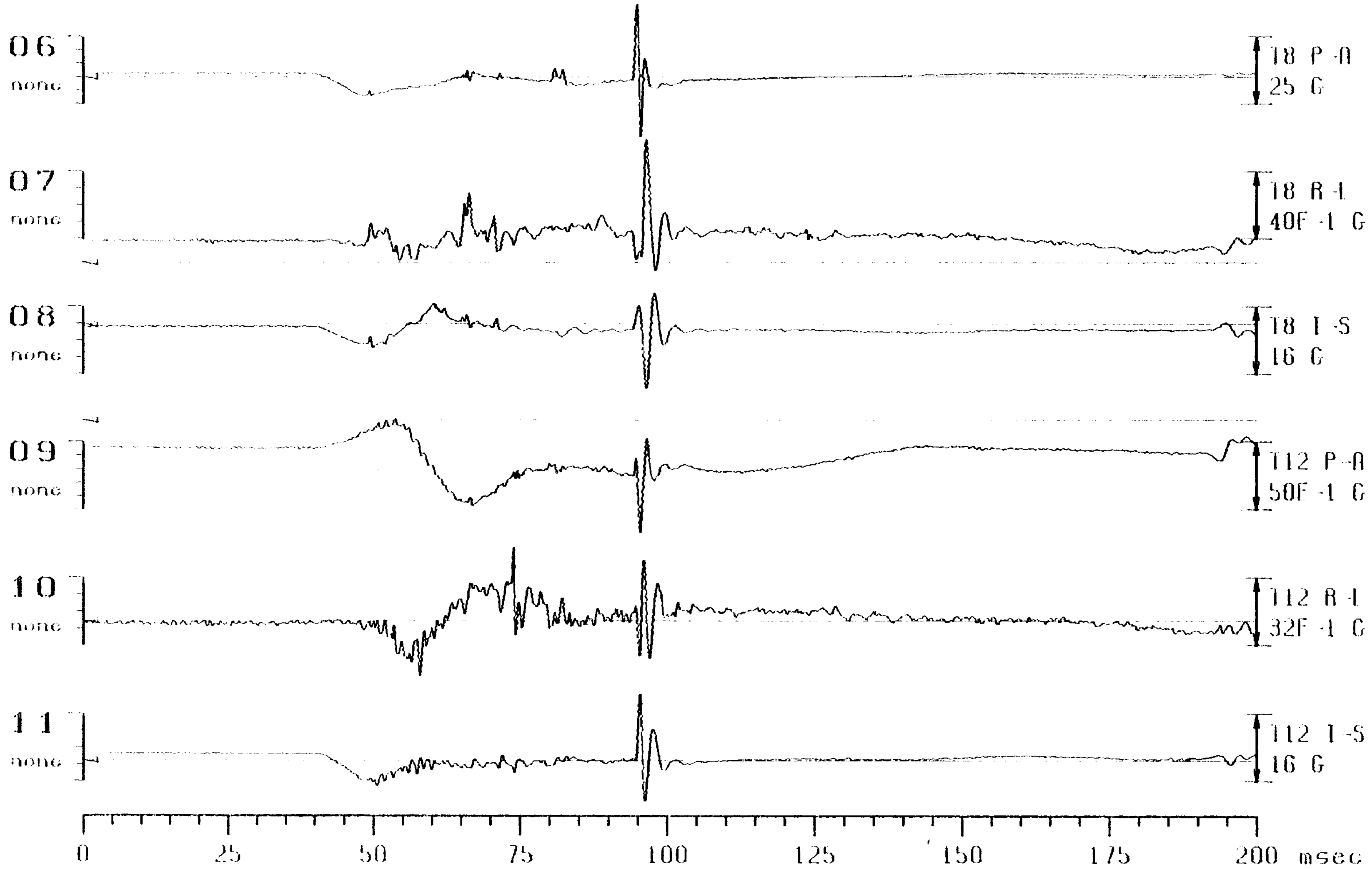
H7 : 166 ← A/D → EL-SØRT 12/03/82 82L487

FILE # 81 210.00 ms = 1344 Pts / 6400 Hz 13:55:34 -13:59:21



C3: 167 ← A/D → EL-SORT 11/24/82 82L487

FILE # 81   210.00 ms : 1344 Pts / 6400 Hz   *14:24:54-14:28:13*



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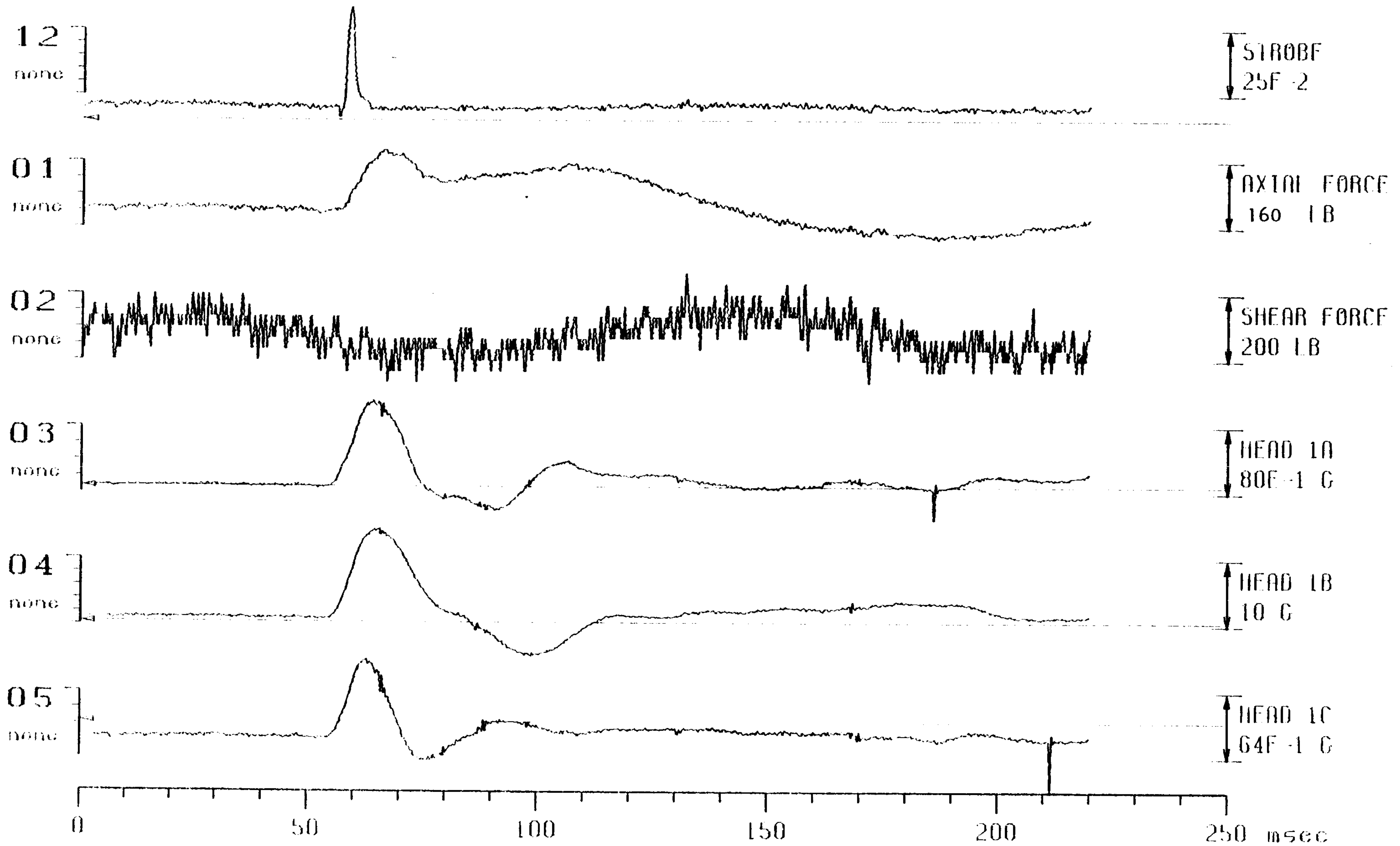

H7: 166   ← A/D → EL-SØRT   12/03/82   82L488

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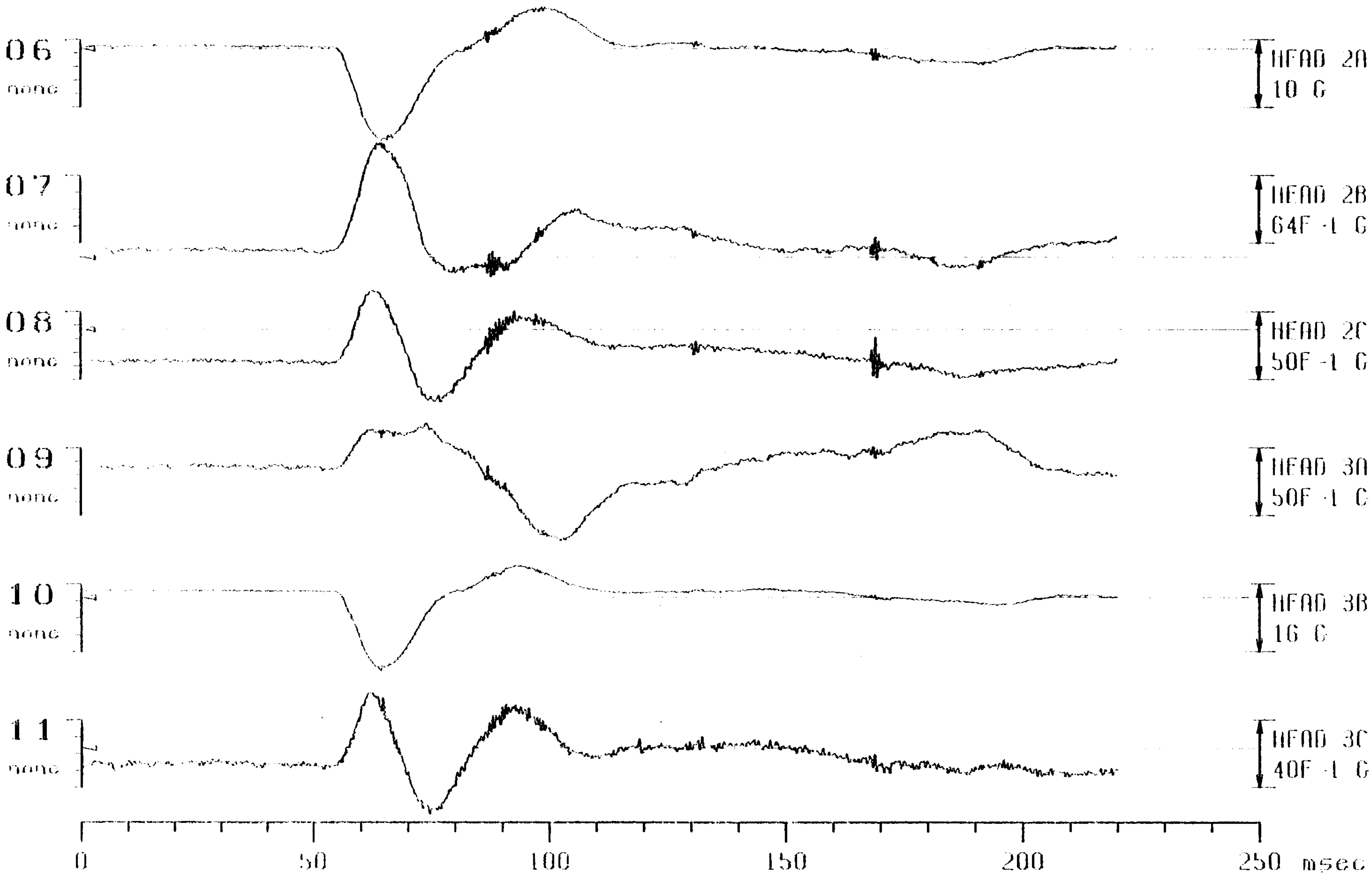

H7 : 166 ← A/A → EL-SØRT 12/03/82 82L488

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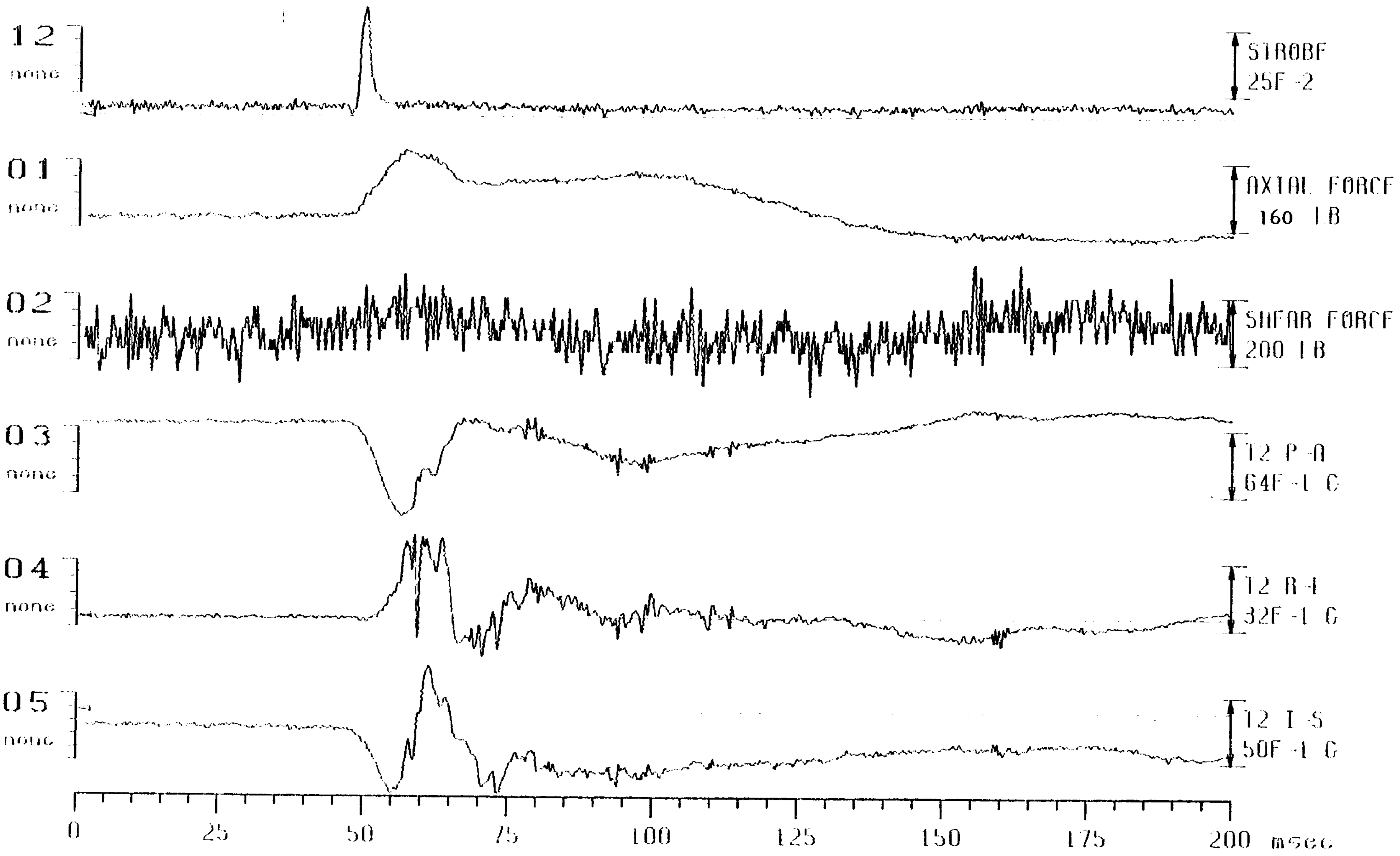
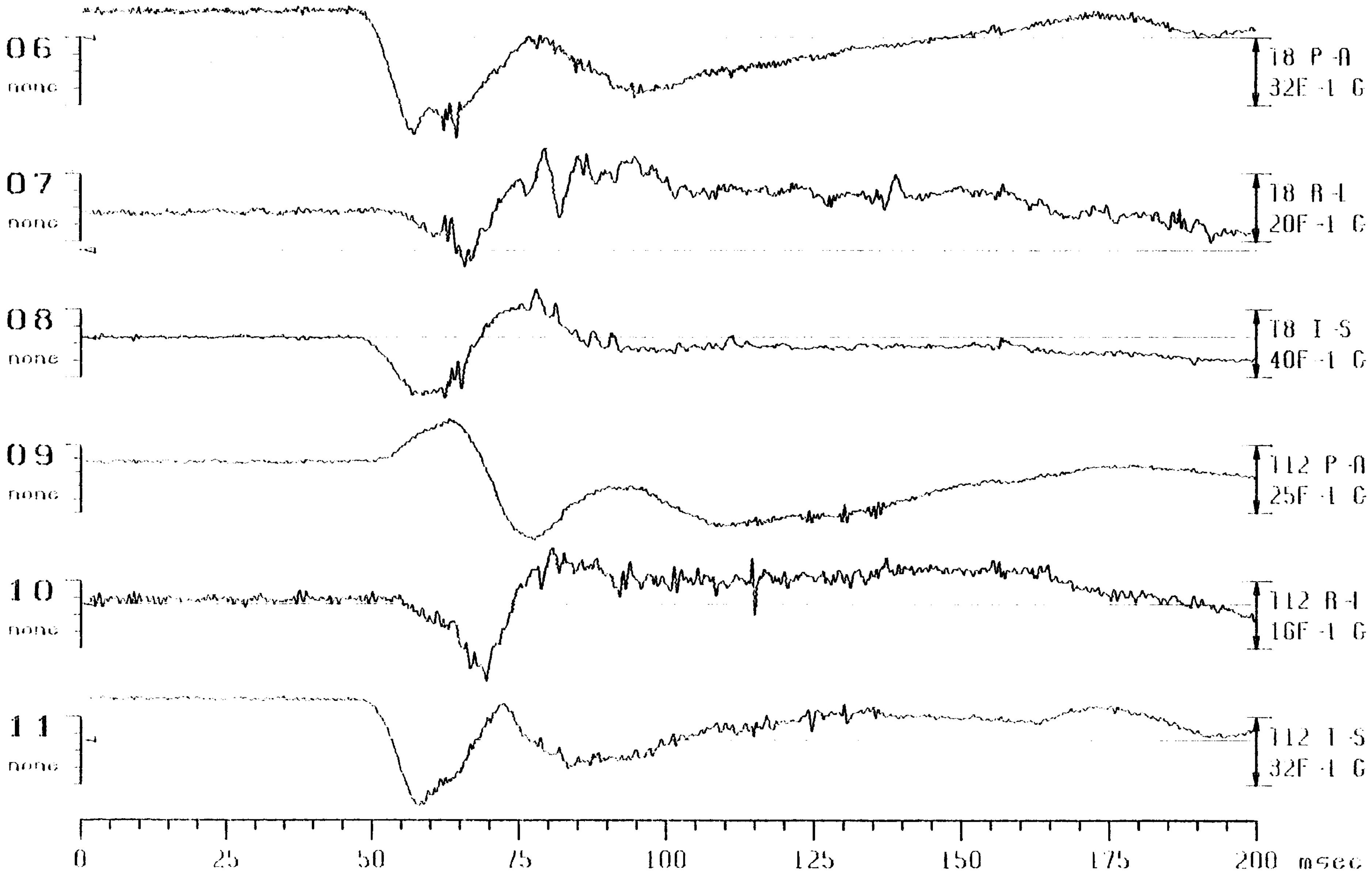


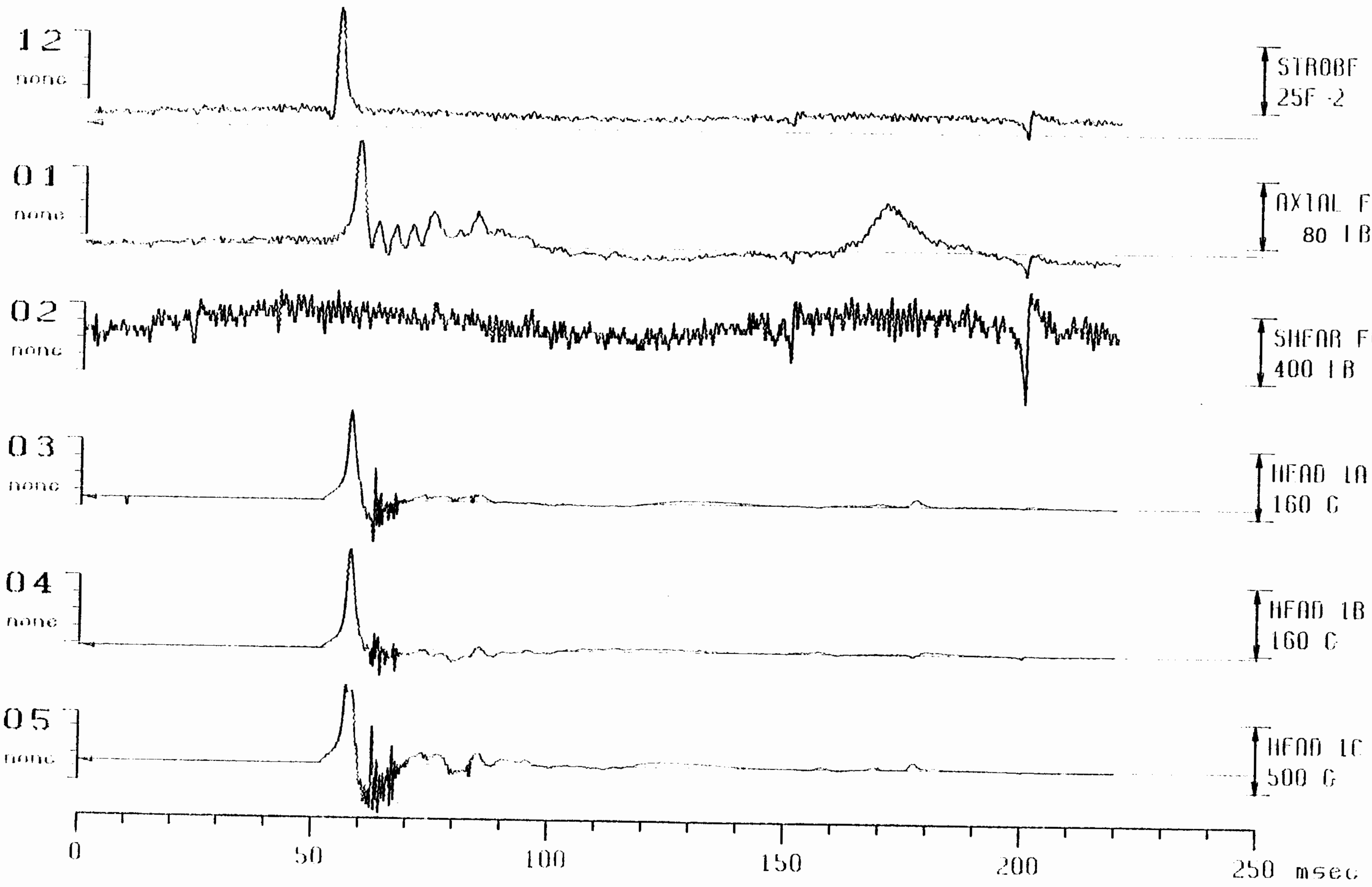
C3: 167   ← A/D → EL-SØRT   11/24/82   82L488

FILE # 8.2 210.00 ms = 1344 Pts / 6400 Hz 14:28:48 → 14:32:14



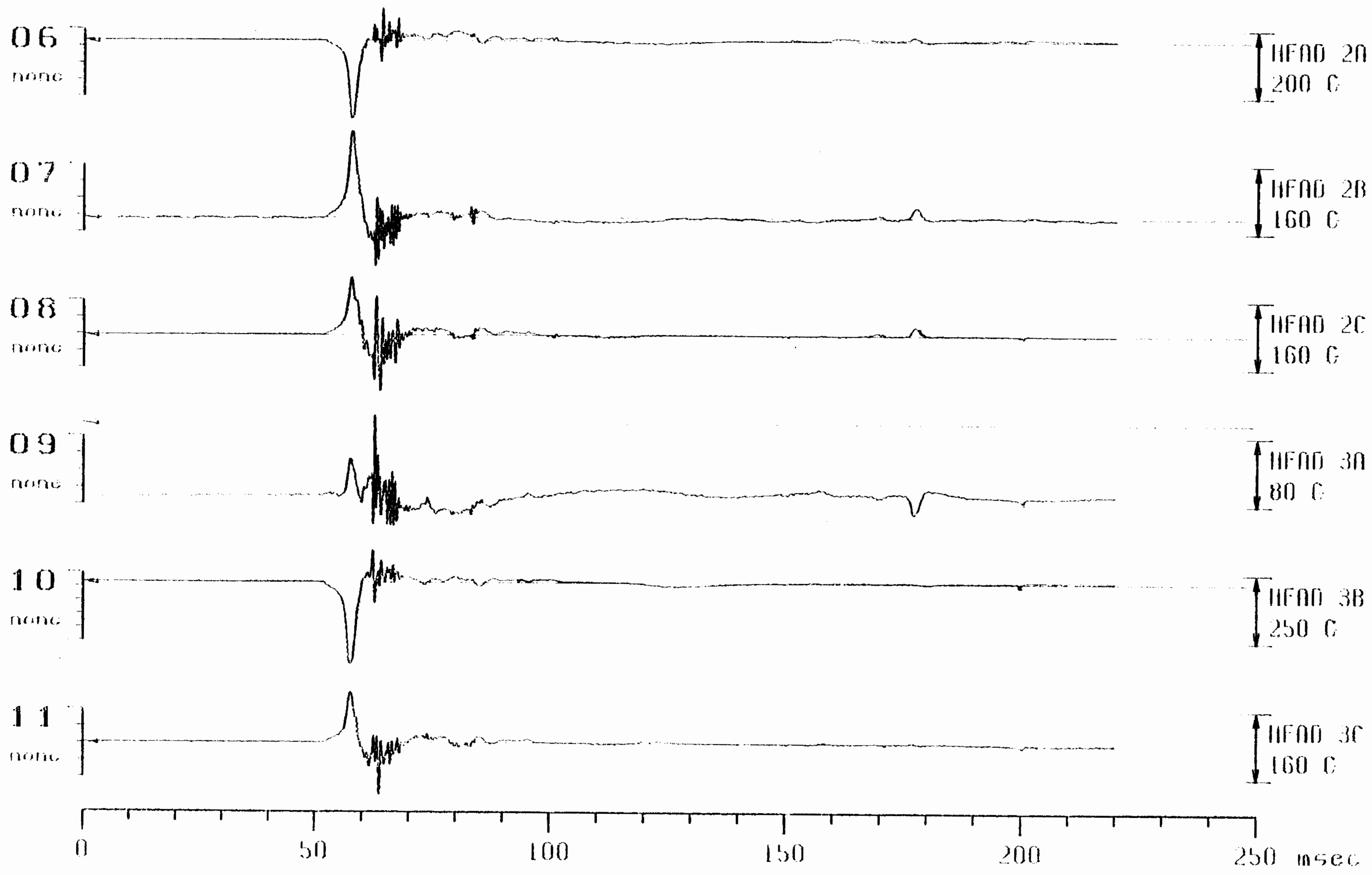
C3: 167 → A/D → EL-SØRT 11/24/82 82L488

FILE # 86   220.00 ms : 1408 Pts / 6400 Hz   14:16:01 -14:19:46



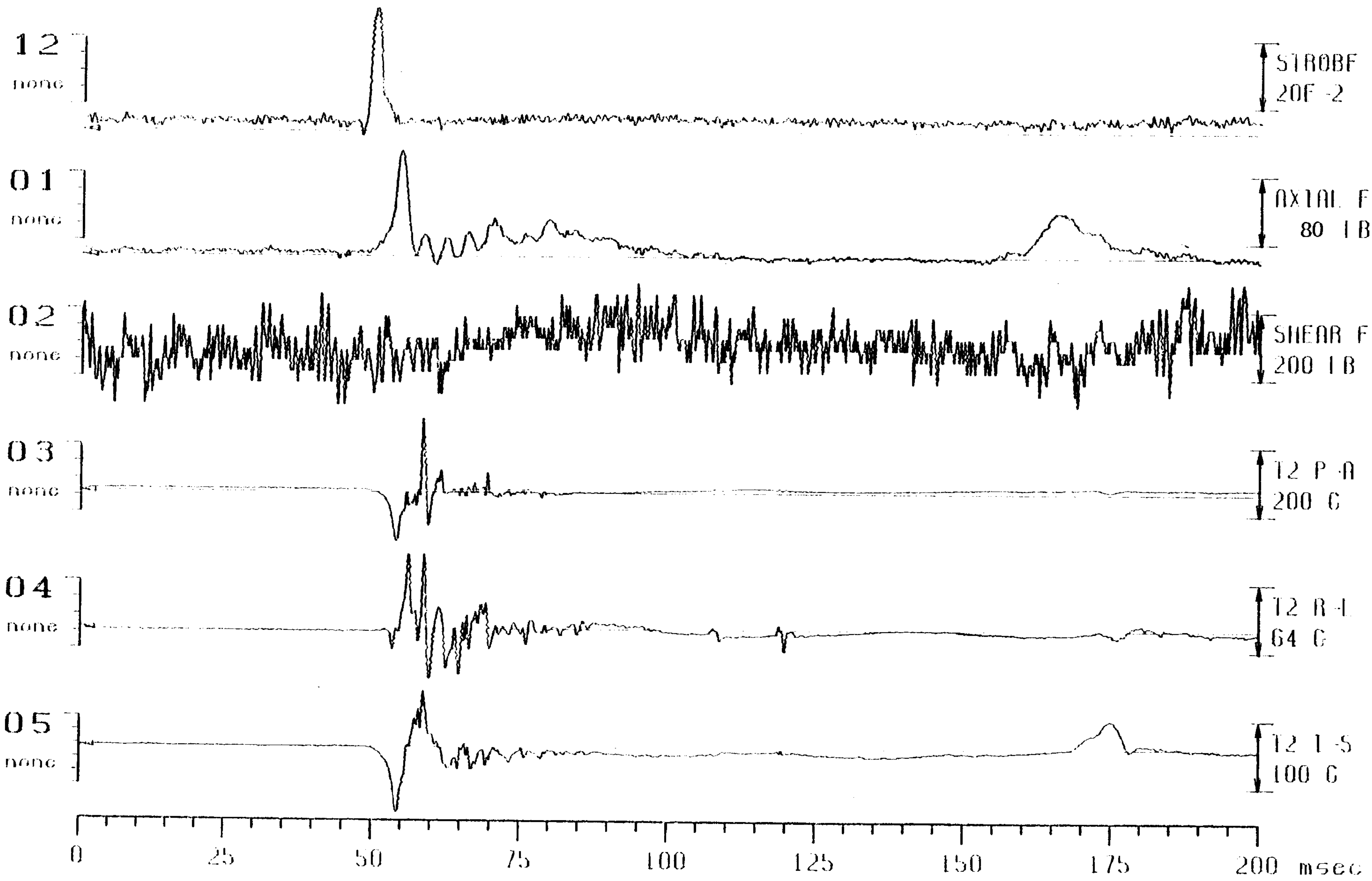
H7 : 166   ← A/D → EL-SORT   12/03/82   82L489

FUF # 86 220.00 ms : 1408 Pts / 6400 Hz 14:43:56•14:47:23



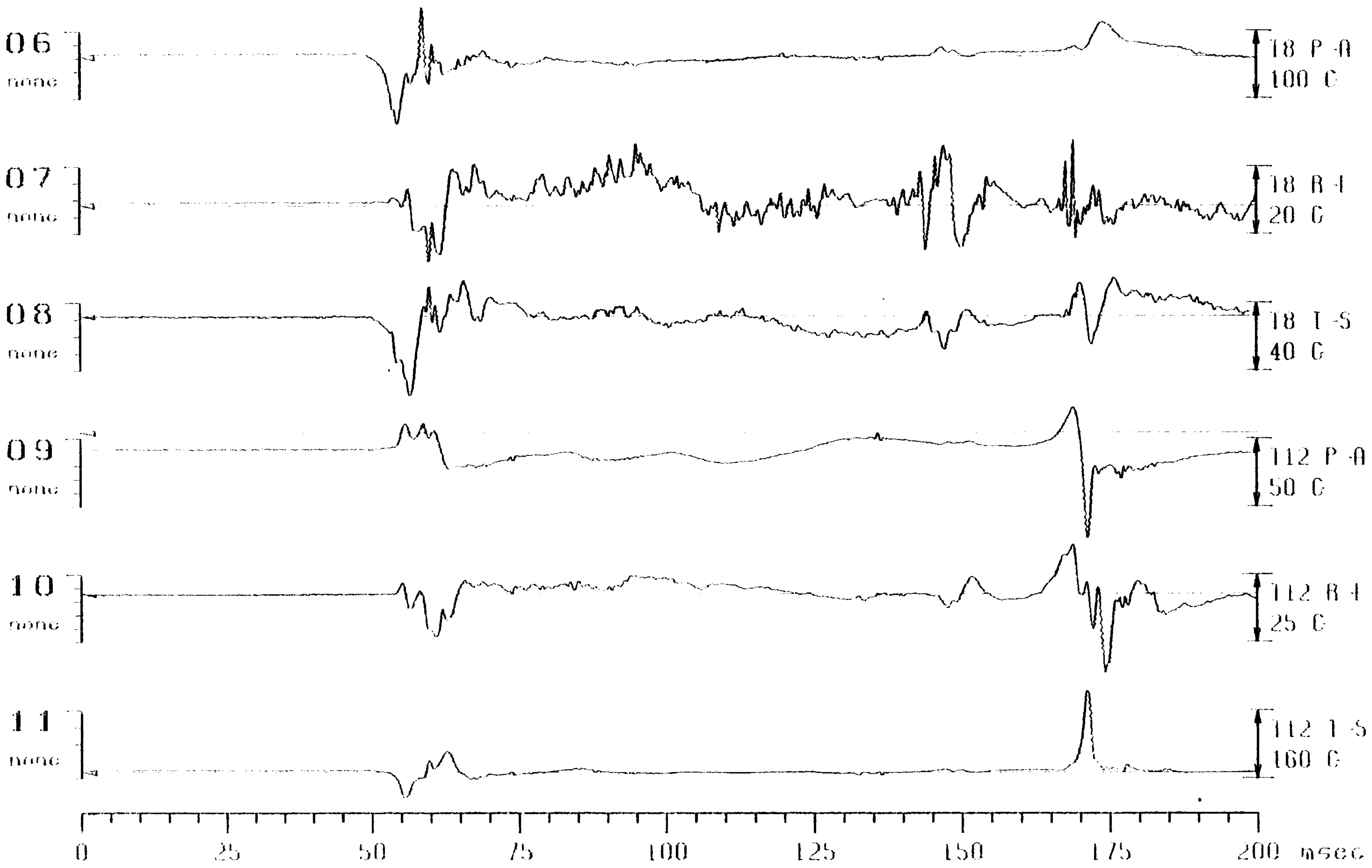
H7 : 166 ← A/A → EL-SØRT 12/03/82 82L489

FILE # 83 210.00 ms = 1344 Pts / 6400 Hz 14:03:38 →14:07:35



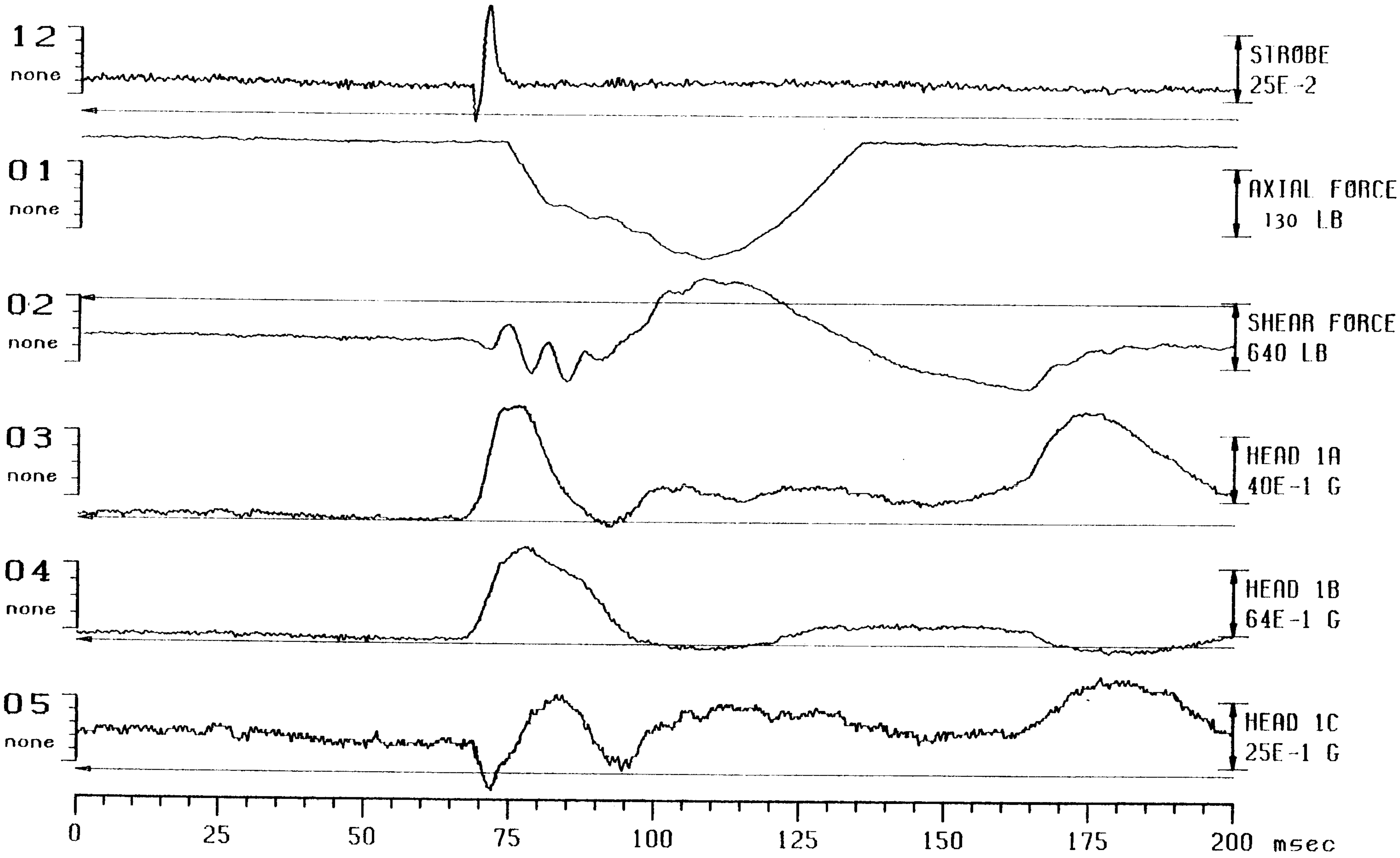
C3: 167 ← A/D → EL-SORT 11/24/82 82L489

FILE # 83 210.00 ms : 1344 Pts / 6400 Hz 14:32:25 -14:35:52



C3 : 167 ← A/D → EL-SORT 11/24/82 82L489

FILE # 92 210.00 ms = 1344 Pts / 6400 Hz 09:43:43→09:47:10



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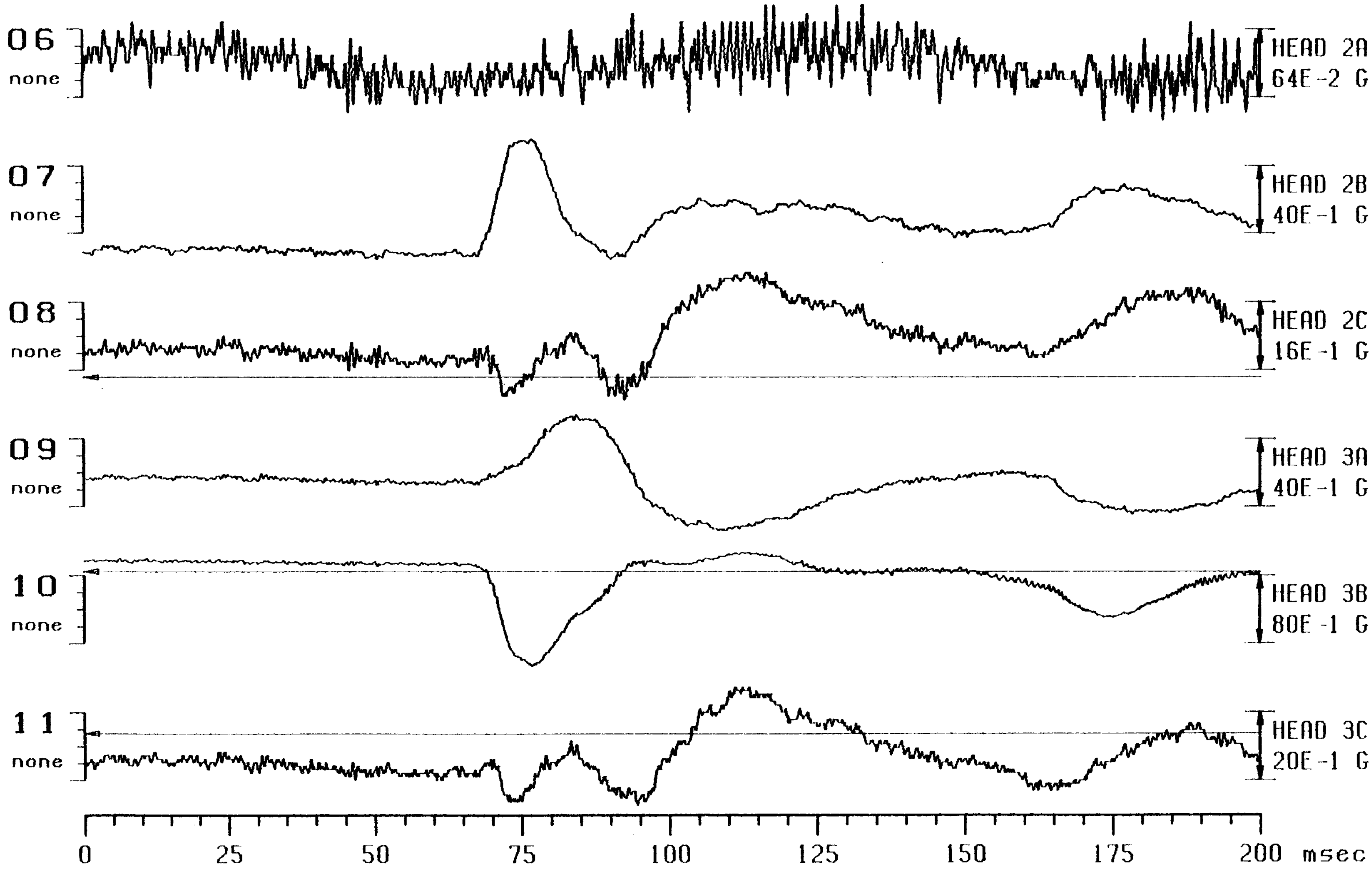

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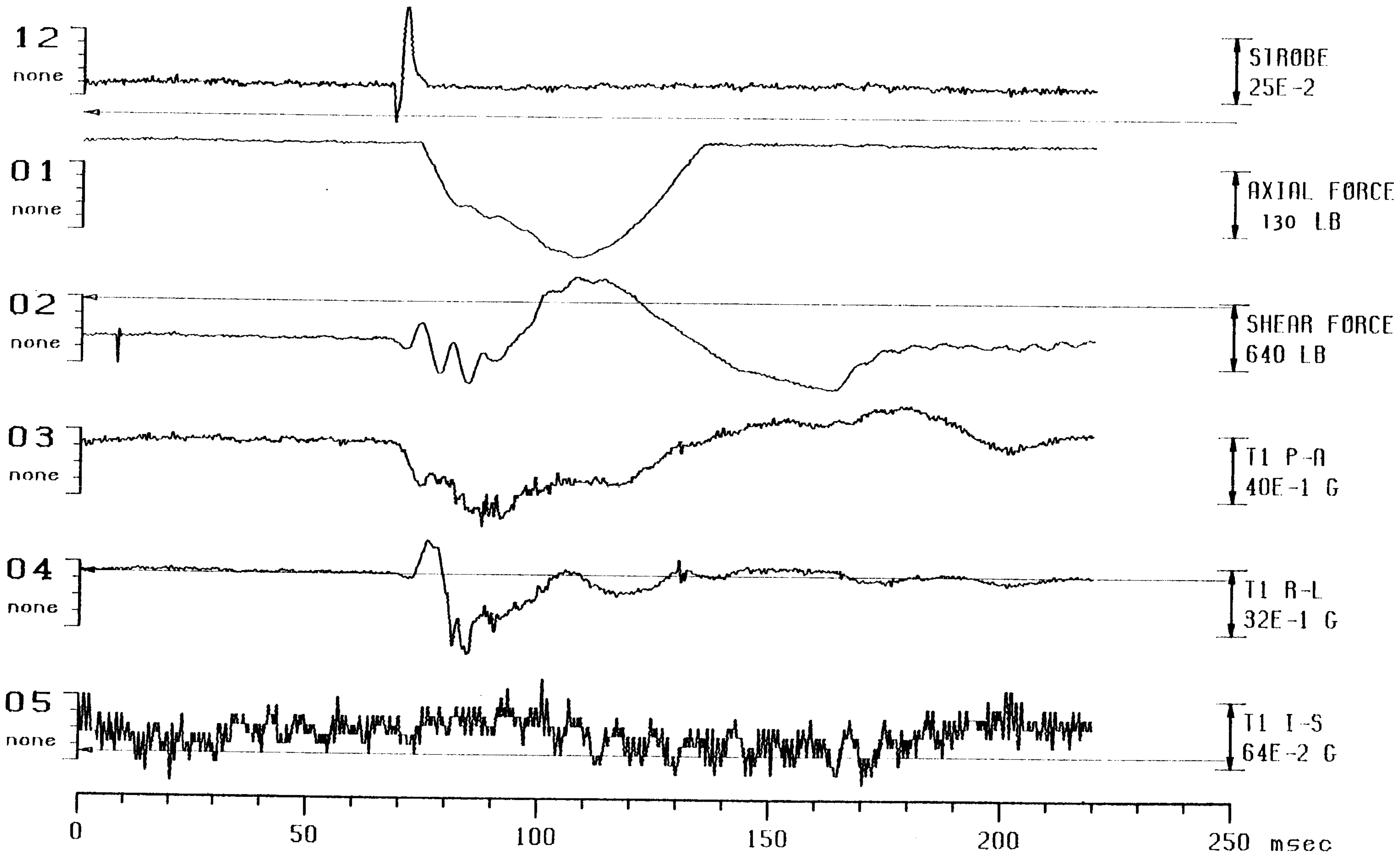

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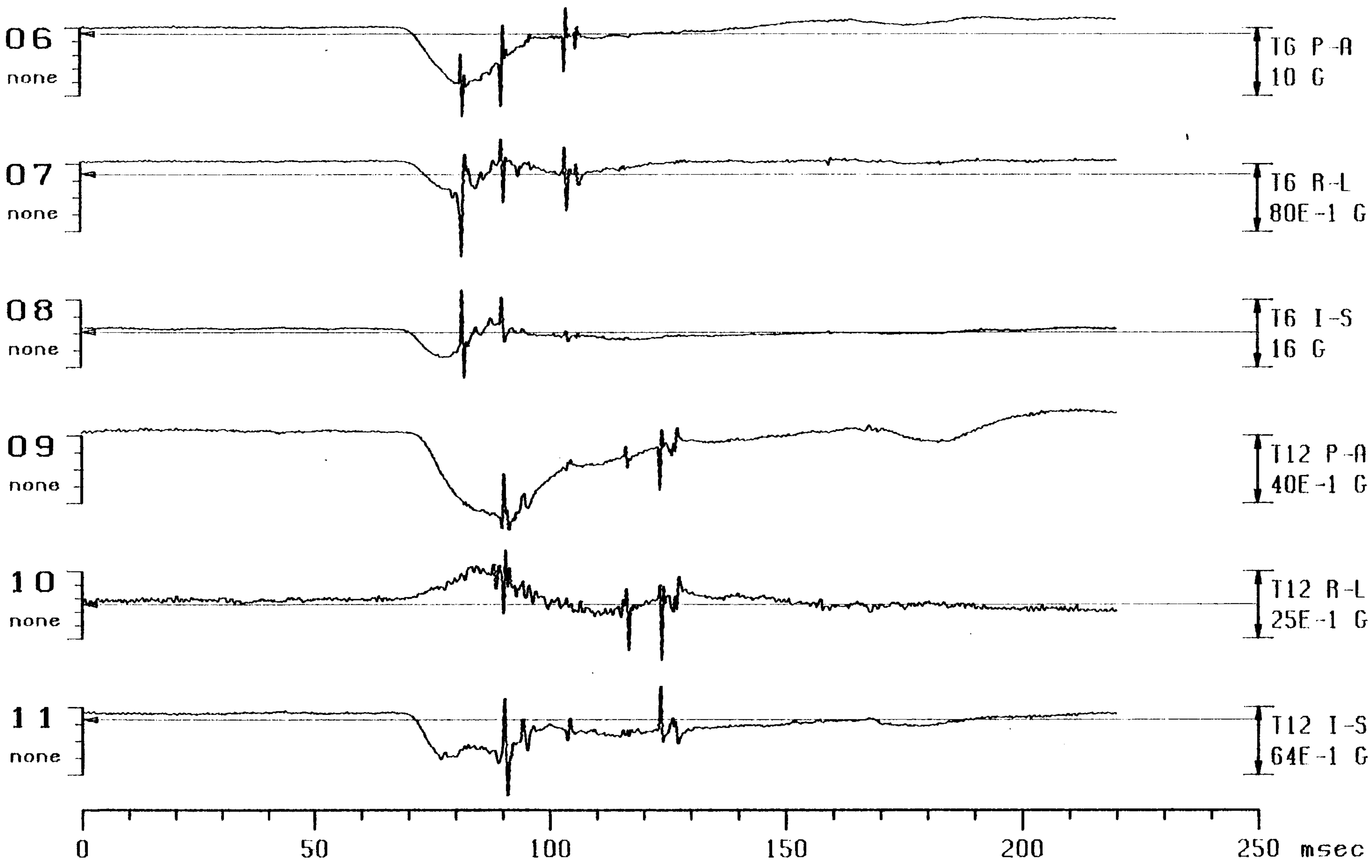

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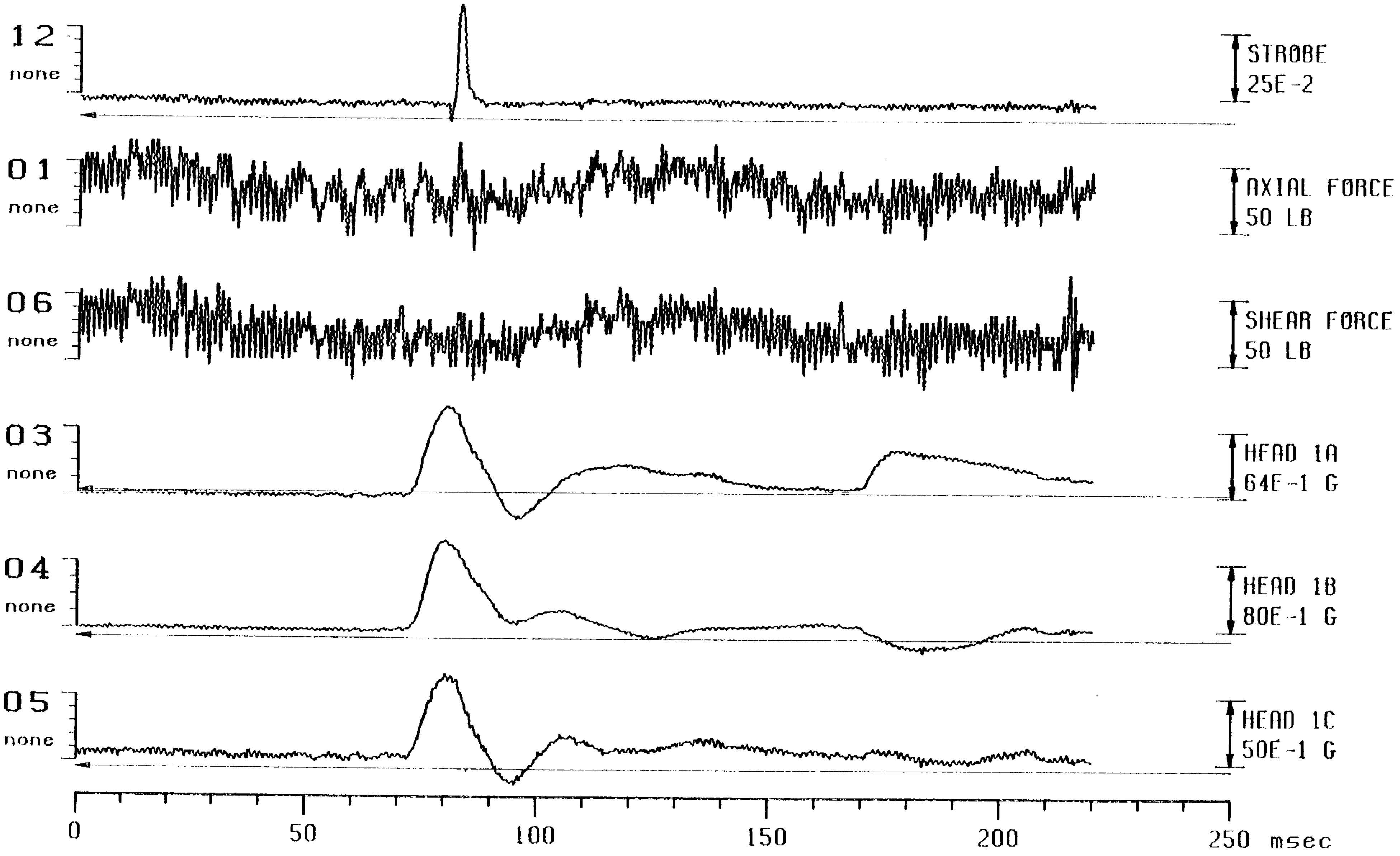

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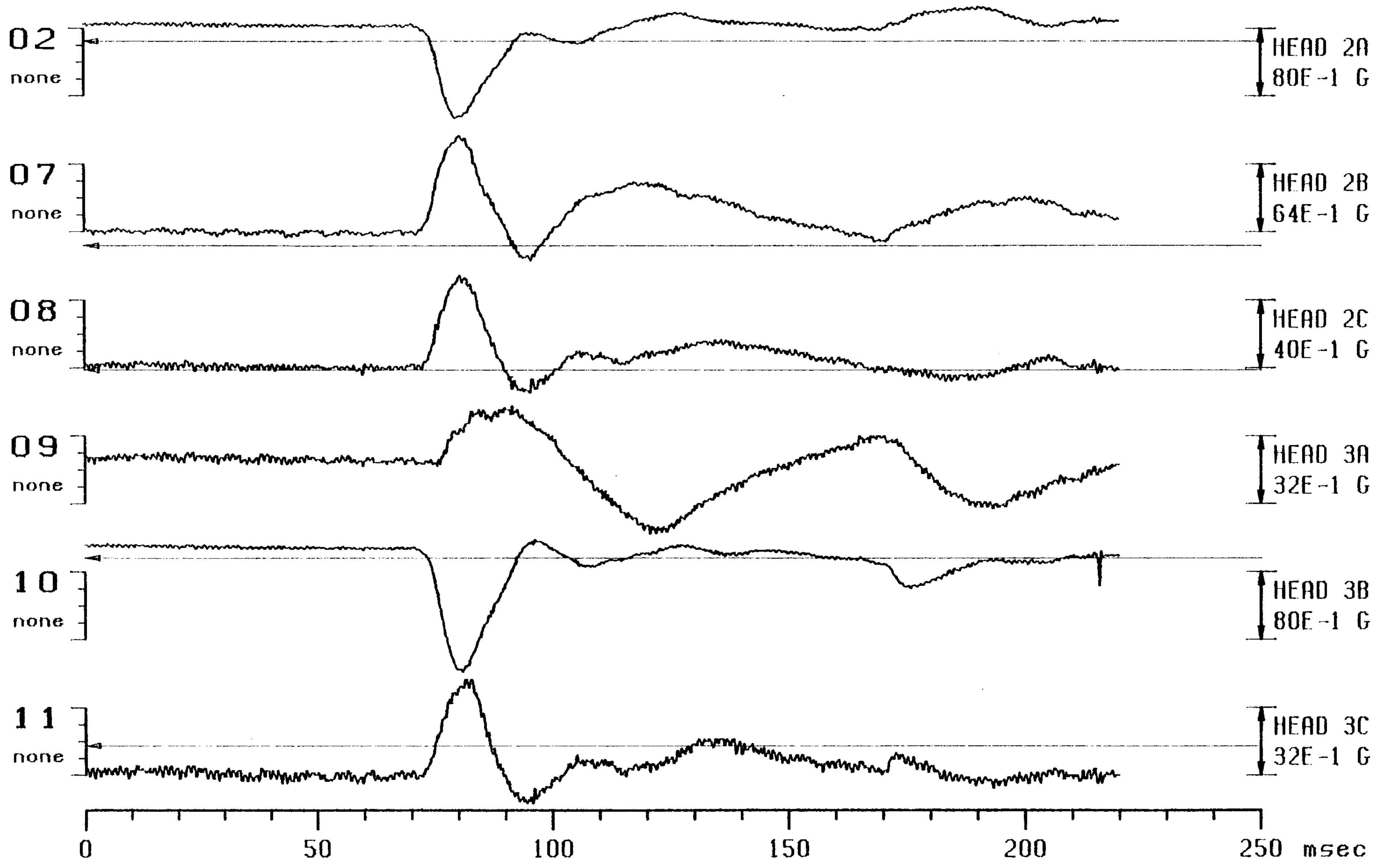
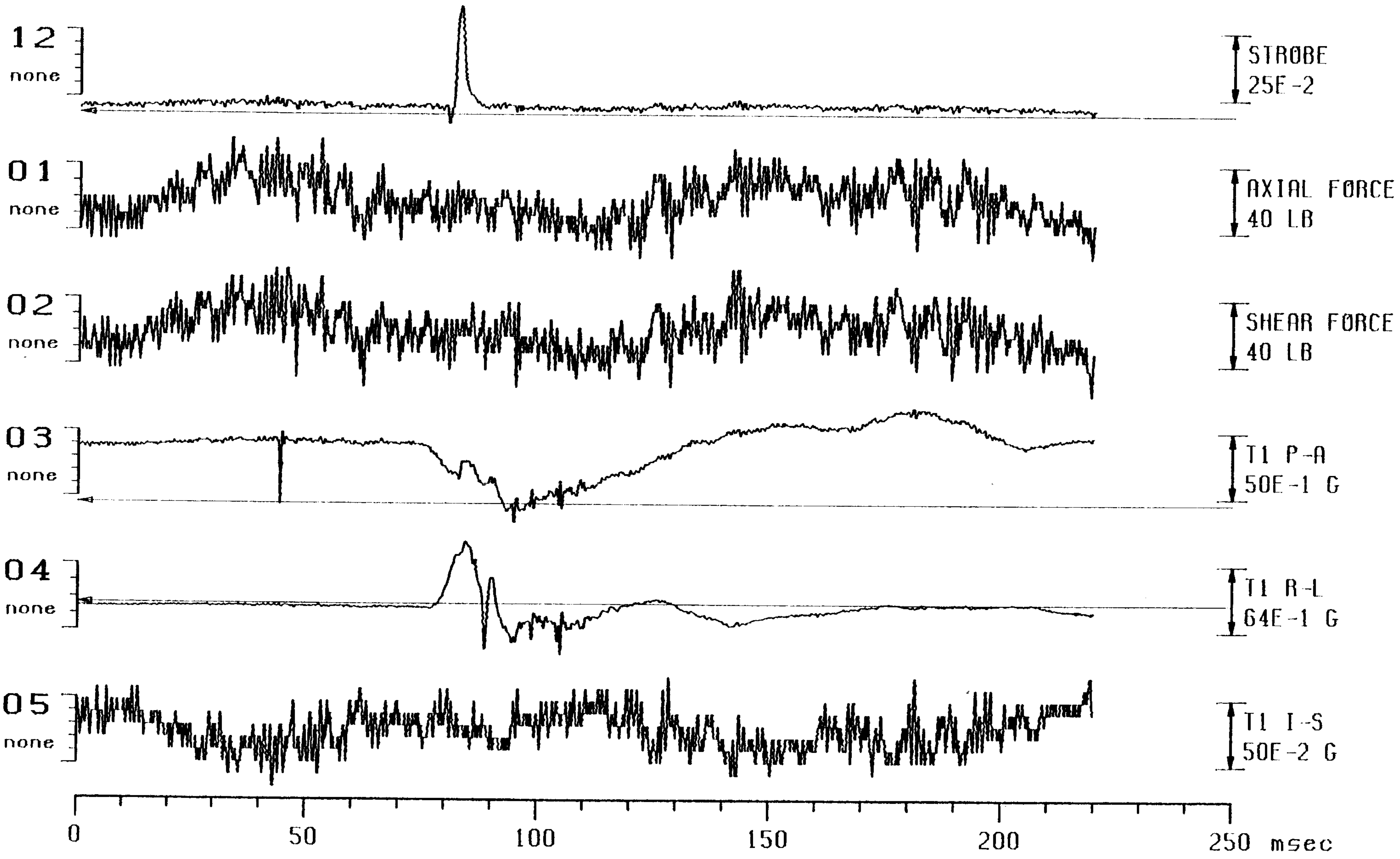


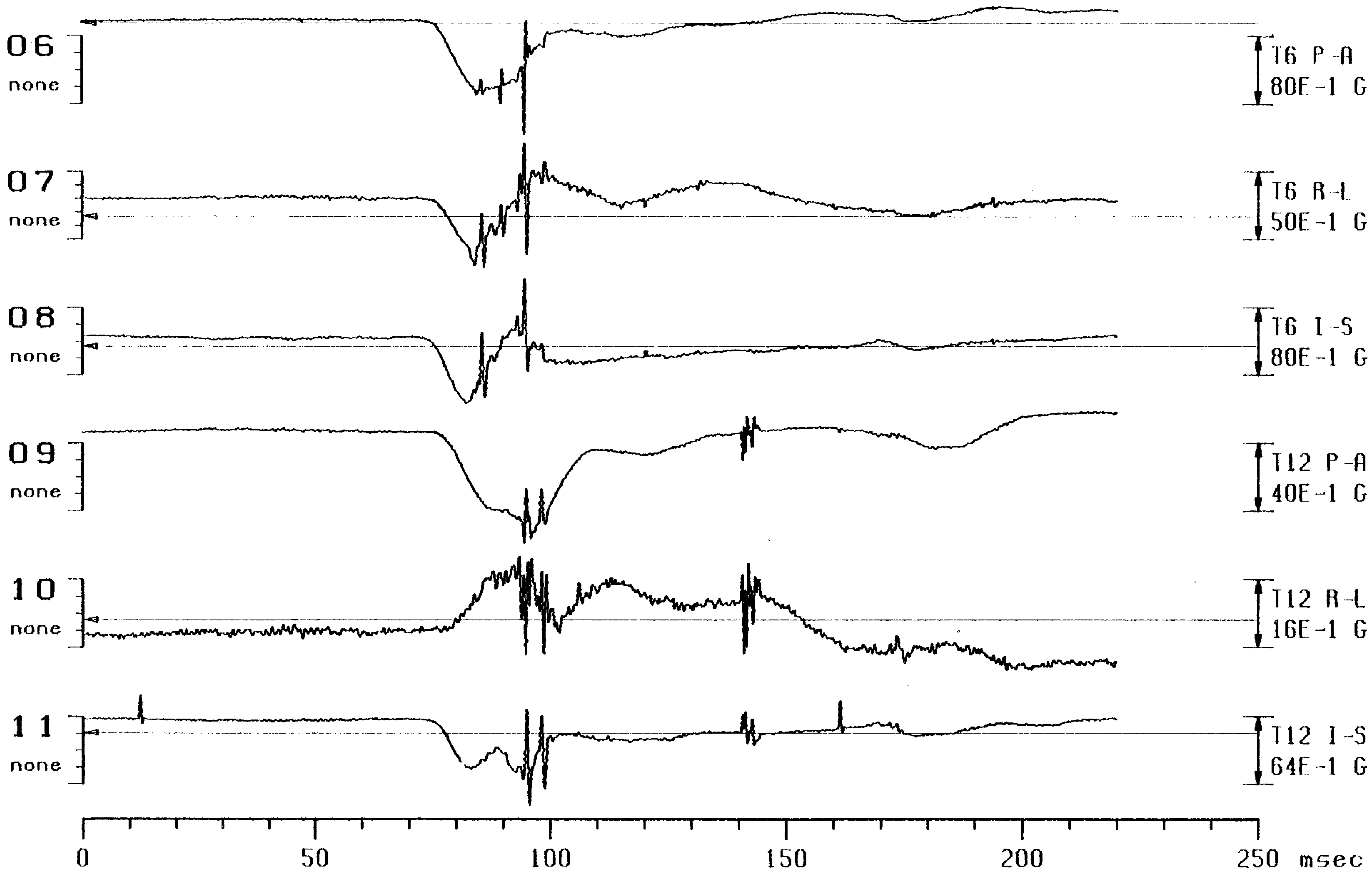
H7: 166   ← A/D → EL-SØRT   12/03/82   *82L491*

FILE # 93 220.00 ms = 1408 Pts / 6400 Hz 12:29:10 •12:33:32



C3: 167 ← A/D → EL-SØRT 12/03/82 *82L491*

Fl[illegible] # 93 220.00 ms = 1408 Pts / 6400 Hz 12:39:24→12:42:46



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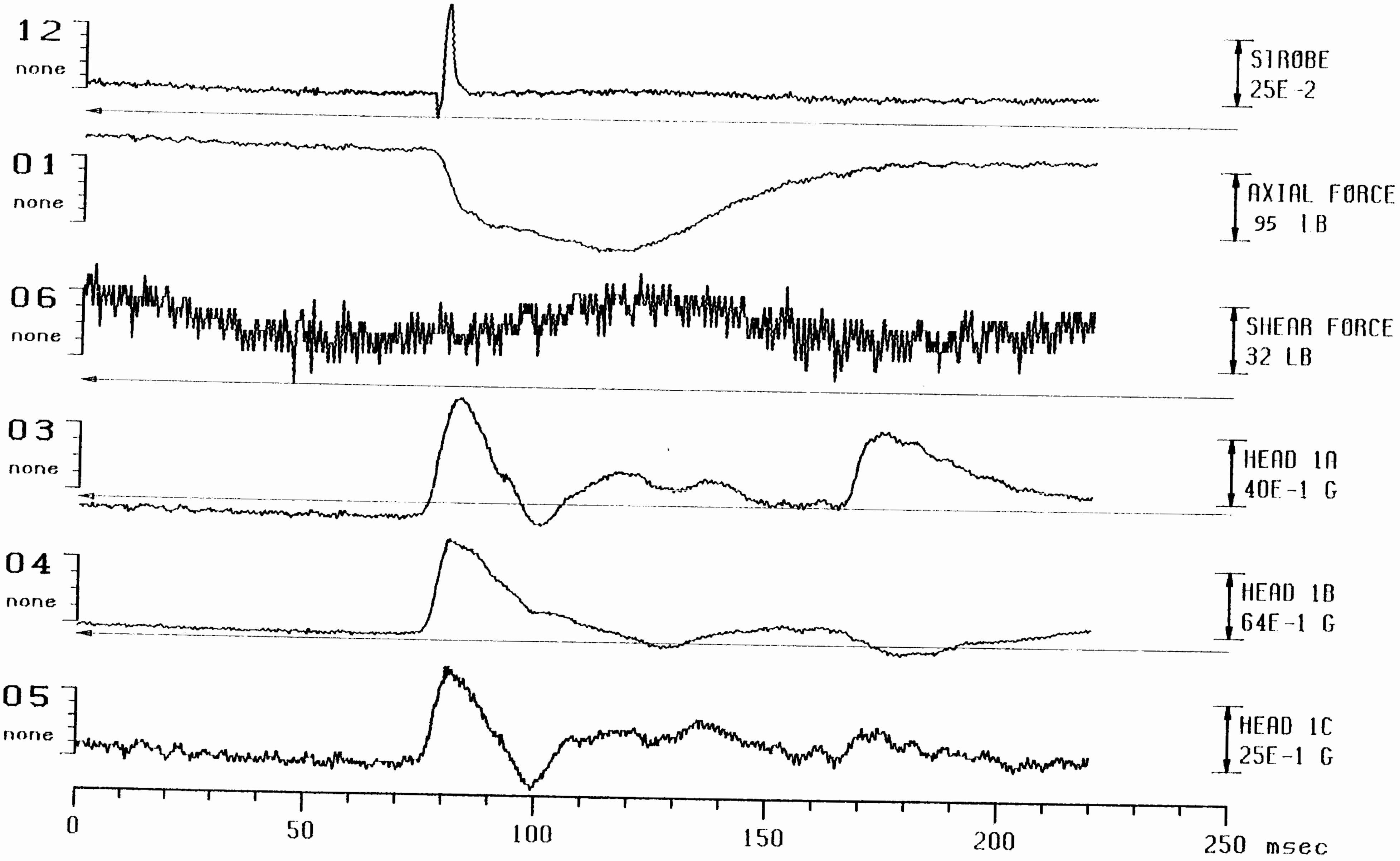

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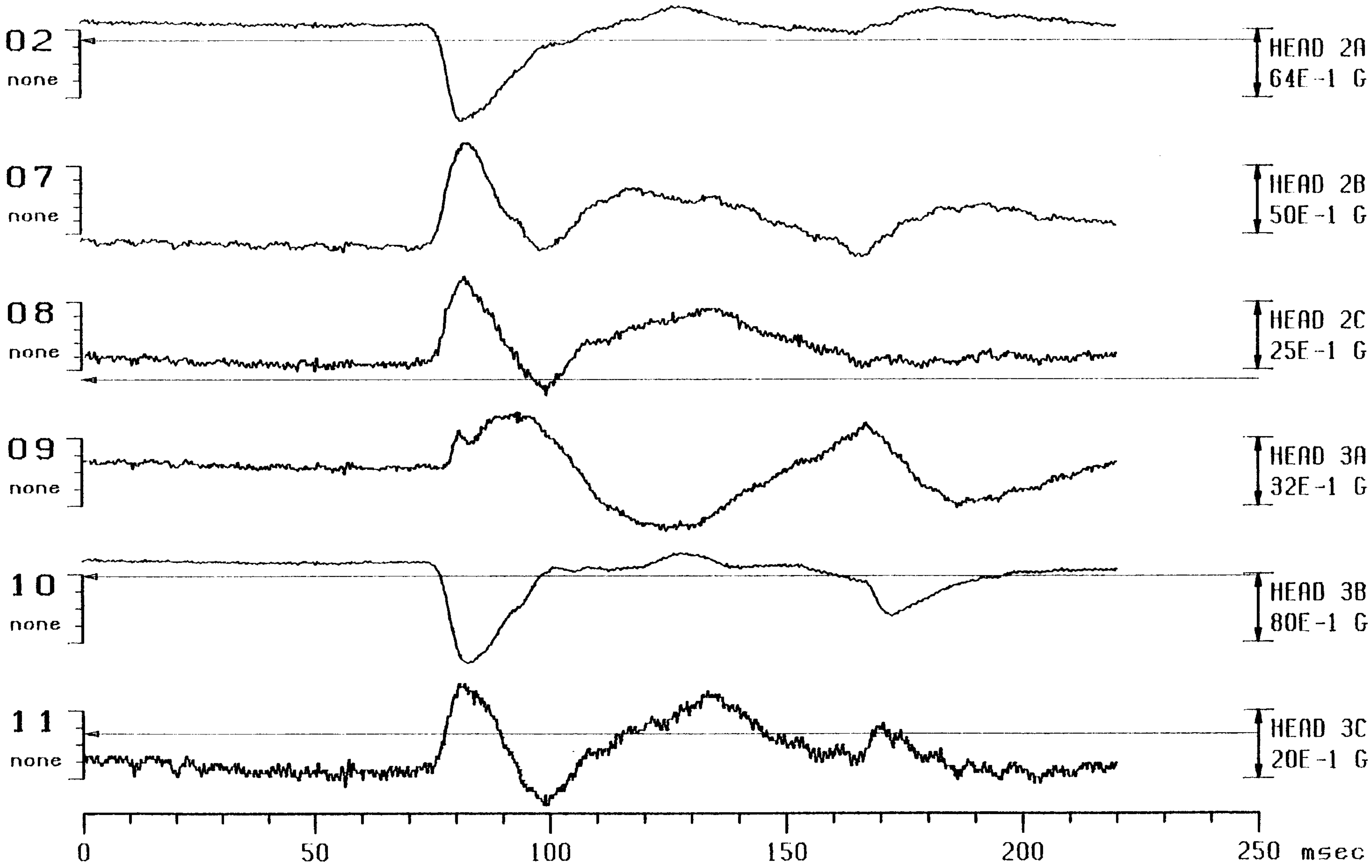

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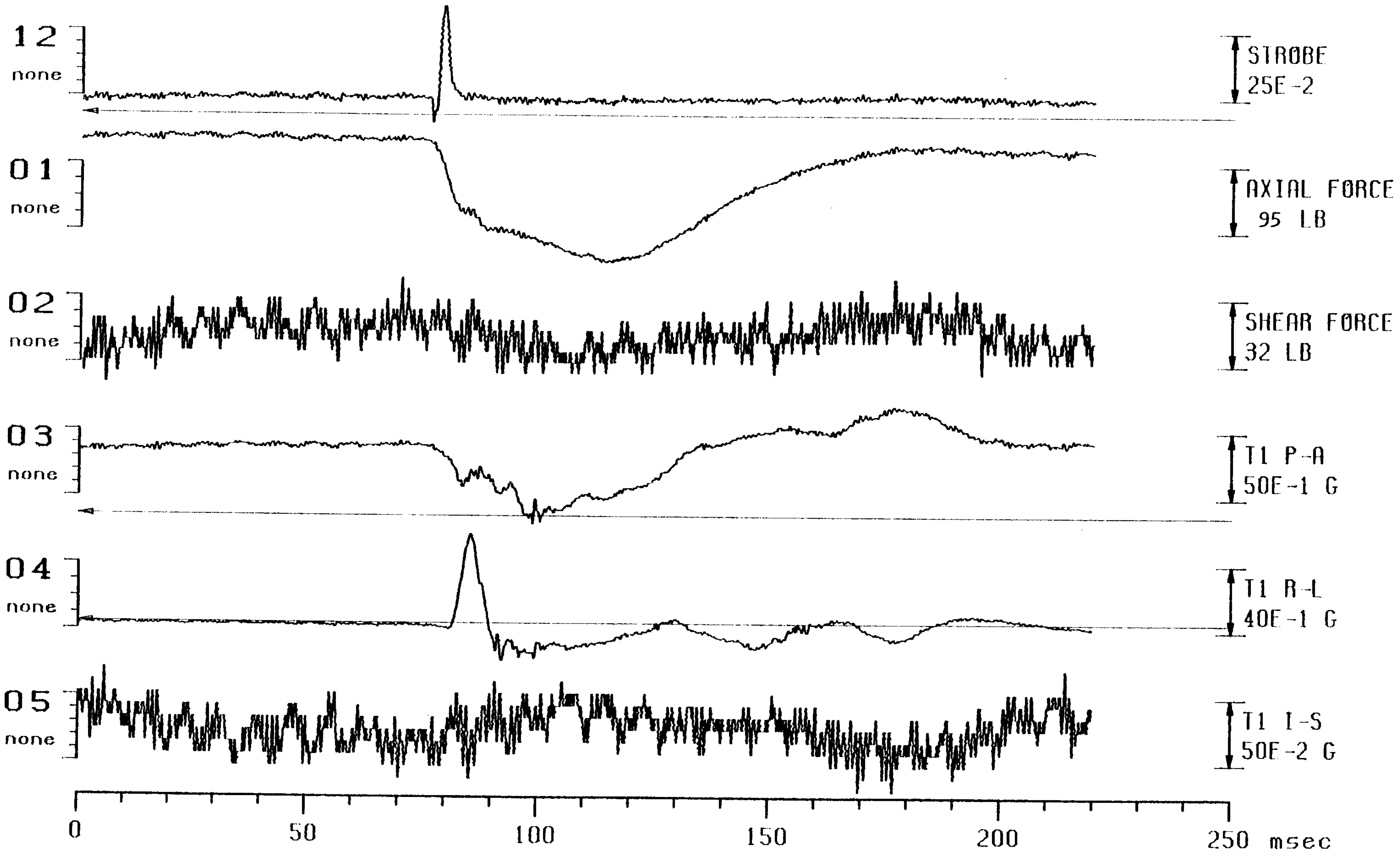
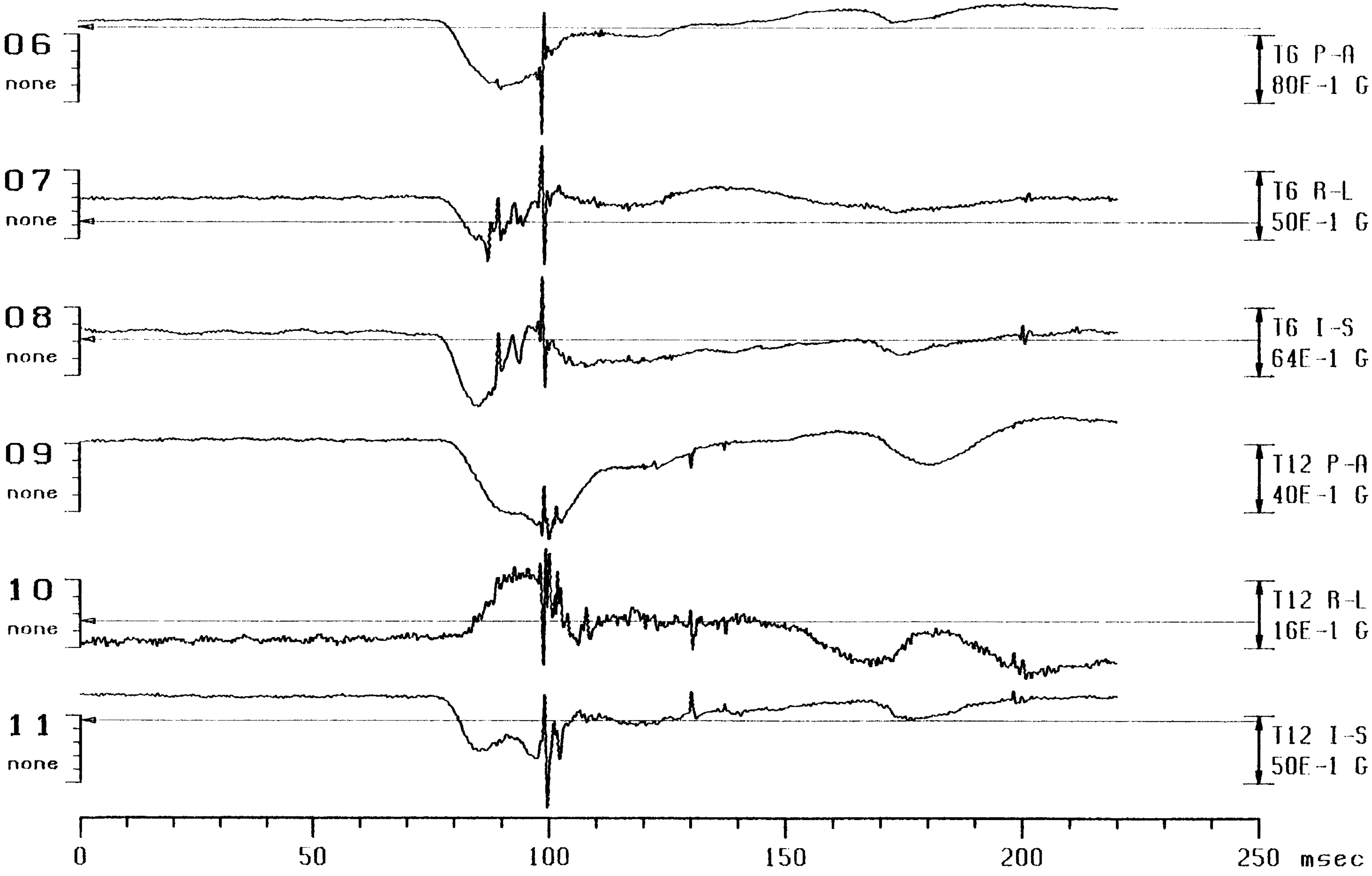
FIL. # 94 220.00 ms = 1408 Pts / 6400 Hz 12:33:54→12:37:56



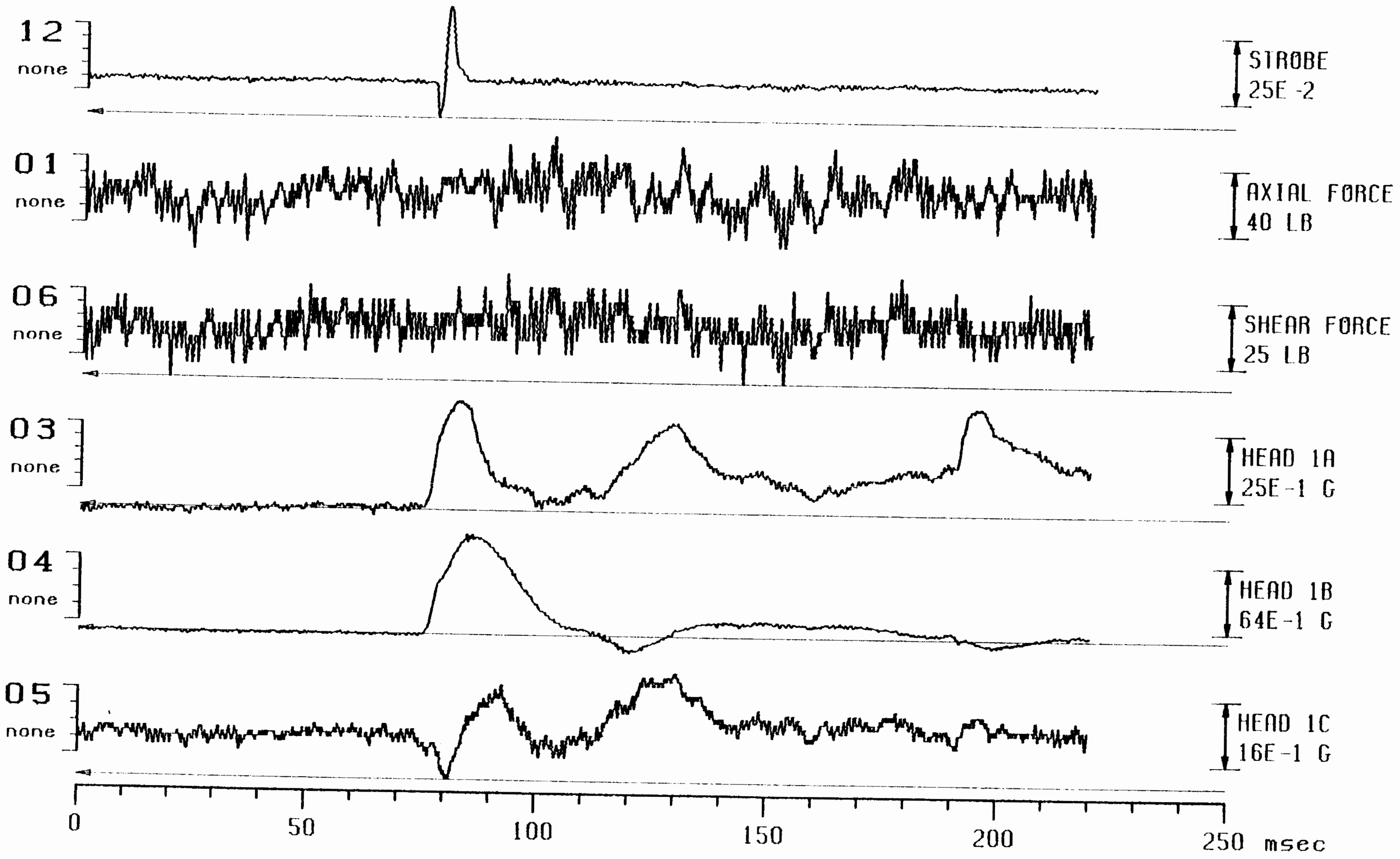
C3: 167 ← A/D → EL-SØRT 12/03/82 82L492

FILE # 94 220.00 ms = 1408 Pts / 6400 Hz 12:42:56→12:46:30



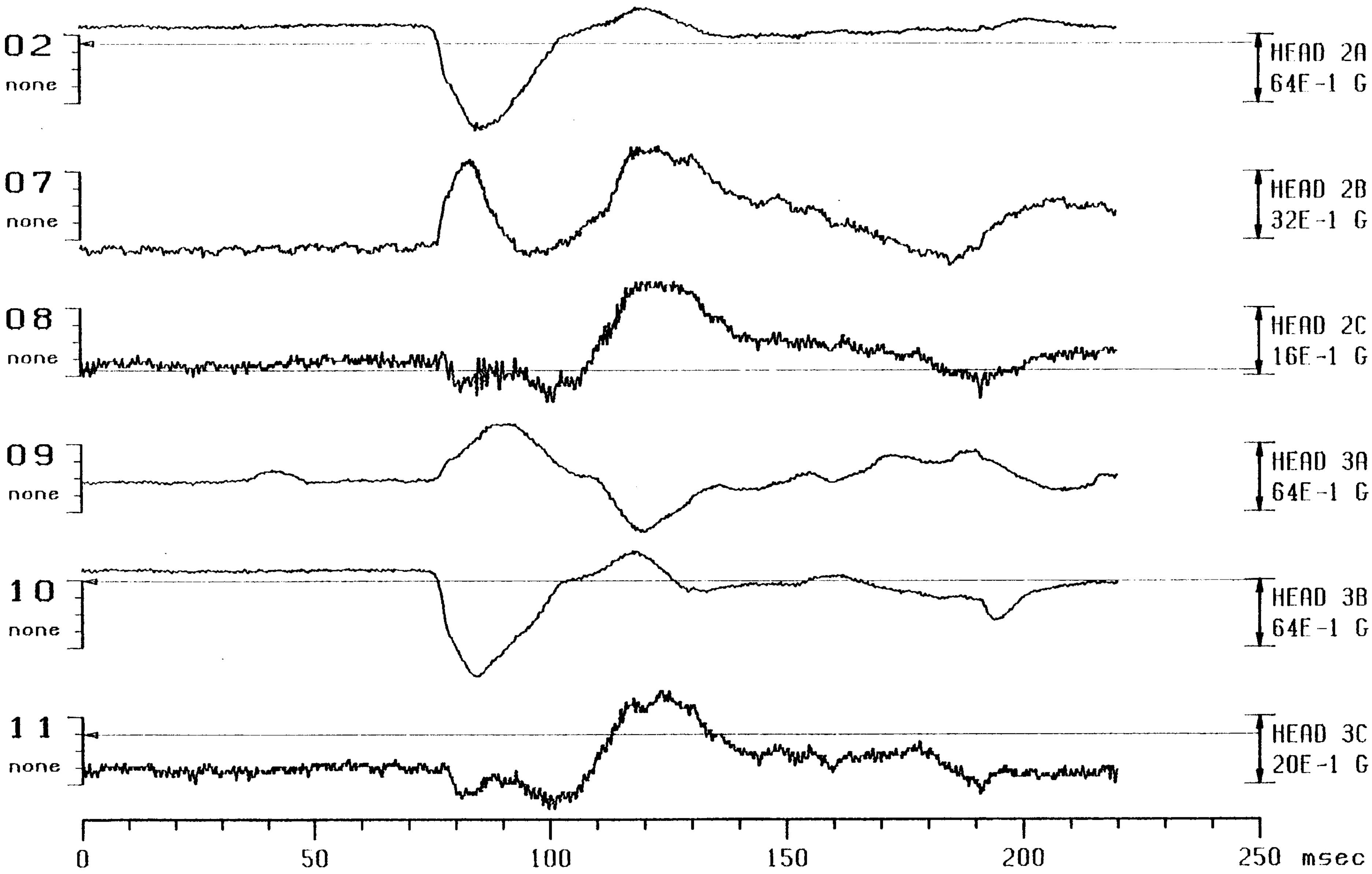
C3: 167 ← A/D → EL-SØRT 12/03/82 82L492

FIL # 90 220.00 ms = 1408 Pts / [illegible]00 Hz *12:00:50→12:05:00*



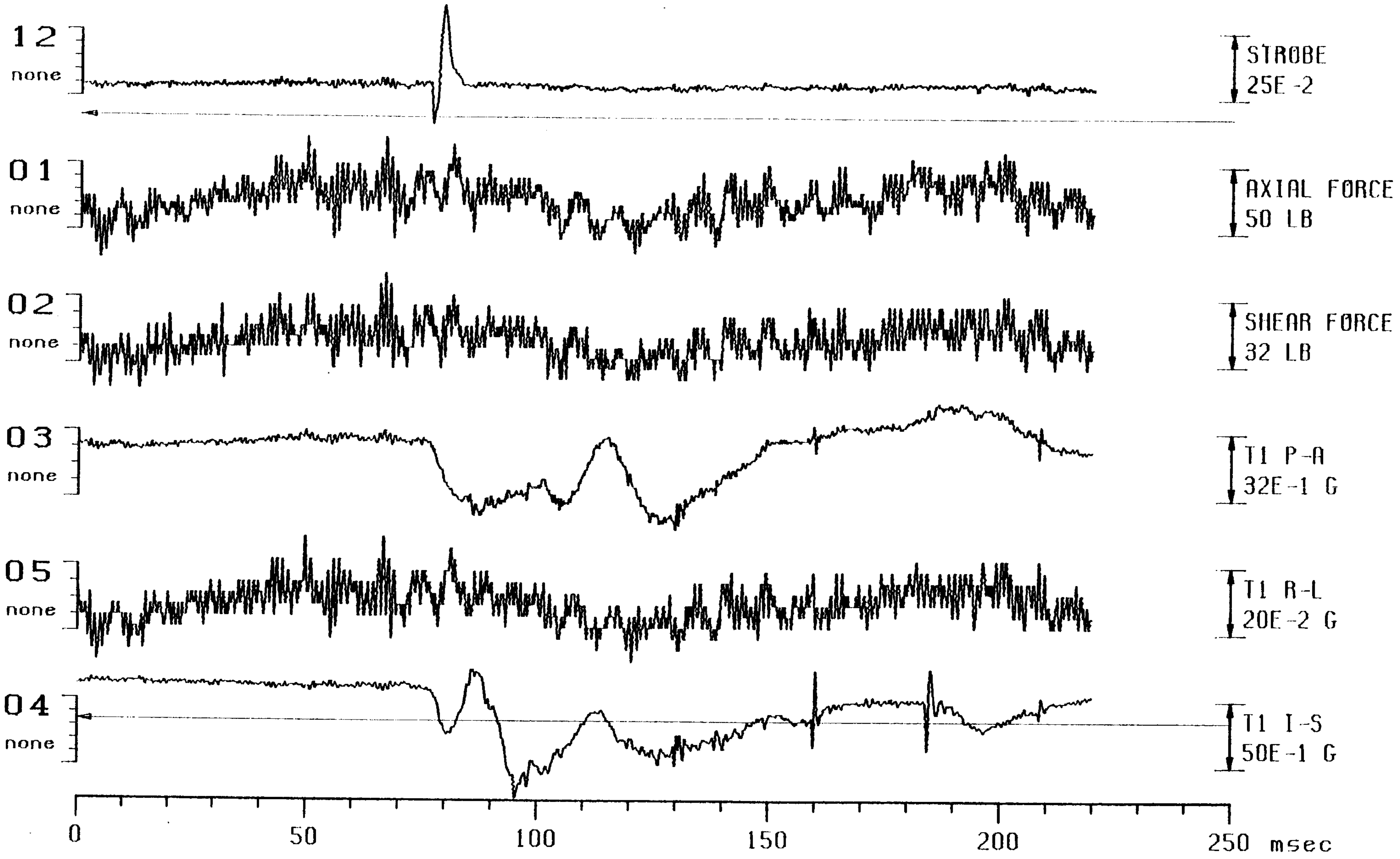
H7 : 166 ← A/D → EL-SØRT 12/03/82 *82L493*

FILE # 90 220.00 ms = 1408 Pts / 6400 Hz 12:19:24→12:23:04



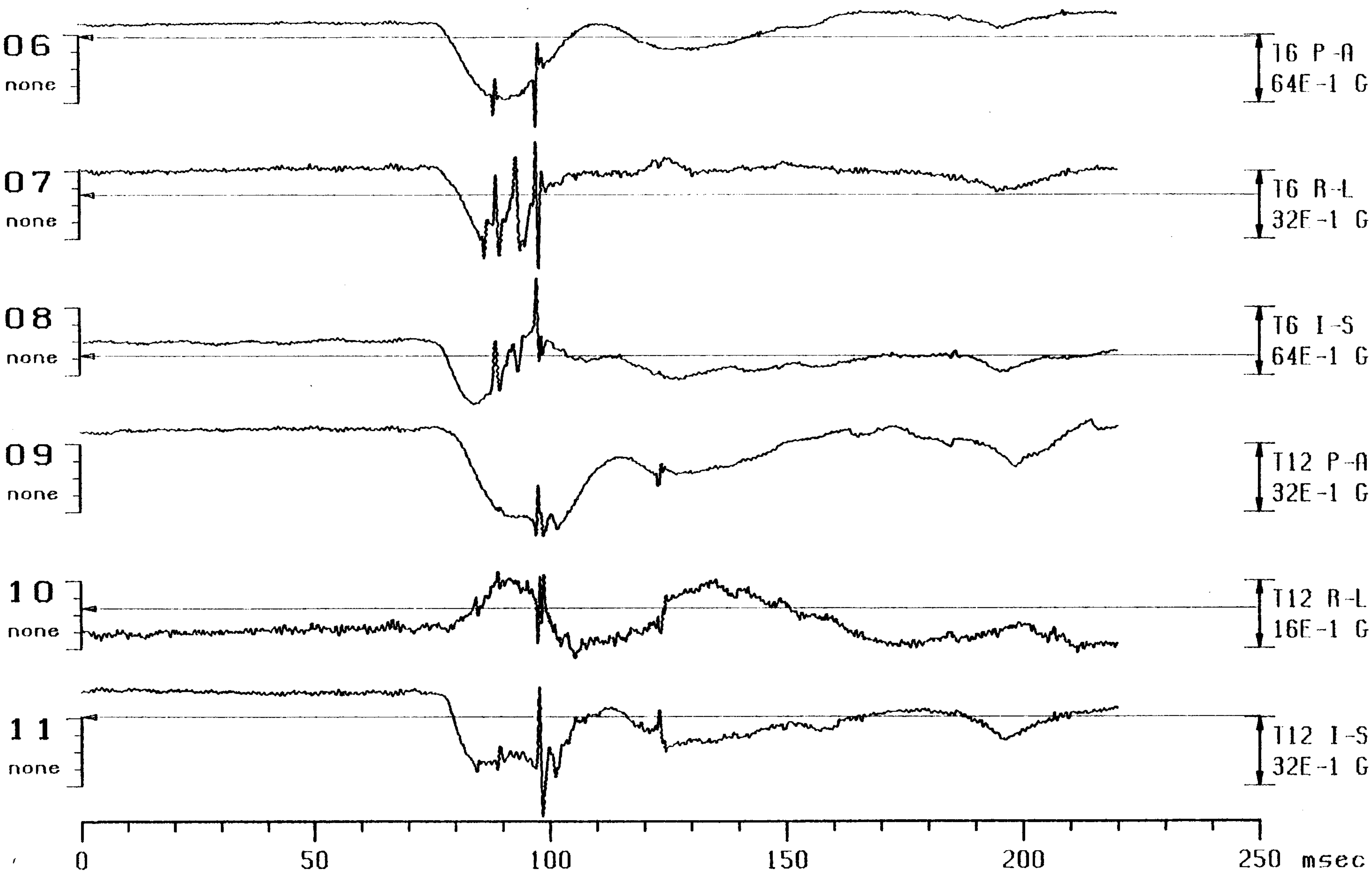
H7 : 166 ← A/D → EL-SØRT 12/03/82 *82L493*

FILE # 95 220.00 ms = 1408 Pts / 6400 Hz 13:38:33→13:42:53



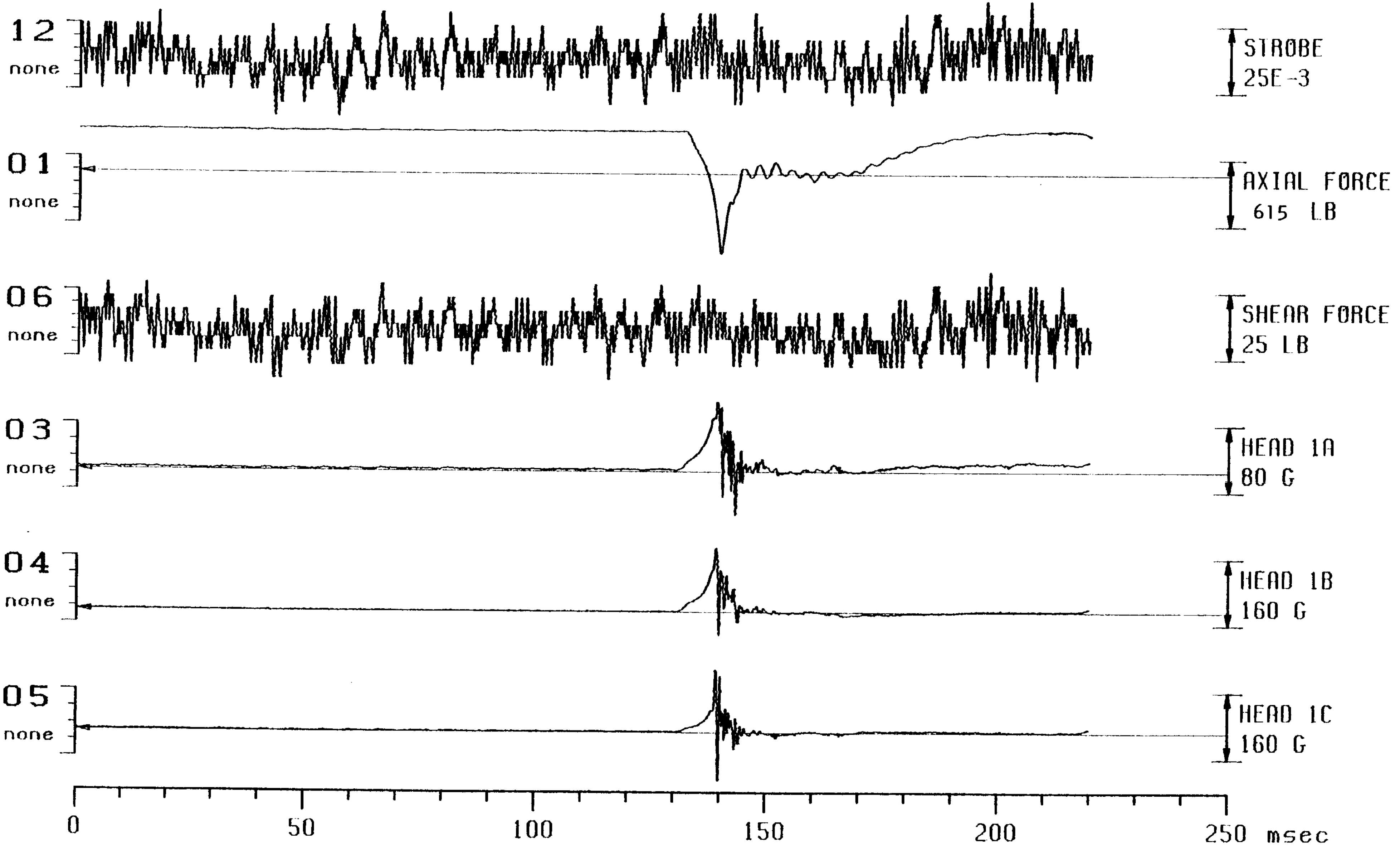
C3: 167 ← A/D → EL-SØRT 12/03/82 82L493

FILE # 95 220.00 ms = 1408 Pts / 6400 Hz 12:47:30→12:50:55



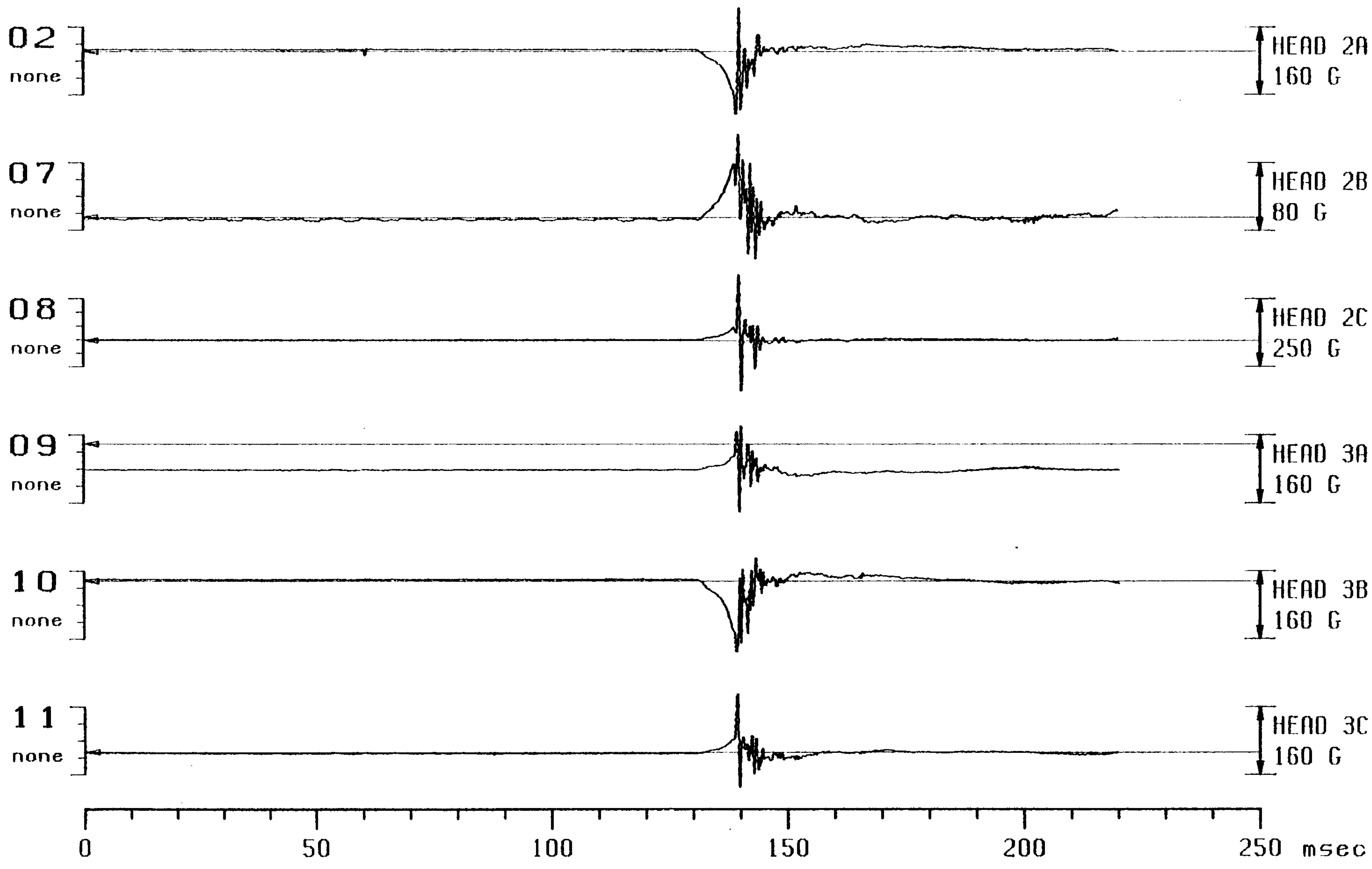
C3: 167 ← A/D → EL-SØRT 12/03/82 82L493

FI E # 91 220.00 ms = 1408 Pts / 400 Hz *12:05:10→12:09:22*



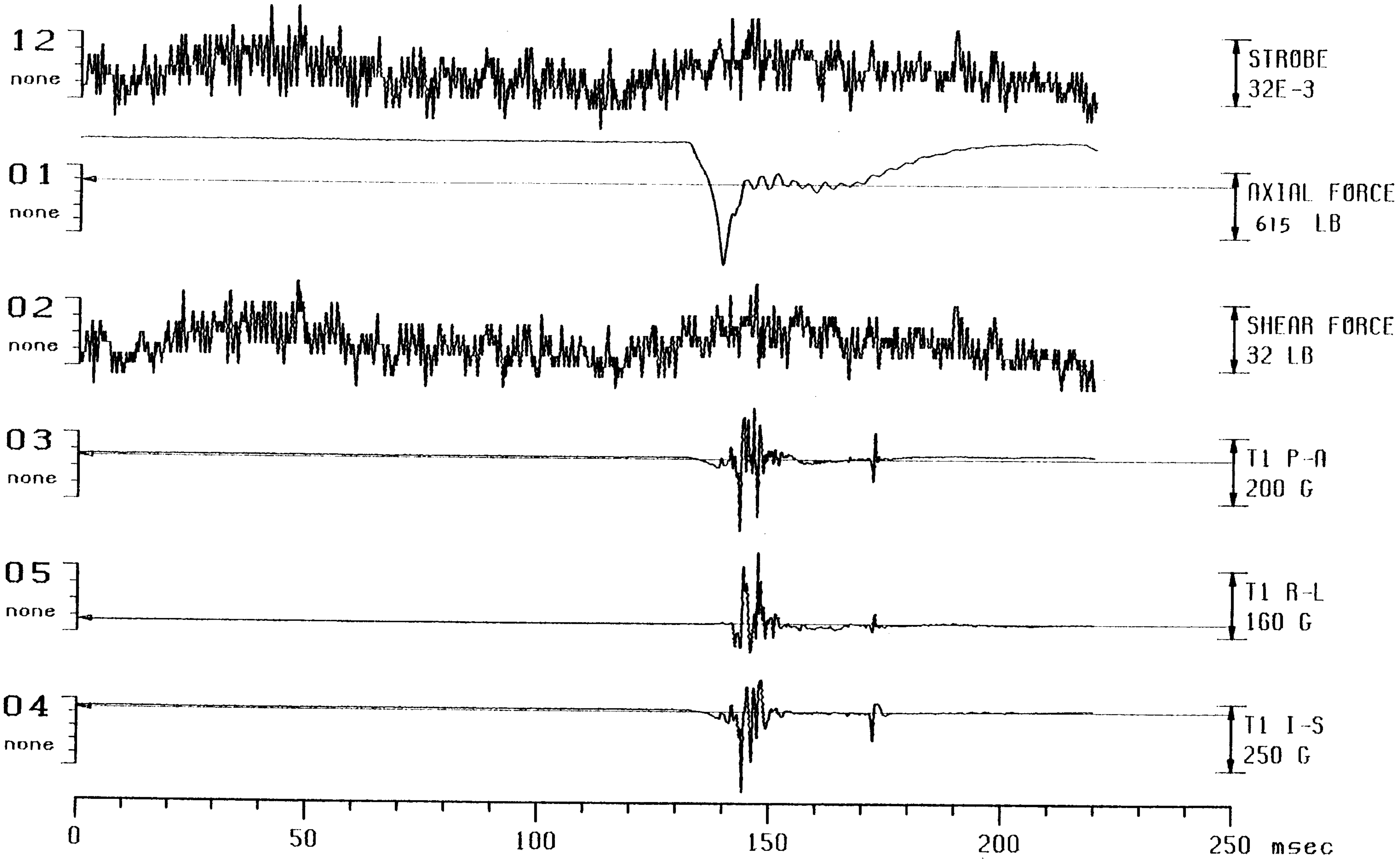
H7: 166 ← A/D → EL-SØRT 12/03/82 *82L494*

FILE # 91 220.00 ms = 1408 Pts / 6400 Hz 12:23:14→12:26:38

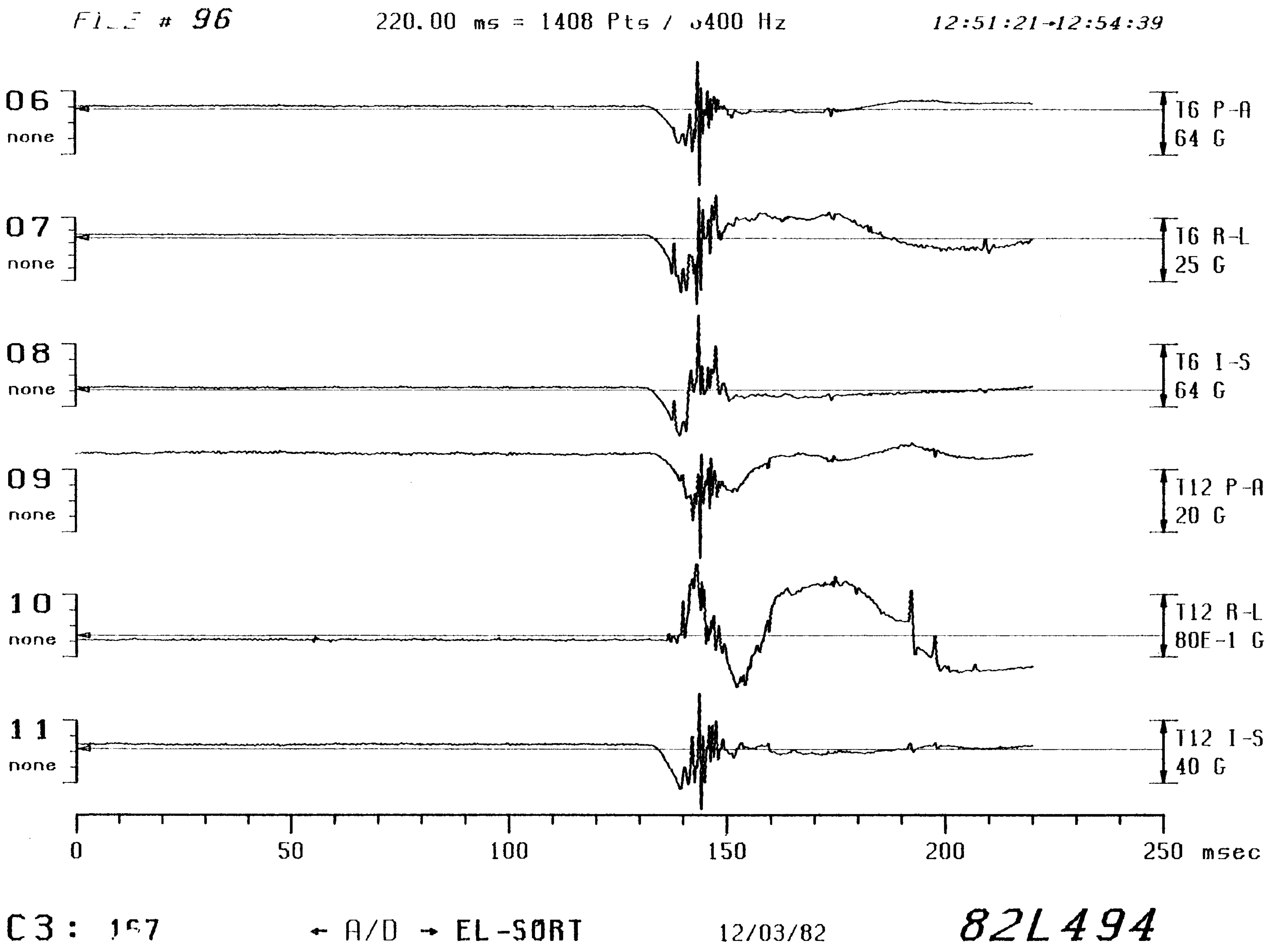


H7: 156 ← A/D → EL-SØRT 12/03/82 82L494

FILE # 96 220.00 ms = 1408 Pts / 6400 Hz *13:43:06→13:47:07*



C3: 167 ← A/D → EL-SØRT 12/03/82 *82L494*


FILE # 96
220.00 ms = 1408 Pts / 6400 Hz
12:51:21→12:54:39
06
none
T6 P-A
64 G
07
none
T6 R-L
25 G
08
none
T6 I-S
64 G
09
none
T12 P-A
20 G
10
none
T12 R-L
80E-1 G
11
none
T12 I-S
40 G
0
50
100
150
200
250 msec
C3: 1[illegible]7
← A/D → EL-SØRT
12/03/82
82L494

APPENDIX B

TEST PROTOCOL

GENERAL MOTORS

STUDY OF CERVICAL SPINE INJURY MECHANISMS

Test Series _______ Through _______

as performed by

the Biomechanics Department of

The University of Michigan Transportation Research Institute

Ann Arbor, Michigan

1982 L Series

December 9, 1982 (rev. October 24, 1982)

TEST DESCRIPTION

Test No.__________ (Low--7 to 13cm, High--1 to 2m)

Cadaver No.________ Sex:_____ Height:_____ Weight:_____

Test description: Head drop, subject in an upsidedown seated position with head flexed forward. Impact is to parietal head surface.

Drop Height: 10cm

Head/plate contact point: centered

Padding: 3cm Ensolite (AL)

Post-impact restraint: 20cm seating foam covering floor

35mm stills: Black/white

CAMERAS	(FPS)	POSITION
Photosonics 1:	500	P-A, S-I
Photosonics 2:	500	R-L, S-I

INITIAL POSITION ANGLES (Est.)

Angle	Head	Neck	Thorax	Legs
	20	20	20	0
	0	0	0	0
	0	0	0	0

ACCELEROMETERS AND LOCATION: Head (9-AX), Spine (3 triaxes)

TARGET LOCATION: Head, Acromion, Spine

December 9, 1982 (rev. October 24, 1982)

TEST DESCRIPTION

Test No.__________ (Low--7 to 13cm, High--1 to 2m)

Cadaver No.________ Sex:_____ Height:_____ Weight:_____

Test description: Head drop, subject in an upsidedown seated position with head flexed forward. Head tilted from mid-sagittal plane. Impact is to left parietal surface.

Drop Height: 10cm

Head/plate contact point: centered

Padding: 3cm Ensolite (AL)

Post-impact restraint: 20cm seating foam covering floor

35mm stills: Black/white

CAMERAS	(FPS)	POSITION
Photosonics 1:	500	P-A, S-I
Photosonics 2:	500	R-L, S-I

INITIAL POSITION ANGLES (Est.)

Angle	Head	Neck	Thorax	Legs
	20	20	20	0
	10	0	0	0
	0	0	0	0

ACCELEROMETERS AND LOCATION: Head (9-AX), Spine (3 triaxes)

TARGET LOCATION: Head, Acromion, Spine

December 9, 1982 (rev. October 24, 1982)

TEST DESCRIPTION

Test No._________ (Low--7 to 13cm, High--1 to 2m)

Cadaver No._______ Sex:____ Height:____ Weight:____

Test description: Head drop, subject in an upsidedown seated position with head flexed forward. Head rotated.

Impact is to left parietal surface.

Drop Height: 10cm

Head/plate contact point: centered

Padding: 3cm Ensolite (AL)

Post-impact restraint: 20cm seating foam covering floor

35mm stills: Black/white

CAMERAS	(FPS)	POSITION
Photosonics 1:	500	P-A, S-I
Photosonics 2:	500	R-L, S-I

INITIAL POSITION ANGLES (Est.)

Angle	Head	Neck	Thorax	Legs
	20	20	20	0
	0	0	0	0
	20	0	0	0

ACCELEROMETERS AND LOCATION: Head (9-AX), Spine (3 triaxes)

TARGET LOCATION: Head, Acromion, Spine

December 9, 1982 (rev. October 24, 1982)

TEST DESCRIPTION

Test No.__________ (Low--7 to 13cm, High--1 to 2m)

Cadaver No.________ Sex:_____ Height:_____ Weight:_____

Test description: Head drop, subject in an upsidedown seated position with head flexed forward. Thorax rotated.

Impact is to left parietal surface.

Drop Height: 10cm

Head/plate contact point: centered

Padding: 3cm Ensolite (AL)

Post-impact restraint: 20cm seating foam covering floor

35mm stills: Black/white

CAMERAS	(FPS)	POSITION
Photosonics 1:	500	P-A, S-I
Photosonics 2:	500	R-L, S-I

INITIAL POSITION ANGLES (Est.)

Angle	Head	Neck	Thorax	Legs
	20	20	20	0
	0	0	10	0
	0	0	0	0

ACCELEROMETERS AND LOCATION: Head (9-AX), Spine (3 triaxes)

TARGET LOCATION: Head, Acromion, Spine

December 9, 1982 (rev. October 24, 1982)

TEST DESCRIPTION

Test No.__________ (Low--7 to 13cm, High--1 to 2m)

Cadaver No.________ Sex:_____ Height:_____ Weight:_____

Test description: Head drop, subject in an upsidedown seated position with head flexed forward. Head tilted and rotated. Thorax rotated. Impact is to left parietal surface.

Drop Height: 1.5m

Head/plate contact point: centered

Padding: 3cm Ensolite (AL)

Post-impact restraint: 20cm seating foam covering floor

35mm stills: Black/white

CAMERAS	(FPS)	POSITION
Photosonics 1:	1000	P-A, S-I
Photosonics 2:	1000	R-L, S-I
HyCam:	3000	P-A, S-I

INITIAL POSITION ANGLES (Est.)

Angle	Head	Neck	Thorax	Legs
	20	20	20	0
	10	0	10	0
	20	0	0	0

ACCELEROMETERS AND LOCATION: Head (9-AX), Spine (3 triaxes)

TARGET LOCATION: Head, Acromion, Spine

TEST DESCRIPTION

Test No.__________ (Low--7 to 13cm, High--1 to 2m)

Cadaver No.________ Sex:_____ Height:_____ Weight:_____

Test description:____

Drop Height:____

Head/plate contact point:___________________________________

Padding:____

Post-impact restraint:______________________________________

35mm stills:______________

CAMERAS	(FPS)	POSITION
Photosonics 1:	_____________	____________
Photosonics 2:	_____________	____________
HyCam:	__________	____________

INITIAL POSITION ANGLES (Est.)

Angle	Head	Neck	Thorax	Legs

ACCELEROMETERS/LOCATION:

TARGET LOCATION:

December 9, 1982 (rev. October 24, 1982)

TEST DESCRIPTION

Test No.__________ .(Low--7 to 13cm, High--1 to 2m)

Cadaver No.________ Sex:_____ Height:_____ Weight:_____

Test description:____

____

____

____

____

Drop Height:____

Head/plate contact point:______________________________________

Padding:____

Post-impact restraint:____

35mm stills:______________

CAMERAS (FPS) POSITION

Photosonics 1: _____________ _____________

Photosonics 2: _____________ _____________

HyCam: __________ _____________

INITIAL POSITION ANGLES (Est.)

Angle	Head	Neck	Thorax	Legs

ACCELEROMETERS/LOCATION:

TARGET LOCATION:

PRE-SURGERY

TASK	TIME	COMMENTS
Pick up cadaver from U of M Anatomy Dept. and transport to UMTRI Biomedical lab.		
Weigh cadaver and log cadaver information.		
Store cadaver if necessary.		
Sanitary preparation.		
Pretest X-rays: (KV/MA/T) head A-P (100/10/1) ___/___/___ thorax A-P (90/10/1) ___/___/___ thorax A-P(2) (90/10/1) ___/___/___ femur (80/10/1) ___/___/___		
Anthropometry.		

ANTHROPOMETRY

Height:__________

Weight:__________

Sex:__________

Age:__________

Stature: left:__________ right:__________

Suprasternale height:__________

Head to C7:__________

Acromion height: left:__________ right:__________

Biacromion:__________

Head breadth (R-L):__________

Head depth (A-P):__________

Head circumference:__________

Neck circumference:__________

Axillary breadth:_____________

Substernale height:_____________

Substernale breadth:_____________

Symphsion height:_____________

Biiliocristale breadth:_____________

Anatomical Anomalies / Clinical Observations

1. Head: a. Brain b. Skull

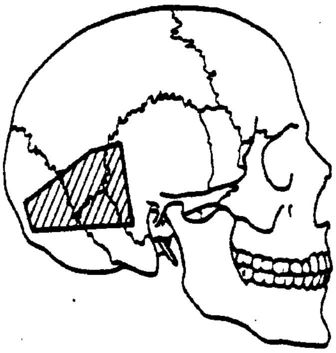
2. Neck:

3. Thorax (ribs, heart, lungs, diaphragm, abdomen):

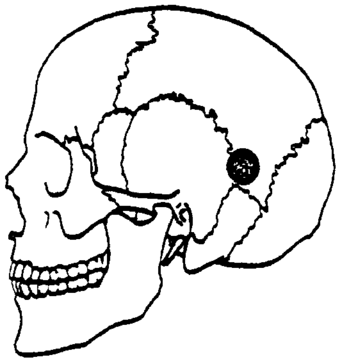
COMMENTS:

HEAD 9-AX MOUNT

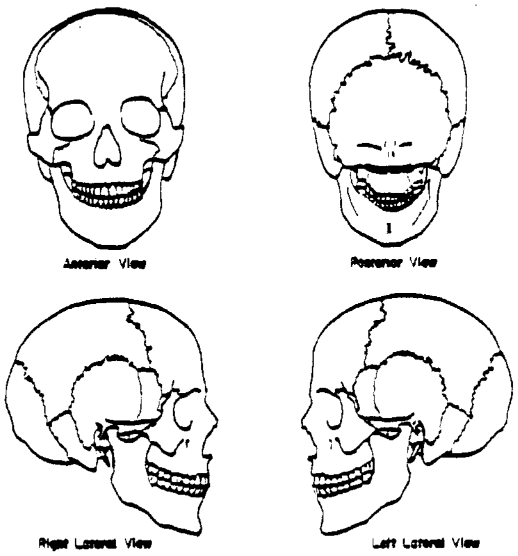
TASK	TIME	COMMENTS
With cadaver supine, locate the occipital/parietal/temporal junction on the right side of the head and remove skin from an area approximately the size of the 9AX plate.		
Drill four holes within this triangular area.		
Attach four feet to the 9-ax plate such that three of the feet can be positioned near the screws.		
Place acrylic around screws.		
Place plate on top of acrylic base, making sure the acrylic goes through the center holes in the plate.		
Insert a strain relief bolt in the acrylic base of the head platform. Make sure bolt does not contact plate.		
Drill hole in left occipital/parietal/temporal junction. Screw in target mount.		



Preferred plate location



Preferred target location



If "preferred" not used,
deviations indicated above.

SPINAL MOUNTS

TASK	TIME	COMMENTS
Spinal mounts go on T1, T8, and T12.		
Make incisions over T1, T8, and T12. Clear muscle and tissue away from process, but do not cut between processes.		
Drill a small hole 1/4" deep in each process.		
Screw mounts on with wood screws (be sure screws are in process).		
IF NEEDED, place stabilizing and mooring devices on each side of the laminae. Secure with Tie Wraps.		
Mold acrylic around (and under) mounts and mooring devices and allow to dry.		
Make sure accelerometers are anatomically oriented.		
Spinal geometry if necessary.		

PREPARATION

TASK	TIME	COMMENTS
Screw lag bolt into left acromion.		
Dress cadaver.		
Using masking tape wrap tape around head covering all but 9AX plate.		
Place parachute harness on cadaver.		
Store cadaver if necessary.		
Transport cadaver to testing area, being careful not to damage mounts.		

ELECTRONICS CHECK AND PRETEST TRIAL RUN

Electronics Check

___ check accelerometers (excitation and zero)

___ check wiring and cables

___ mount accelerometers in triax clusters

___ check amplifiers

___ calibrate tape with impedance-matching amp

___ recorder

___ complete wiring

___ check strobe, gate, timer, rope cutters

___ run trial test

___ load platform calibrated day before test

___ load Photosonics and HyCam cameras with Kodak 16mm 7242-#FB-430 color film

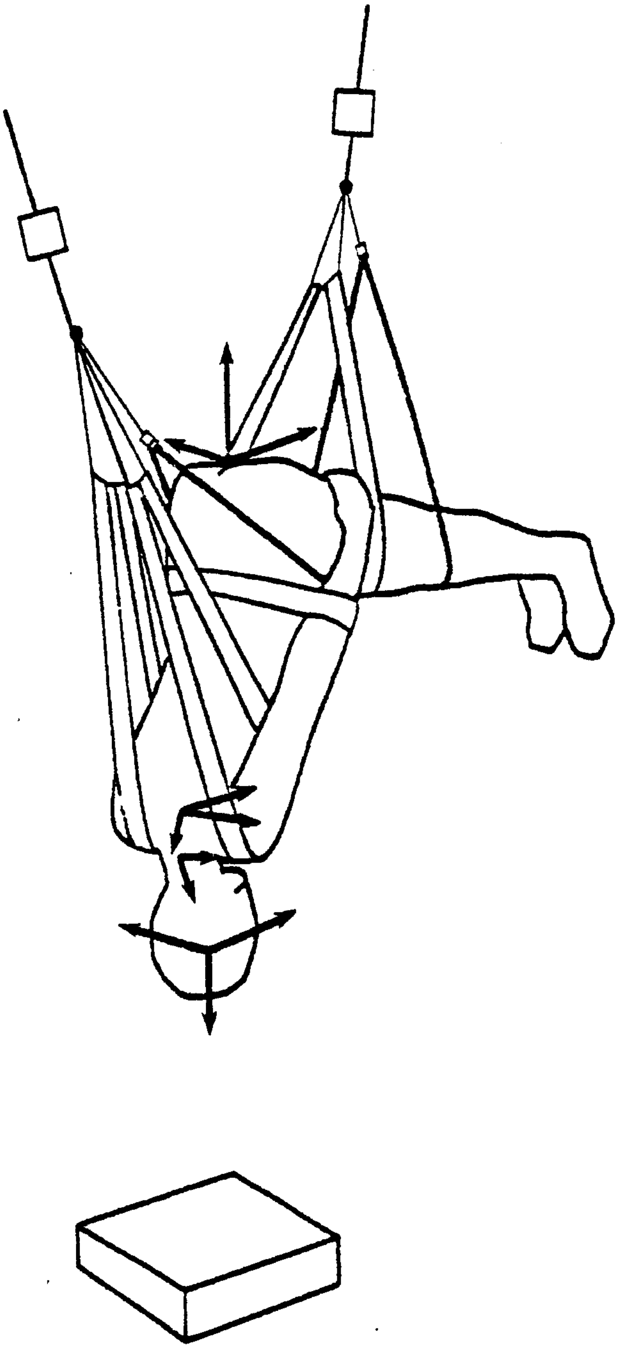
Pretest Trial Run

1. ___ Suspend rubber tube five inches from impact plate with fiber tape.
2. ___ Tape all accelerometers (while still in sleeves) to rubber tube with paper tape.
3. ___ Attach the contact switches to the impact plate.
4. ___ Run trial test.
5. ___ Record all signals, gate, and strobe.
6. ___ Put a one-volt signal on a junk tape and check to see if one volt is played back. Use signal generator or impedance-matching amp with the scope to calibrate output.

HEAD IMPACT 1
(Low Drop)

Test No.__________

TASK	TIME	COMMENTS
Head impact 1. (Low Drop)		
Attach ball targets and phototargets.		
Attach thorax belts and pelvis/leg belts to cadaver.		
Using pulleys and adjusting belts, hoist cadaver into position.		
Using plumb line to anticipate contact point, continue positioning cadaver.		
Set up head catch system.		
Final positioning (see figure).		
Place BLT on platform; take short exposure.		
Measure and record head, neck, thorax, leg angles. Record drop height:___		
Setup photos.		
Final checklist.		
Run test.		



HEAD IMPACT 1

Timer Box Setup

EQUIPMENT	TIMER VALUES		
__________ Impact	Delay		Run
Gate (start)	1500	1	0200
Lights (start)	0005	2	2600
		3	
Thorax rope cutter (5)	0490	4	0050
Photosonics I (start)	0900	5	1030
		6	
Leg / pelvis rope cutter (5)	0490	7	0050
Photosonics II (start)	0900	8	1030

December 9, 1982 (rev. October 24, 1982)

FINAL CHECKLIST

____ doors locked

____ load platform calibrated

____ check transducers and time base

____ all timer box switches to 'off'

____ timer box values correct and correct timers charged

____ power on

____ timing lights on

____ strobe charged

____ gate trigger established

____ cameras set and in correct positions

____ cameras set at correct FPS -- 500 FPS for low drop
1000 FPS for high drop

____ Newtonian reference

____ calibration target and all targets in view of cameras

____ rope cutters threaded and nylon strings unfrayed

____ rope cutter cables free

____ backdrops in place

____ overhead hoists in correct positions

____ all four break bolts on hoists locked

____ hoist cables out of camera view

____ targets in view of cameras

____ padding

____ final positioning

____ BLT calibration target exposed

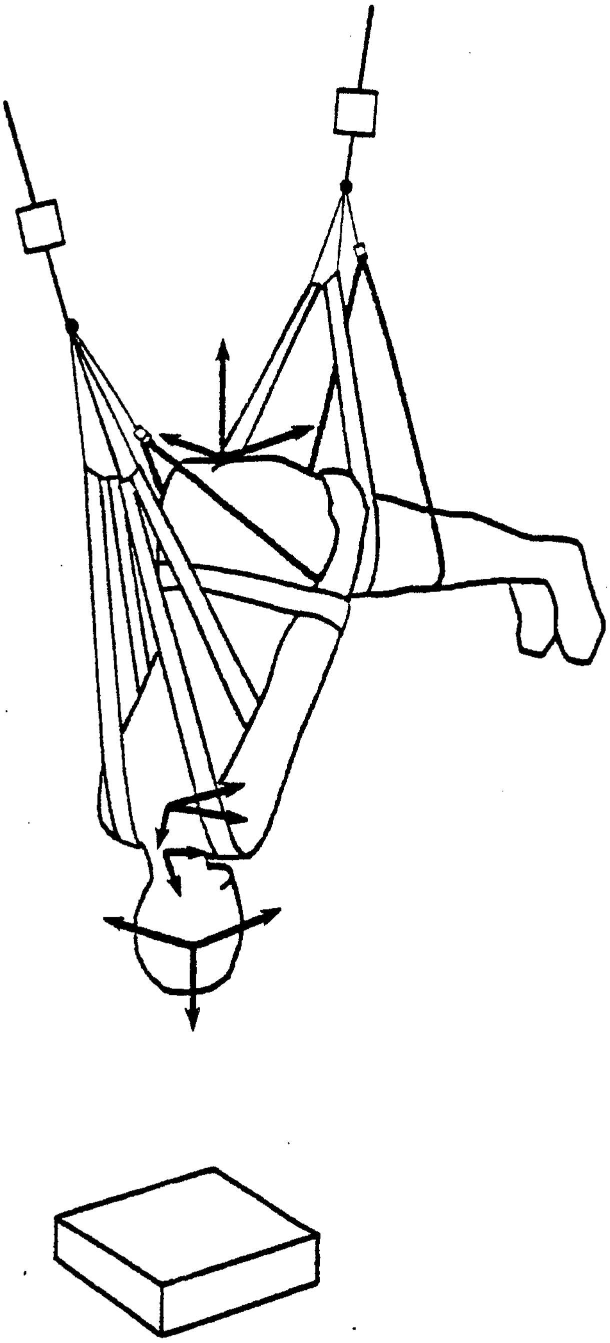
____ drop height recorded

____ head, neck, thorax, leg angles recorded

HEAD IMPACT 2
(Low Drop)

Test No.__________

TASK	TIME	COMMENTS
Reposition cadaver setting new initial angles.		
Check head catch system.		
Final positioning		
IF NEEDED, BLT update.		
Measure and record head, neck, thorax, leg angles. Record drop height:___.		
Setup photos.		
Final checklist.		
Run test.		



HEAD IMPACT 2

Timer Box Setup

EQUIPMENT	TIMER VALUES		
________ Impact	Delay		Run
Gate (start)	1500	1	0200
Lights (start)	0005	2	2600
		3	
Thorax rope cutter (5)	0490	4	0050
Photosonics I (start)	0900	5	1030
		6	
Leg / pelvis rope cutter (5)	0490	7	0050
Photosonics II (start)	0900	8	1030

FINAL CHECKLIST

____ doors locked

____ load platform calibrated

____ check transducers and time base

____ all timer box switches to 'off'

____ timer box values correct and correct timers charged

____ power on

____ timing lights on

____ strobe charged

____ gate trigger established

____ cameras set and in correct positions

____ cameras set at correct FPS -- 500 FPS for low drop
1000 FPS for high drop

____ Newtonian reference

____ calibration target and all targets in view of cameras

____ rope cutters threaded and nylon strings unfrayed

____ rope cutter cables free

____ backdrops in place

____ overhead hoists in correct positions

____ all four break bolts on hoists locked

____ hoist cables out of camera view

____ targets in view of cameras

____ padding

____ final positioning

____ BLT calibration update

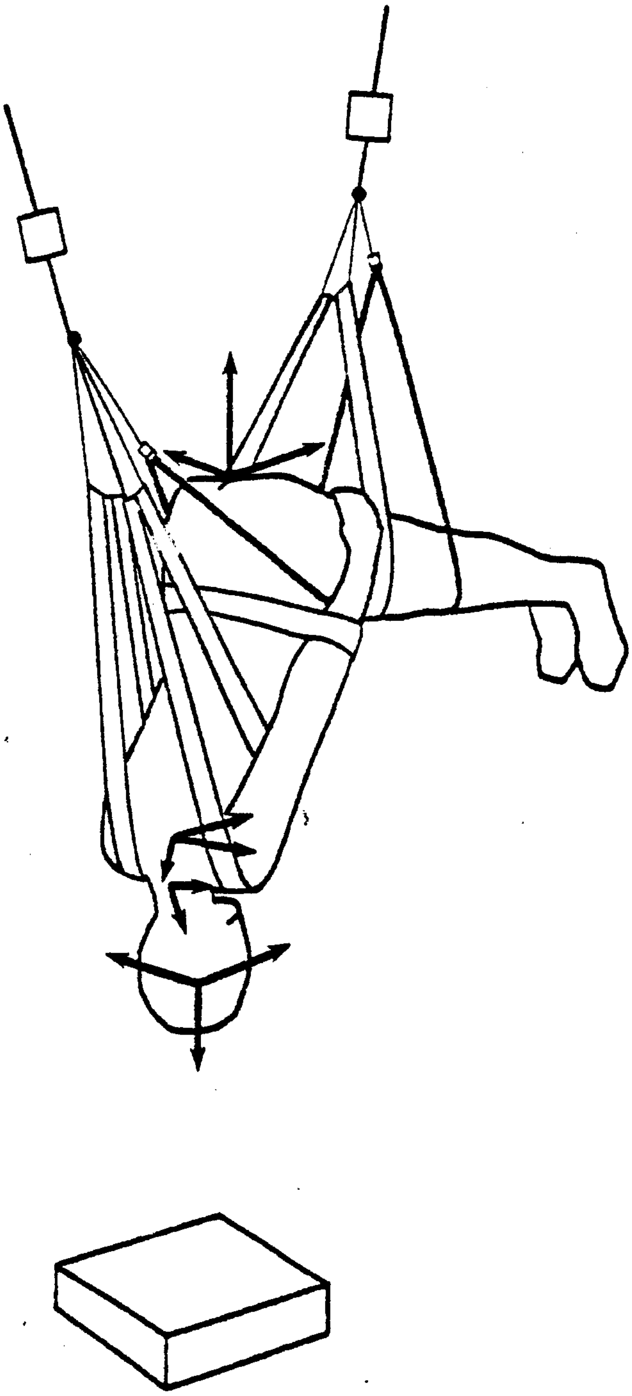
____ drop height recorded

____ head, neck, thorax, leg angles recorded

HEAD IMPACT 3
(Low Drop)

Test No.__________

TASK	TIME	COMMENTS
Reposition cadaver setting new initial angles.		
Check head catch system.		
Final positioning		
IF NEEDED, BLT update.		
Measure and record head, neck, thorax, leg angles. Record drop height:___.		
Setup photos.		
Final checklist.		
Run test.		



HEAD IMPACT 3

Timer Box Setup

EQUIPMENT	TIMER VALUES		
__________ Impact	Delay		Run
Gate (start)	1500	1	0200
Lights (start)	0005	2	2600
		3	
Thorax rope cutter (5)	0490	4	0050
Photosonics I (start)	0900	5	1030
		6	
Leg / pelvis rope cutter (5)	0490	7	0050
Photosonics II (start)	0900	8	1030

FINAL CHECKLIST

____ doors locked

____ load platform calibrated

____ check transducers and time base

____ all timer box switches to 'off'

____ timer box values correct and correct timers charged

____ power on

____ timing lights on

____ strobe charged

____ gate trigger established

____ cameras set and in correct positions

____ cameras set at correct FPS -- 500 FPS for low drop
1000 FPS for high drop

____ Newtonian reference

____ calibration target and all targets in view of cameras

____ rope cutters threaded and nylon strings unfrayed

____ rope cutter cables free

____ backdrops in place

____ overhead hoists in correct positions

____ all four break bolts on hoists locked

____ hoist cables out of camera view

____ targets in view of cameras

____ padding

____ final positioning

____ BLT calibration update

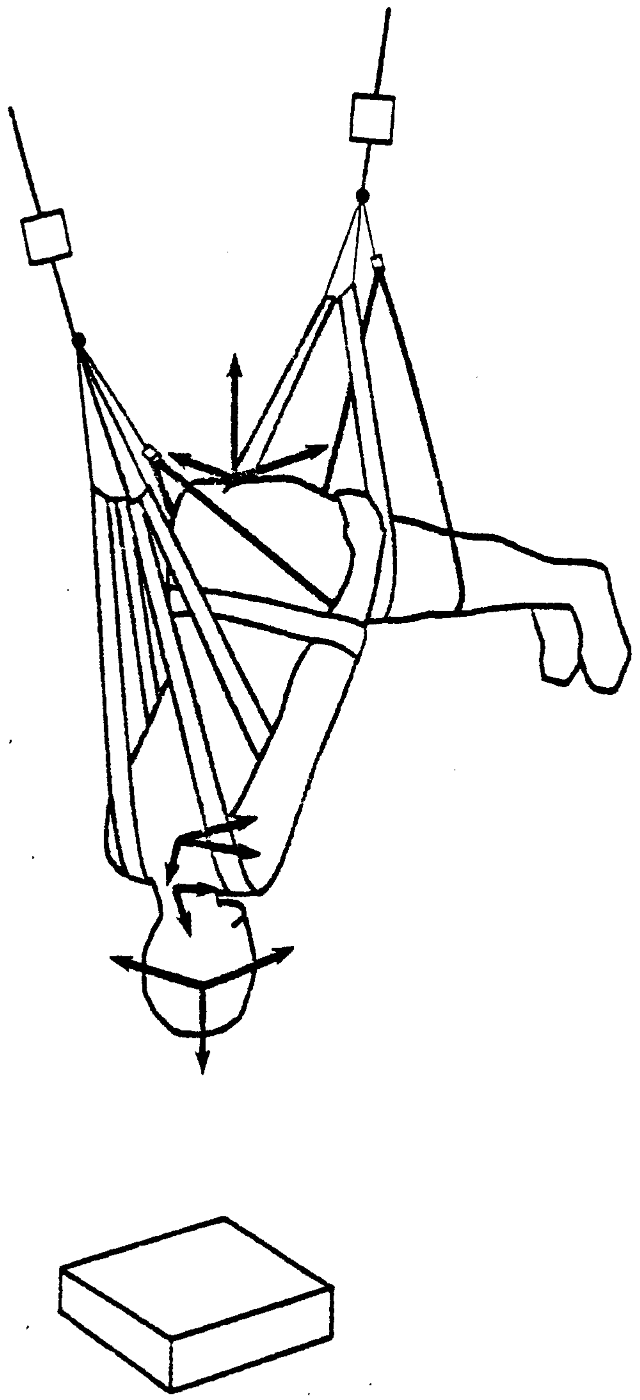
____ drop height recorded

____ head, neck, thorax, leg angles recorded

HEAD IMPACT 4
(Low Drop)

Test No.__________

TASK	TIME	COMMENTS
Reposition cadaver setting new initial angles.		
Check head catch system.		
Final positioning		
IF NEEDED, BLT update.		
Measure and record head, neck, thorax, leg angles. Record drop height:___"		
Setup photos.		
Final checklist.		
Run test.		



HEAD IMPACT 4

Timer Box Setup

EQUIPMENT	TIMER VALUES		
__________ Impact	Delay		Run
Gate (start)	1500	1	0200
Lights (start)	0005	2	2600
		3	
Thorax rope cutter (5)	0490	4	0050
Photosonics I (start)	0900	5	1030
		6	
Leg / pelvis rope cutter (5)	0490	7	0050
Photosonics II (start)	0900	8	1030

FINAL CHECKLIST

____ doors locked

____ load platform calibrated

____ check transducers

____ all timer box switches to 'off'

____ timer box values correct and correct timers charged

____ power on

____ timing lights on

____ strobe charged

____ gate trigger established

____ cameras set and in correct positions

____ cameras set at correct FPS -- 500 FPS for low drop
1000 FPS for high drop

____ Newtonian reference

____ calibration target and all targets in view of cameras

____ rope cutters threaded and nylon strings unfrayed

____ rope cutter cables free

____ backdrops in place

____ overhead hoists in correct positions

____ all four break bolts on hoists locked

____ hoist cables out of camera view

____ targets in view of cameras

____ padding

____ final positioning

____ BLT calibration update

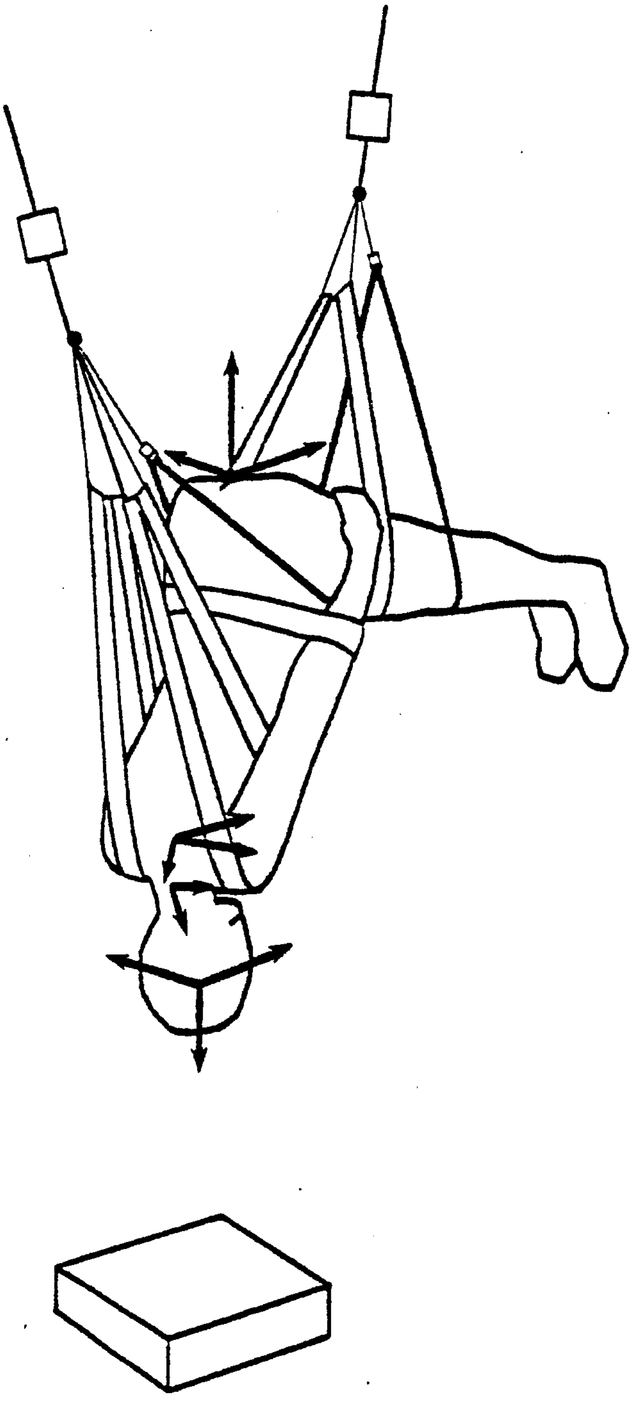
____ drop height recorded

____ head, neck, thorax, leg angles recorded

HEAD IMPACT 5
(High Drop)

Test No.__________

TASK	TIME	COMMENTS
Reposition cadaver setting new initial angles and new drop height.		
Check head catch system.		
Final positioning		
IF NEEDED, BLT update.		
Measure and record head, neck, thorax, leg angles. Record drop height:___.		
Setup photos.		
Set cameras at 1000 FPS.		
Final checklist.		
Run test.		



HEAD IMPACT 5

Timer Box Setup

EQUIPMENT	TIMER VALUES		
__________ Impact	Delay		Run
Gate (start)	1500	1	0200
Lights (start)	0005	2	2600
HyCam (start)	0700	3	1800
Thorax rope cutter (3)	0356	4	0050
Photosonics I (start)	0300	5	1600
		6	
Leg/pelvis rope cutter (3)	0356	7	0050
Photosonics II (start)	0300	8	1600

FINAL CHECKLIST

____ doors locked

____ load platform calibrated

____ check transducers and time base

____ all timer box switches to 'off'

____ timer box values correct and correct timers charged

____ power on

____ timing lights on

____ strobe charged

____ gate trigger established

____ cameras set and in correct positions

____ cameras set at correct FPS -- 500 FPS for low drop
1000 FPS for high drop

____ Newtonian reference

____ calibration target and all targets in view of cameras

____ rope cutters threaded and nylon strings unfrayed

____ rope cutter cables free

____ backdrops in place

____ overhead hoists in correct positions

____ all four break bolts on hoists locked

____ hoist cables out of camera view

____ targets in view of cameras

____ padding

____ final positioning

____ BLT calibration update

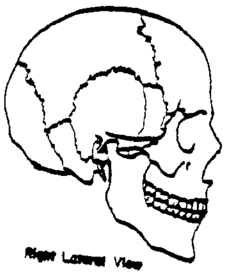
____ drop height recorded

____ head, neck, thorax, leg angles recorded

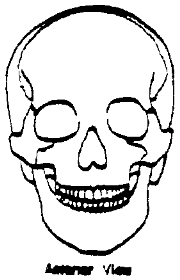
POST TEST PROCEDURE

TASK	TIME	COMMENTS
Remove all targets and triax clusters.		
Store cadaver if necessary.		
Transport cadaver to anatomy lab.		
Remove all instrumentation, except for 9AX head plate.		
Remove head and transport it to X-Ray Room for post test radiographs.		

Z-X
(Profile)



Z-Y
(Frontal)



X-RAYS (X-RAY ROOM)

Reference Point	Z-X Distance from Table	Z-Y Distance from Table
R. Eye		
L. Eye		
R. Ear		
L. Ear		
Q1		
Q2		
Q3		
CG		

	KVP	MA	SEC	LABEL	
Z-X					(100/10/1)
Z-Y					(100/10/1)

AUTOPSY

TASK	TIME	COMMENTS
After completion of radiographs, transport head to Anatomy Room for commencement of Autopsy.		
Autopsy		
SAVE RIBS RIGHT SIDE 4, 5, 6		

Observed Injuries

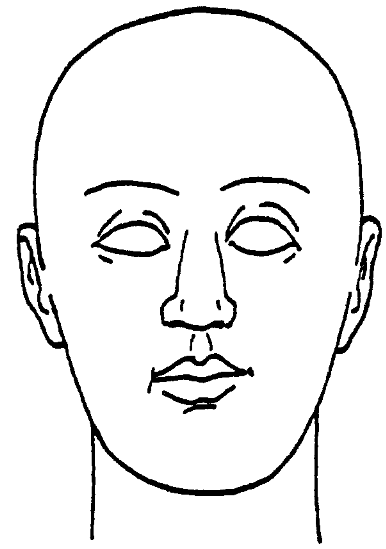
1. Head: a. Brain b. Skull

2. Neck:

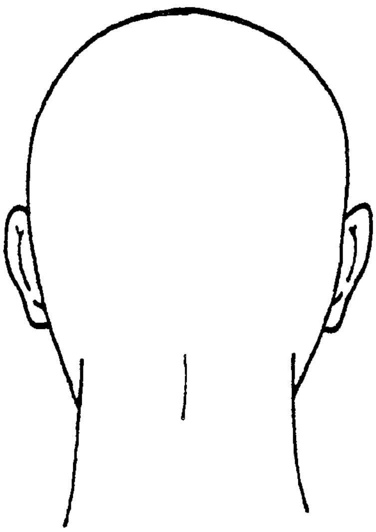
3. Thorax (ribs, heart, lungs, diaphragm, abdomen):

COMMENTS:

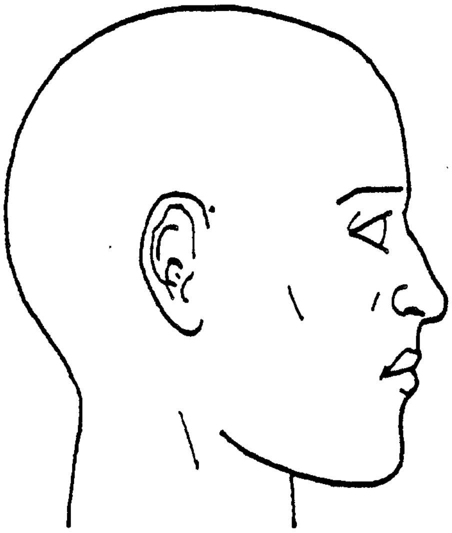
TEST NO. ____________



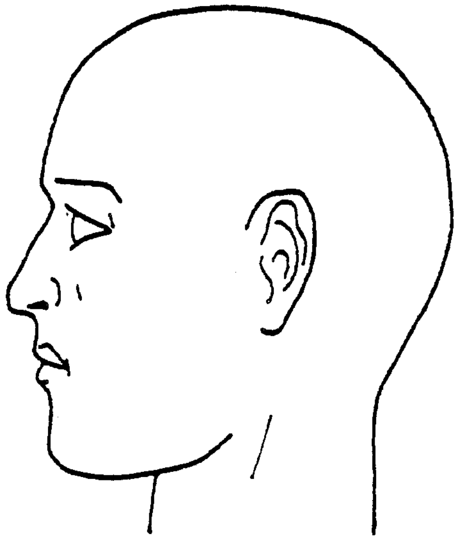
Anterior View



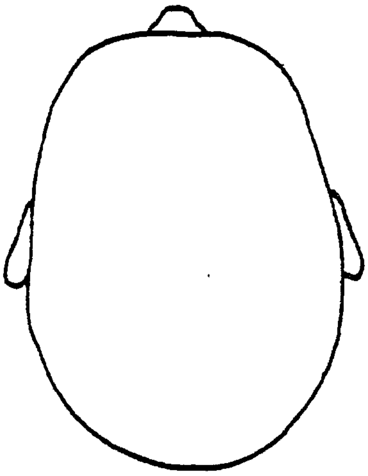
Posterior View



Right Lateral View

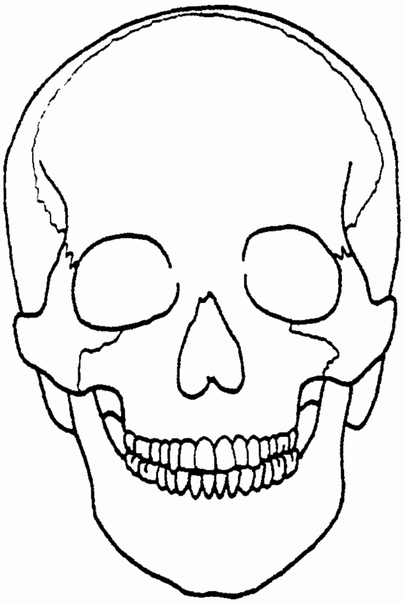


Left Lateral View

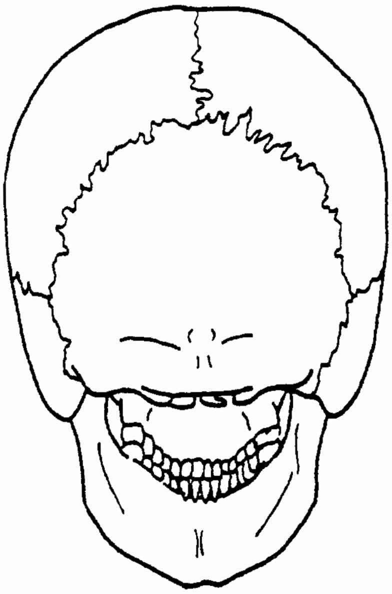


Superior View

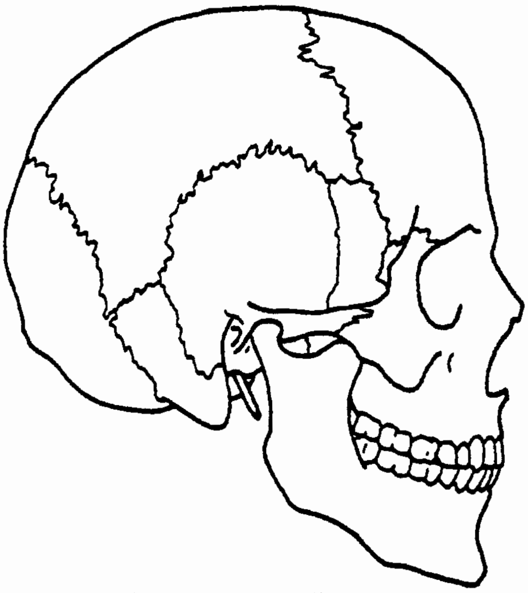
TEST NO. ____________



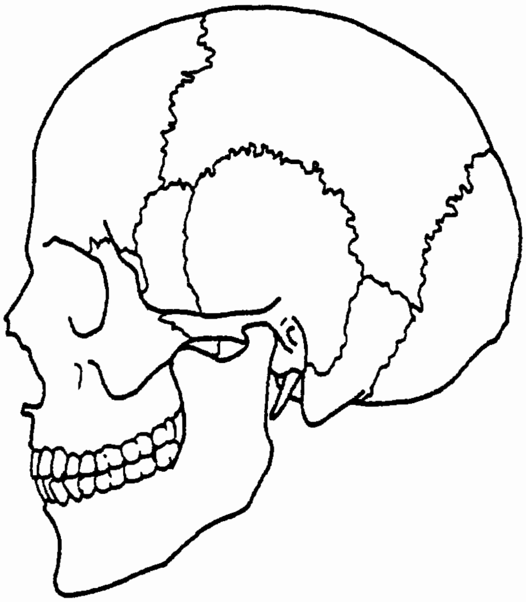
Anterior View



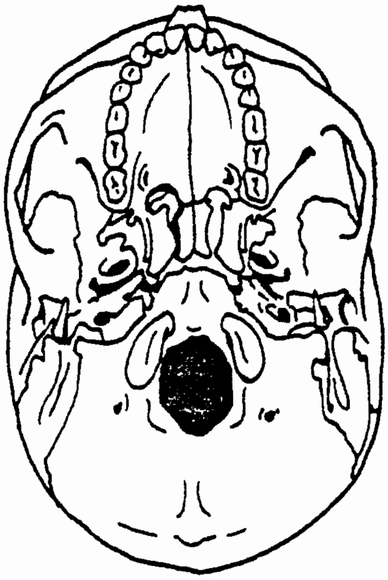
Posterior View



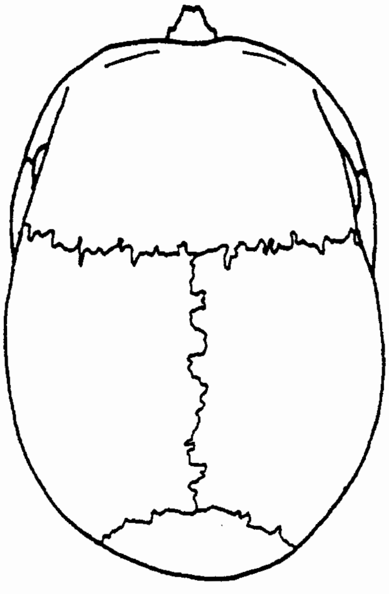
Right Lateral View



Left Lateral View



Inferior View



Superior View

TEST NO. ____________

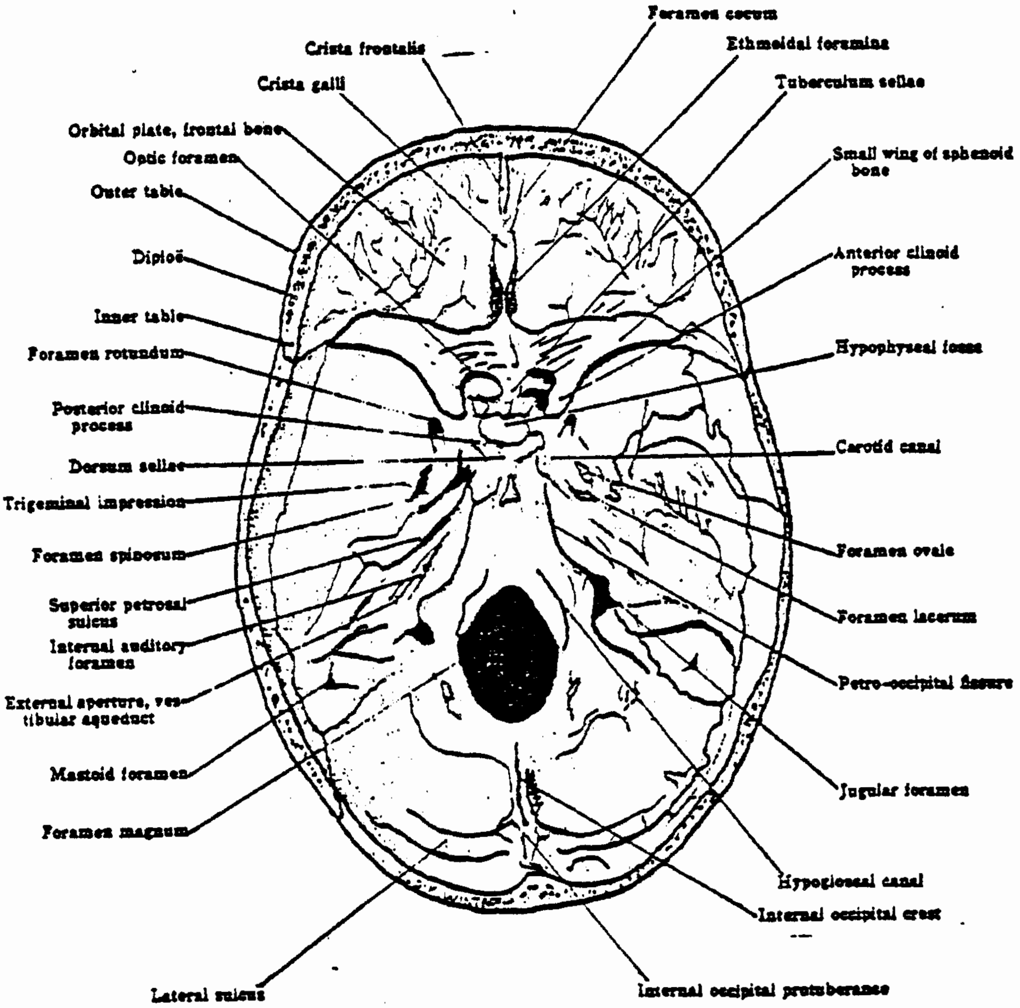
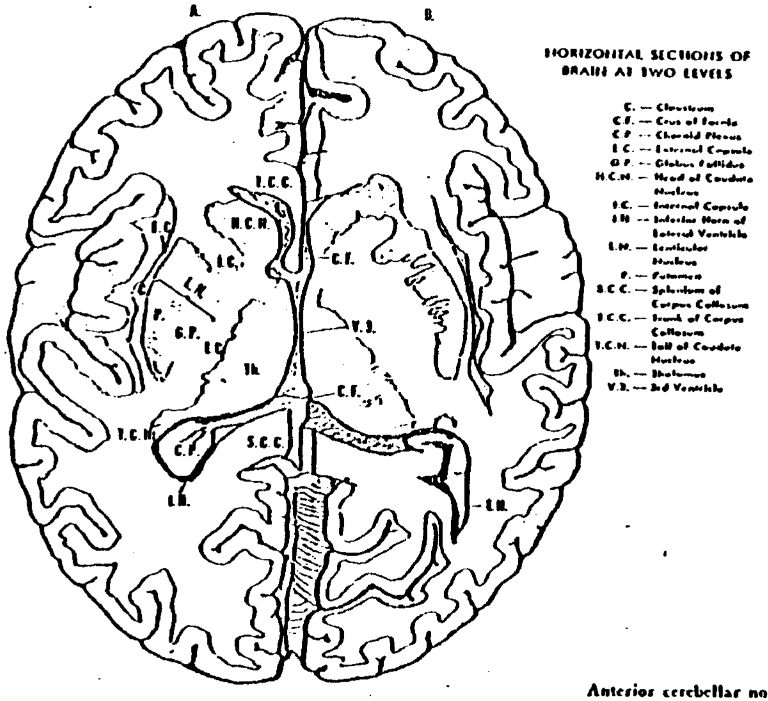
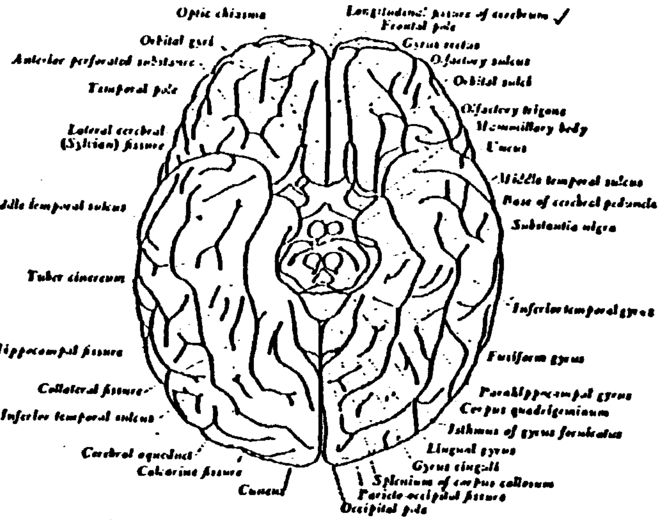


FIG. 109.—THE SKULL, INTERNAL ASPECT OF THE BASE.

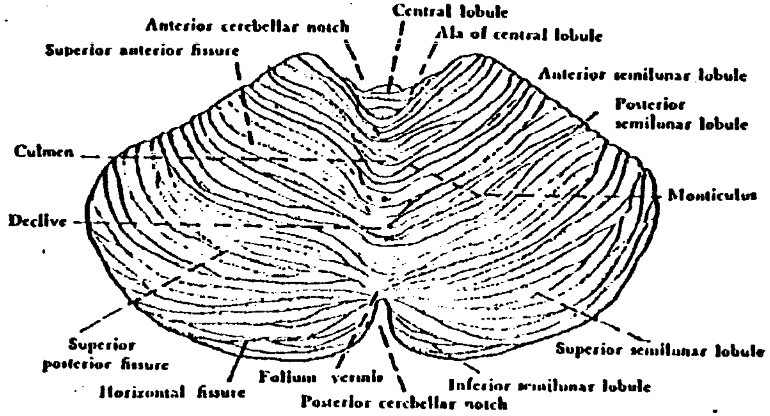
TEST NO. ______________



HORIZONTAL SECTIONS OF BRAIN AT TWO LEVELS

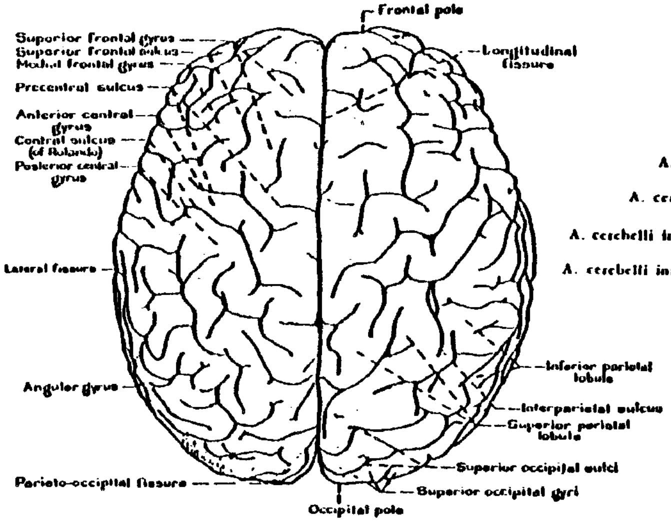


Basal aspect of the human cerebral hemisphere. (Sobotta-McMurrich.)

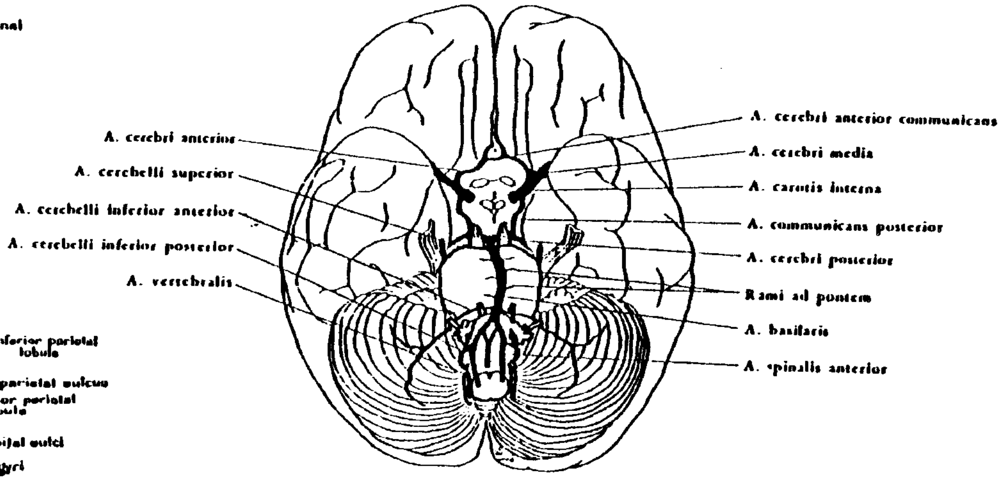


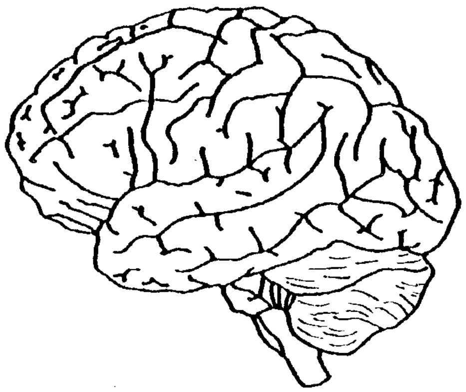
—Upper Surface of Cerebellum.

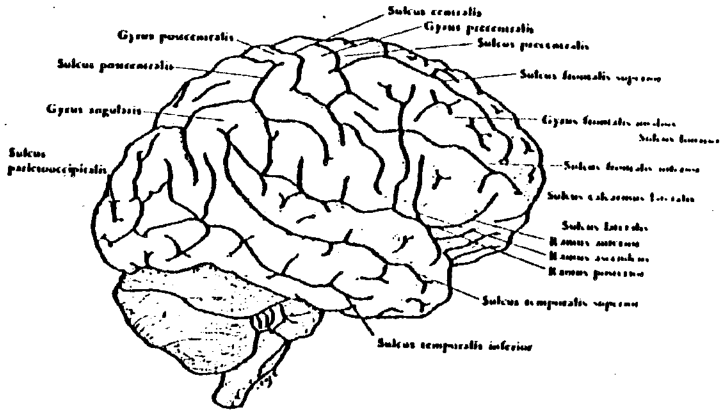
TEST NO. ____________



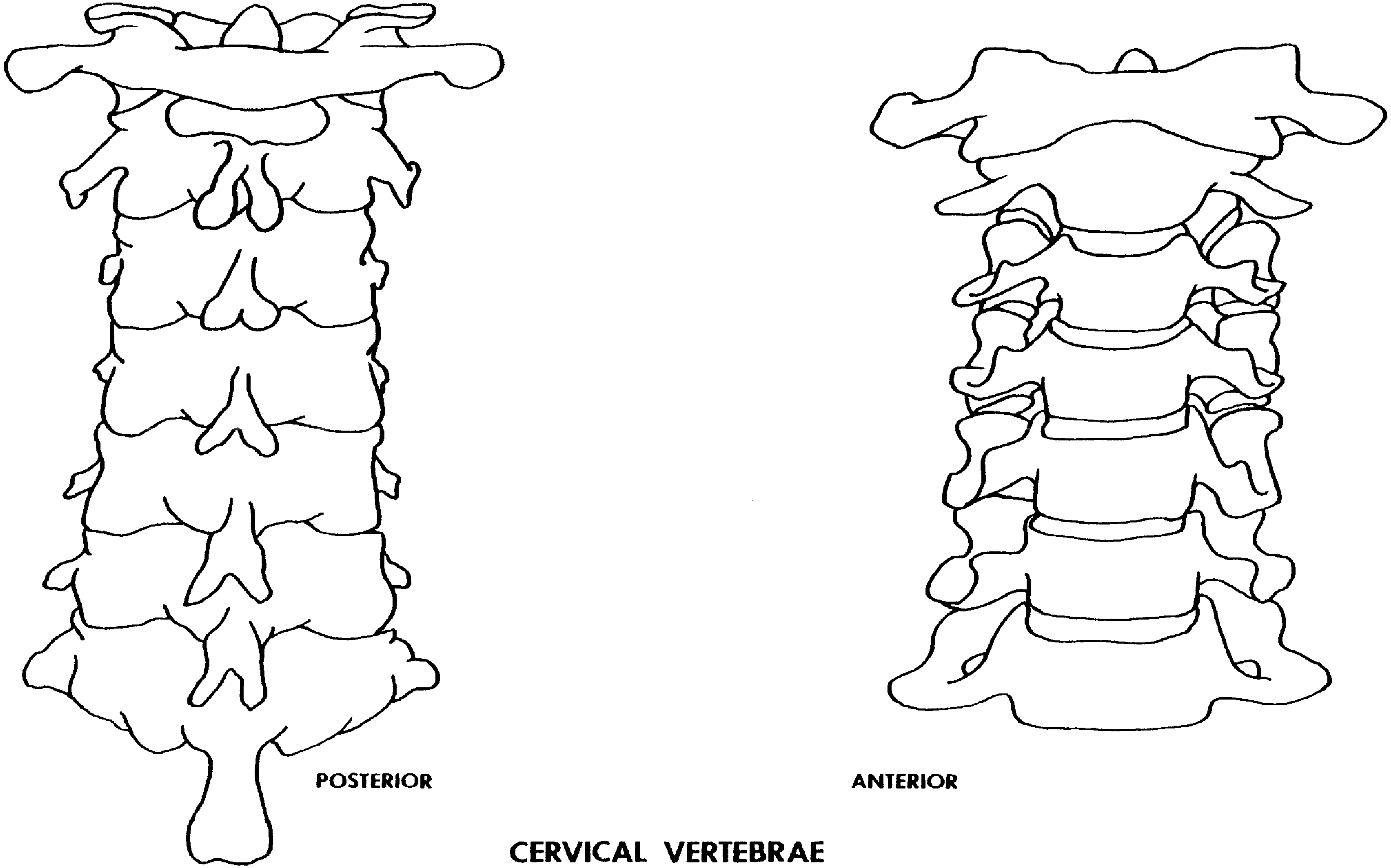
—Cerebral Hemispheres Viewed from Above.







TEST NO. ____________________

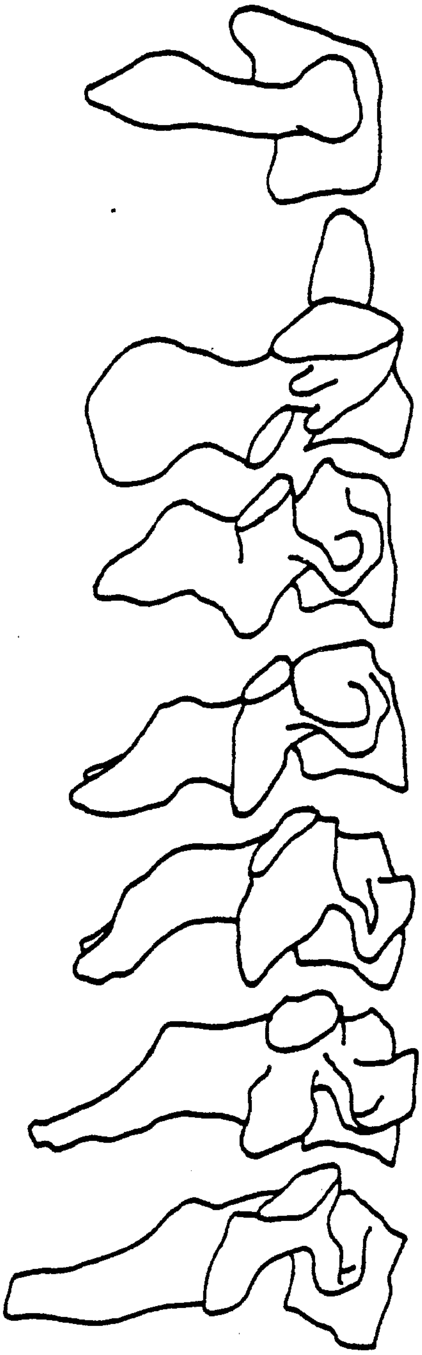


POSTERIOR

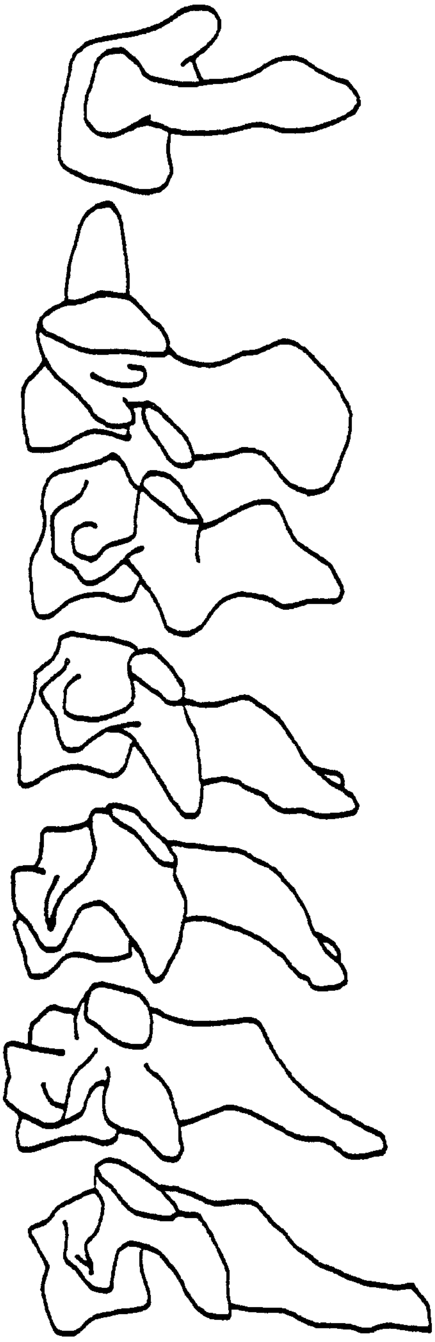
ANTERIOR

CERVICAL VERTEBRAE

TEST NO. ____________

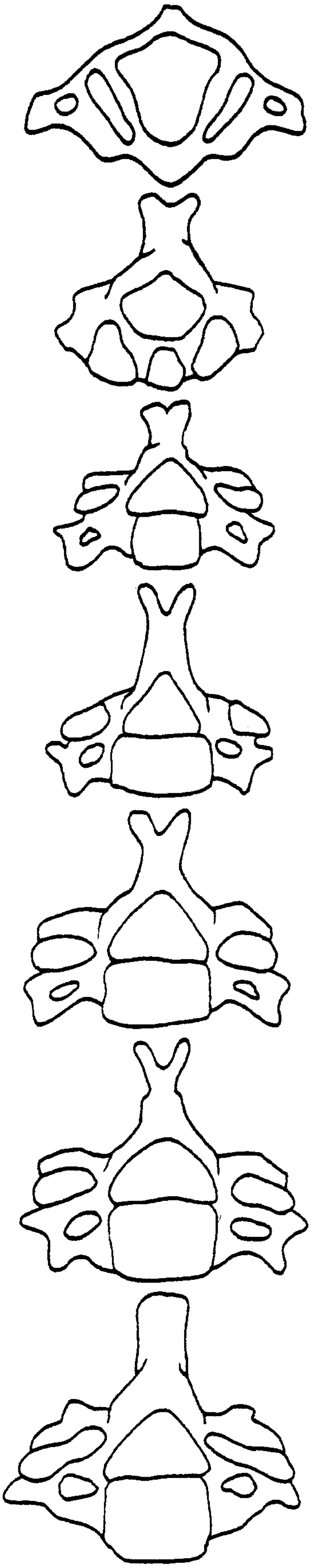


Right Profile

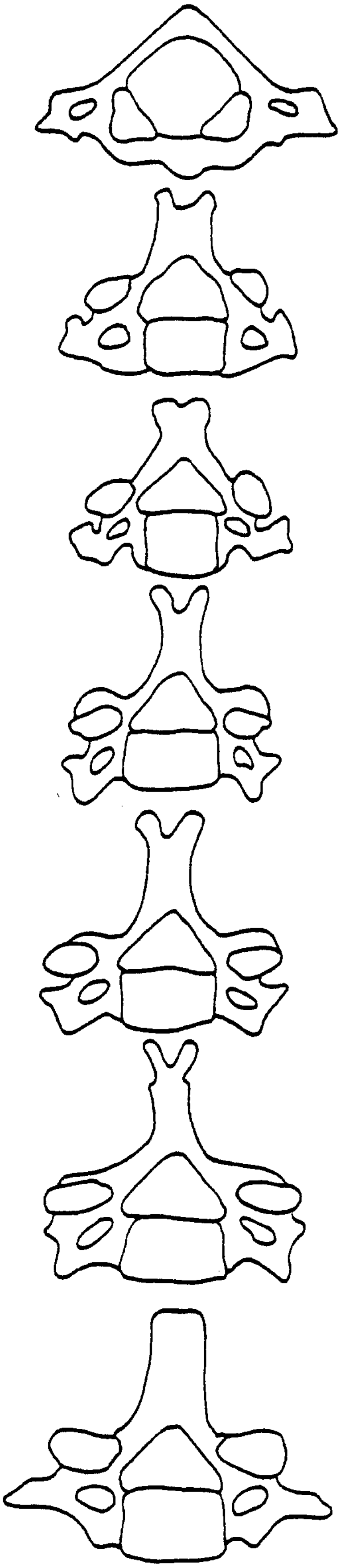


Left Profile

TEST NO. ______________

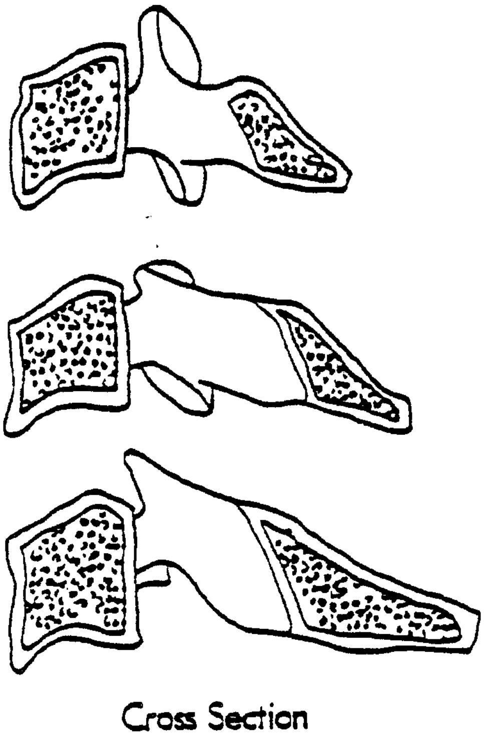


VIEW FROM ABOVE



VIEW FROM BELOW

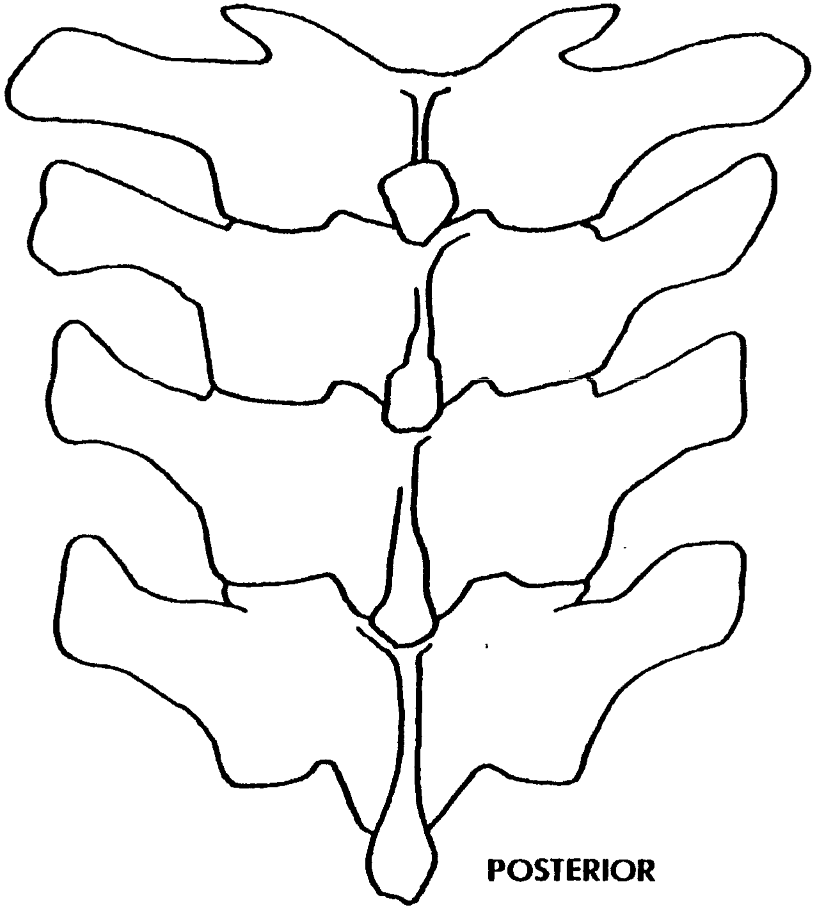
TEST NO. ____________



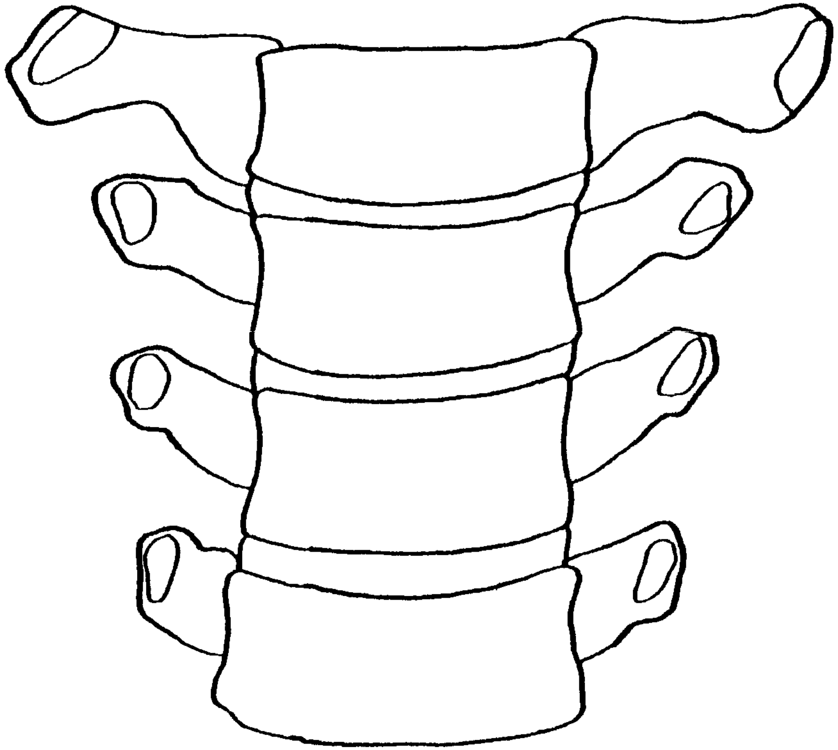
Cross Section

TEST NO. ____________________

THORACIC VERTEBRAE (T1 - T4)



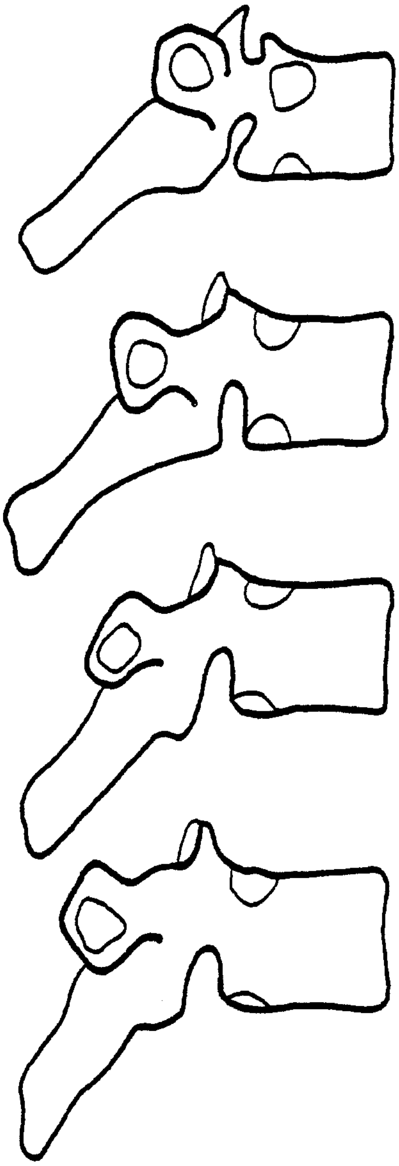
POSTERIOR



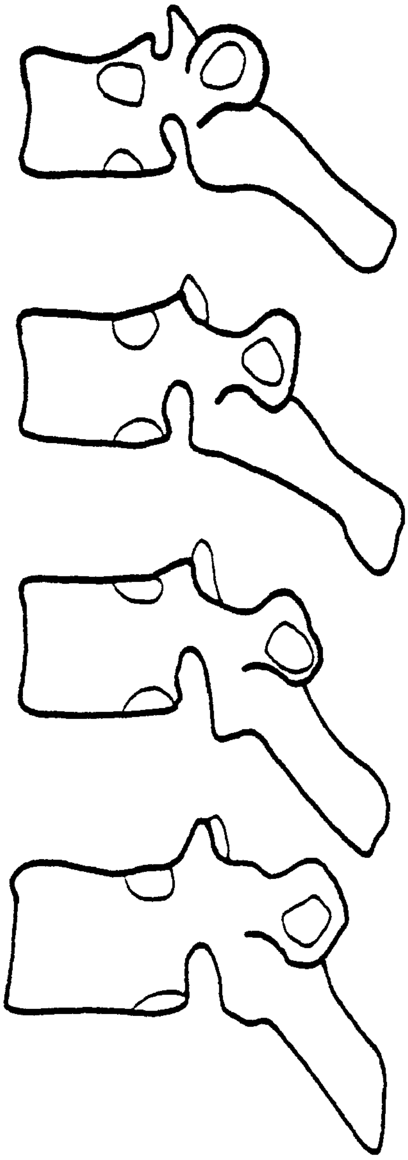
ANTERIOR

TEST NO. ________________

THORACIC VERTEBRAE (T1 - T4)



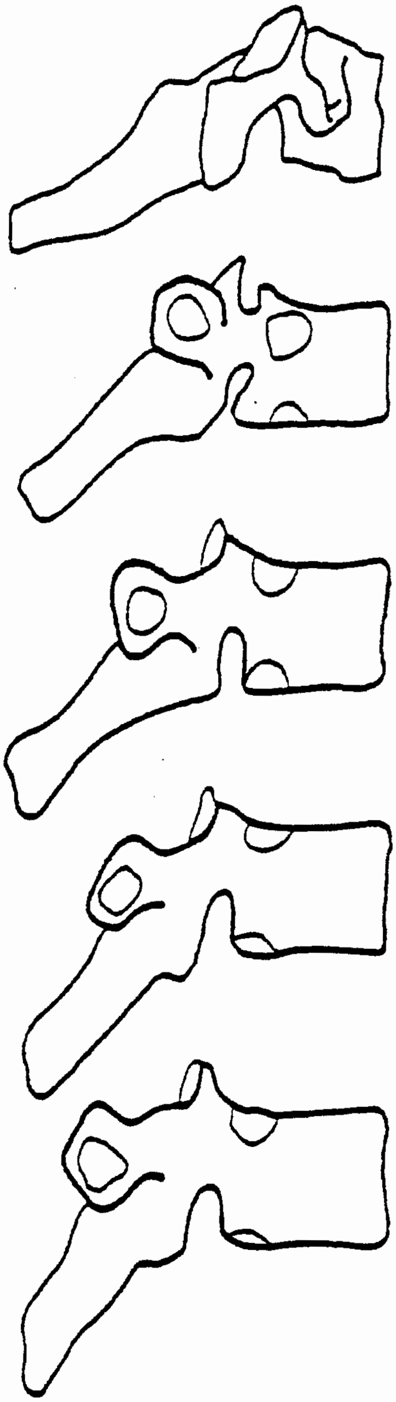
RIGHT PROFILE



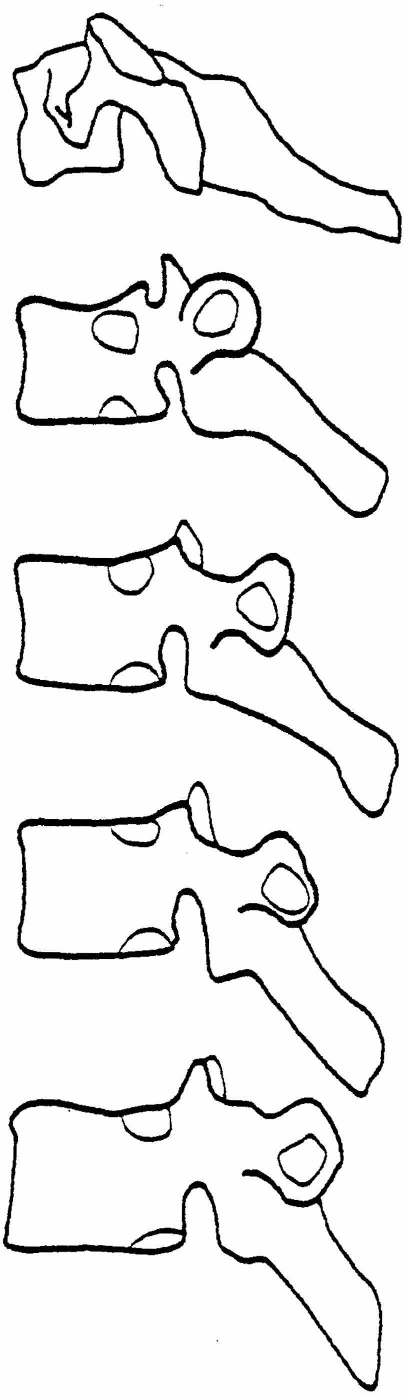
LEFT PROFILE

TEST NO. ________________

CERVICAL VERTEBRA (C7)
THORACIC VERTEBRAE (T1 - T4)

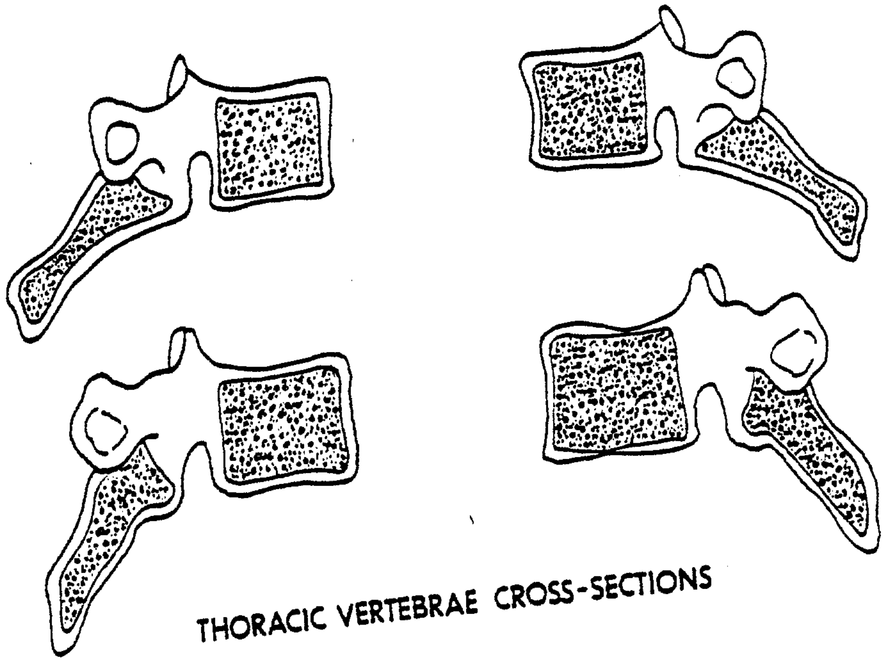


RIGHT PROFILE



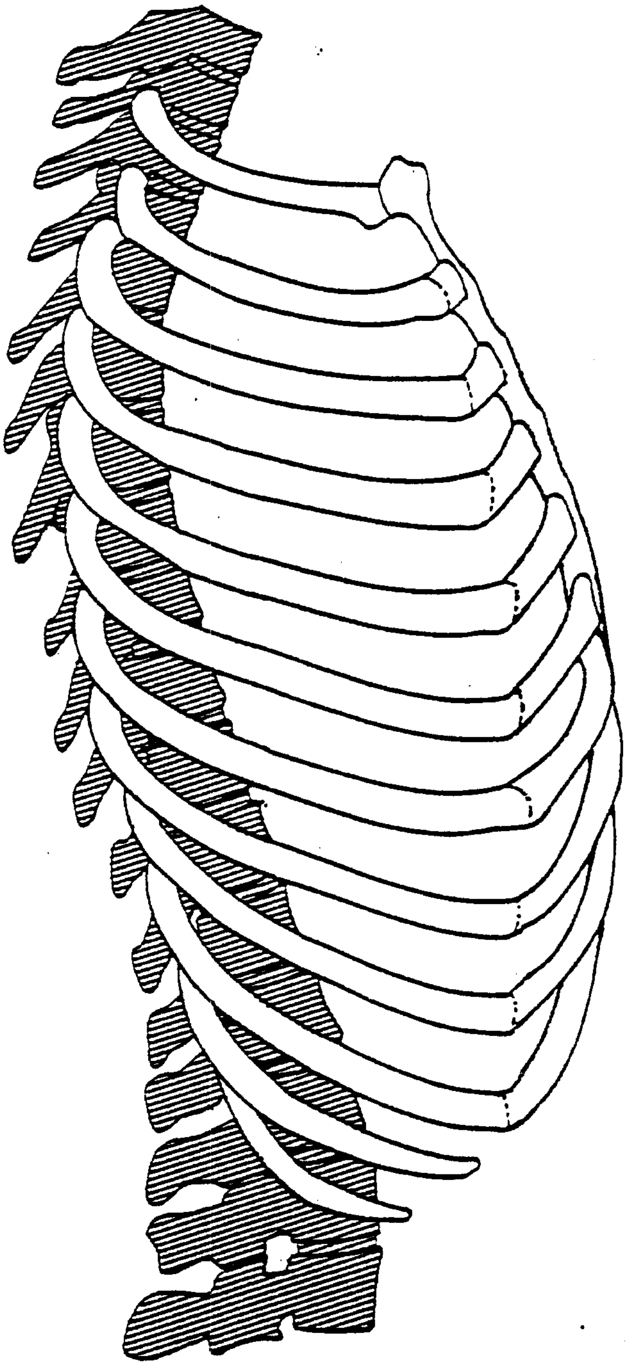
LEFT PROFILE

TEST NO. ____________



THORACIC VERTEBRAE CROSS-SECTIONS

Test No.____________



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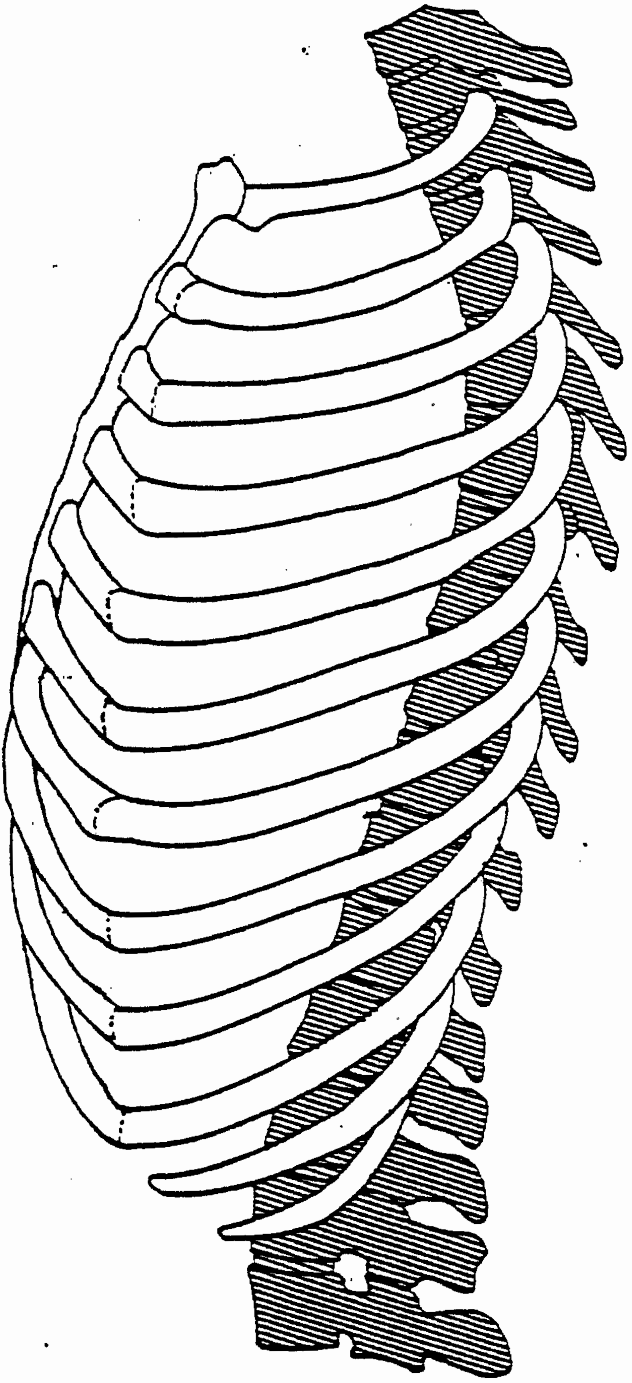


APPENDICES

ANATOMY ROOM SETUP

MEASUREMENT

___ Anthropometer

___ Metric measuring tape

PAPER AND PLASTICS

___ Visqueen on autopsy table

___ Blue pads on table

___ Gauze

TAPES AND STRINGS

___ Silver tape

___ Masking tape

___ Adhesive tape

___ Fiber tape

___ Flat waxed string

SCALPELS

___ 2 large (#8) handles

___ 2 medium (#4) handles

___ 2 small (#3) handles

___ 2 #60 blades

___ 5 #22 blades

___ 5 #15 blades

___ 2 #12 blades

FORCEPS

___ 2 hooked

___ 2 large plain

___ 2 small plain

HEMOSTATS

___ needle

___ small straight

___ small curved

___ large straight

___ large curved

SCISSORS

___ 2 small

___ 2 medium

___ 2 large

SPREADERS

___ 2 large

___ 2 medium

NEEDLES

___ 2 double curved

CLOTHING

___ Tampons

___ Thermoknit longjohns and top

___ Cotton socks

___ Blue vinyl pants and top

___ Body harnesses

___ Shoulder and pelvis support system

BOLTS AND SCREWS

___ 3 lengths of wood screws

___ 1-72 screws

___ Strain relief bolt

___ Wood and metal self-tapping screw boxes

MOUNTS AND ACCESSORIES

___ Spine(3)

___ Nine-accelerometer plates (small, and 4 feet)

___ Dental acrylic

___ Bone wax

TOOLS

___ Electric hair clippers

___ Electric drill

___ Drill bits

___ hammer

___ large and small screwdrivers

___ nut driver (for lag bolts)

___ Executive Slinky object space calibrated and nearly functional

TESTING AREA SETUP

APPARATUS

___ hoists

___ backdrops

___ timer box

___ 2 light panels

___ both camera supports

___ BLT

___ strobe

MATERIALS

___ rags

___ foam (at least 4 sheets of 3x4 ft 6")

___ A.L. Ensolite

___ Seating foam

ROPE CUTTERS

___ thorax, 1/8"

___ leg/pelvis, 1/8"

___ nylon strings (20 18" 1/8")

TOOLS

___ Allen wrench for load platform

___ Supply of piezoresistive cables

___ low-noise connectors

MISCELLANEOUS

___ calculator

___ Strobes

___ foam padding

CART SETUP

TAPES

___ adhesive

___ fiber

___ silver

___ masking

___ black

___ double stick

PAPER AND PLASTIC

___ blue pads

___ gauze

___ gloves

___ plastic garbage bags

SCALPELS

___ 1 medium (#4) handle

___ 1 small (#3) handle

___ 5 #22 blades

___ 2 #15 blades

___ 1 #12 blade

SURGICAL TOOLS

___ 2 forceps

___ 2 hemostats

___ large scissors

___ 2 double curved needles

STRING

___ flat waxed string

___ black thread

TOOLS

___ small (1-72) screwdriver

___ large screwdriver

___ nut driver

___ ball driver (6-32)

___ 1-72 screws

___ 2-56 screws

MISCELLANEOUS

___ ball targets

___ paper targets

___ bone wax

___ alcohol

___ Q-tips

AUTOPSY SETUP

PAPER AND PLASTICS

___ Visqueen on autopsy table

___ blue pads

___ gauze

TAPE

___ silver tape

___ masking tape

___ fiber tape

SCALPELS

___ 2 large (#8) handles

___ 2 medium (#4) handles

___ 2 small (#3) handles

___ 2 #60 blades

___ 10 #22 blades

___ 5 #15 blades

___ 2 #12 blades

FORCEPS

___ 2 hooked

___ 2 large plain

___ 2 small plain

HEMOSTATS

___ needle

___ small straight

___ small curved

___ large straight

___ large curved

SCISSORS

___ 2 small

___ 2 medium

___ 2 large

SPREADERS

___ 3 medium

___ 3 large

MISCELLANEOUS

___ Stryker saw and blade

___ bone shears

___ wedge

___ rib cutters

TIMER BOX SETUP

EQUIPMENT	TIMER VALUES		
__________ Impact	Delay		Run
Gate (start)	1500	1	0200
Lights (start)	0005	2	2600
HyCam (start)	0700	3	1800
Thorax rope cutter(3)	0356	4	0050
Photosonics I (start)	0300	5	1600
		6	
Leg/pelvis rope cutter (3)	0356	7	0050
Photosonics II (start)	0300	8	1600

For impact height of 1.5 meters, contact time is derived from the formula and calculated to be 553 ms. For impact height of 1.1 meters, contact time is calculated to be 474 ms. The lights require a mininum of 1500 ms to illuminate the test area. Both photosonics require a minimum of 1200 ms to reach full speed of 1000 FPS. The HyCam requires 800 ms to reach full speed.

APPENDIX C

COORDINATE SYSTEMS AND TRANSFORMATIONS

Accurate documentation of the three-dimensional motion of the head in the laboratory reference frame requires that acceleration data obtained in the arbitrary instrumentation frame be first described in terms of the standard anatomical system, and finally transformed to the laboratory reference system such that kinematic responses between subjects may be compared. The algorithm for transformation from the instrumentation frame to the anatomical frame is established for any subject.[1] However, as the laboratory reference frame used and subject configuration are unique to this study, the transformation between the anatomical frame and the laboratory frame must be formulated.

One method for describing data obtained in one reference system in terms of another (arbitrary) system is that of Euler Angle Transformation. Three successive rotations of the first system are required to align its axes with those of any arbitrary system.

In this study, we wish to describe the anatomical reference frame in terms of the laboratory reference frame. To accomplish this, three angles describing the rotation of the anatomical system axes with respect to the reference system axes are measured for each subject when in position for a test (Fig. 1). It is then necessary to rotate the anatomical system through these angles to align its axes with the laboratory system axes. This involves two intermediate orientations of the anatomical system. Figure 2 illustrates this transformation.

The associated direction cosine matrix transformations, the Euler matrix, and the equations describing one system in terms of the other are presented in Section 1.

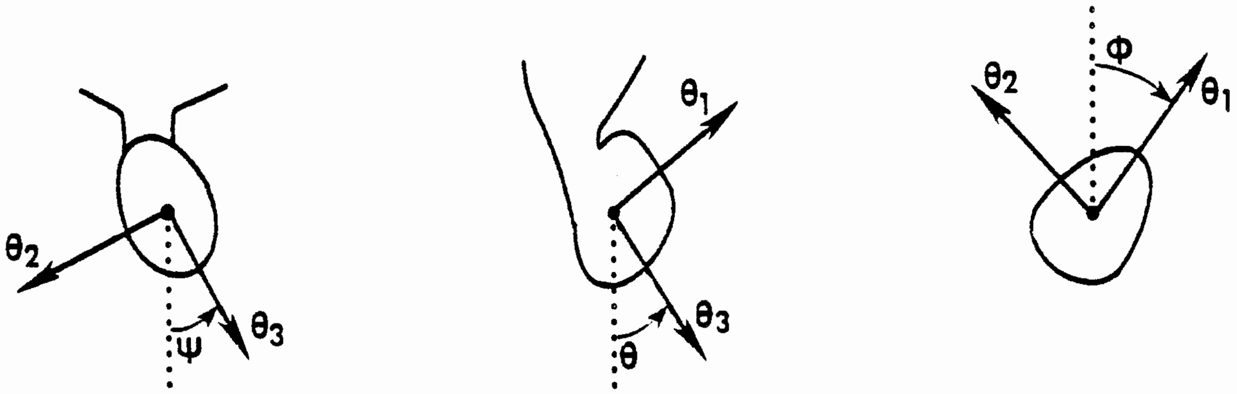
Similar transformations may be performed on the neck and thorax coordinate systems (Sections 2,3). These are much simpler because only one and two angles, respectively, are required to align these systems with the laboratory reference configuration. By this analysis, the initial conditions for all subjects are stated in common terms.

---

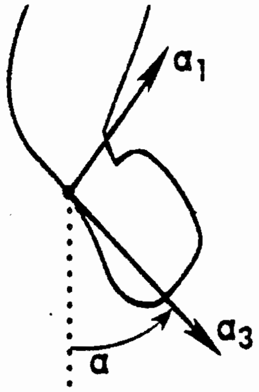
[1] G.S. Nusholtz, J.W. Melvin, and N.M. Alem. "Head Impact Response Comparisons of Human Surrogates," 23rd Stapp Car Crash Conference Proceedings. Warrendale, Pa.: Society of Automotive Engineers, 1979, pp. 497-541. SAE Paper No. 791020.

ANGLE DEFINITIONS

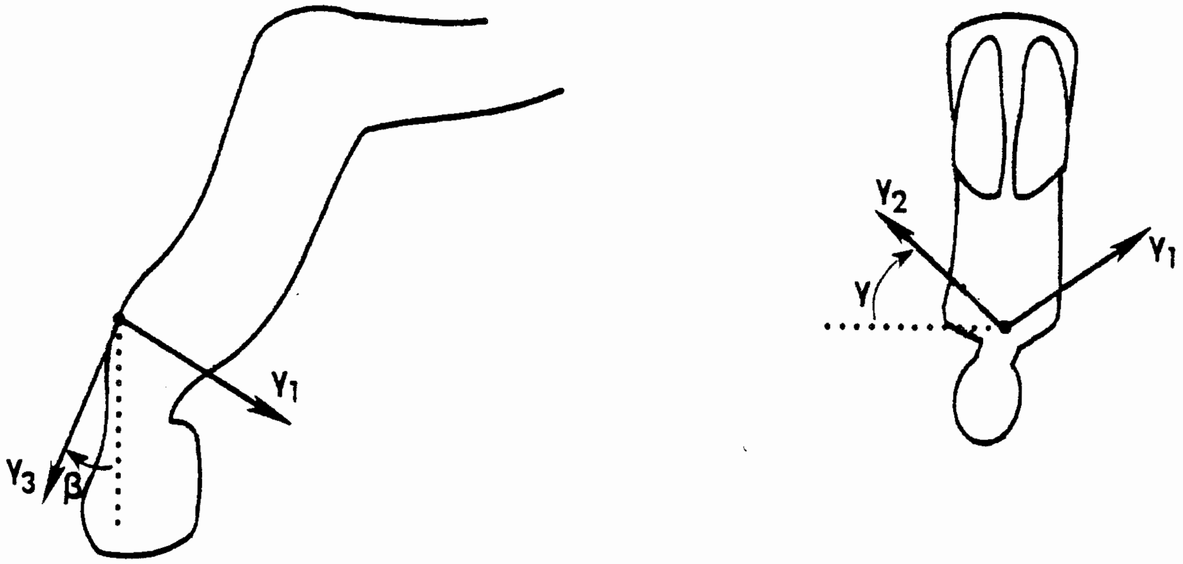
HEAD - Three angles (ψ,θ,ϕ) corresponding to rotations of the head coordinate system about the 1,2, and 3 axes, respectively, are measured:



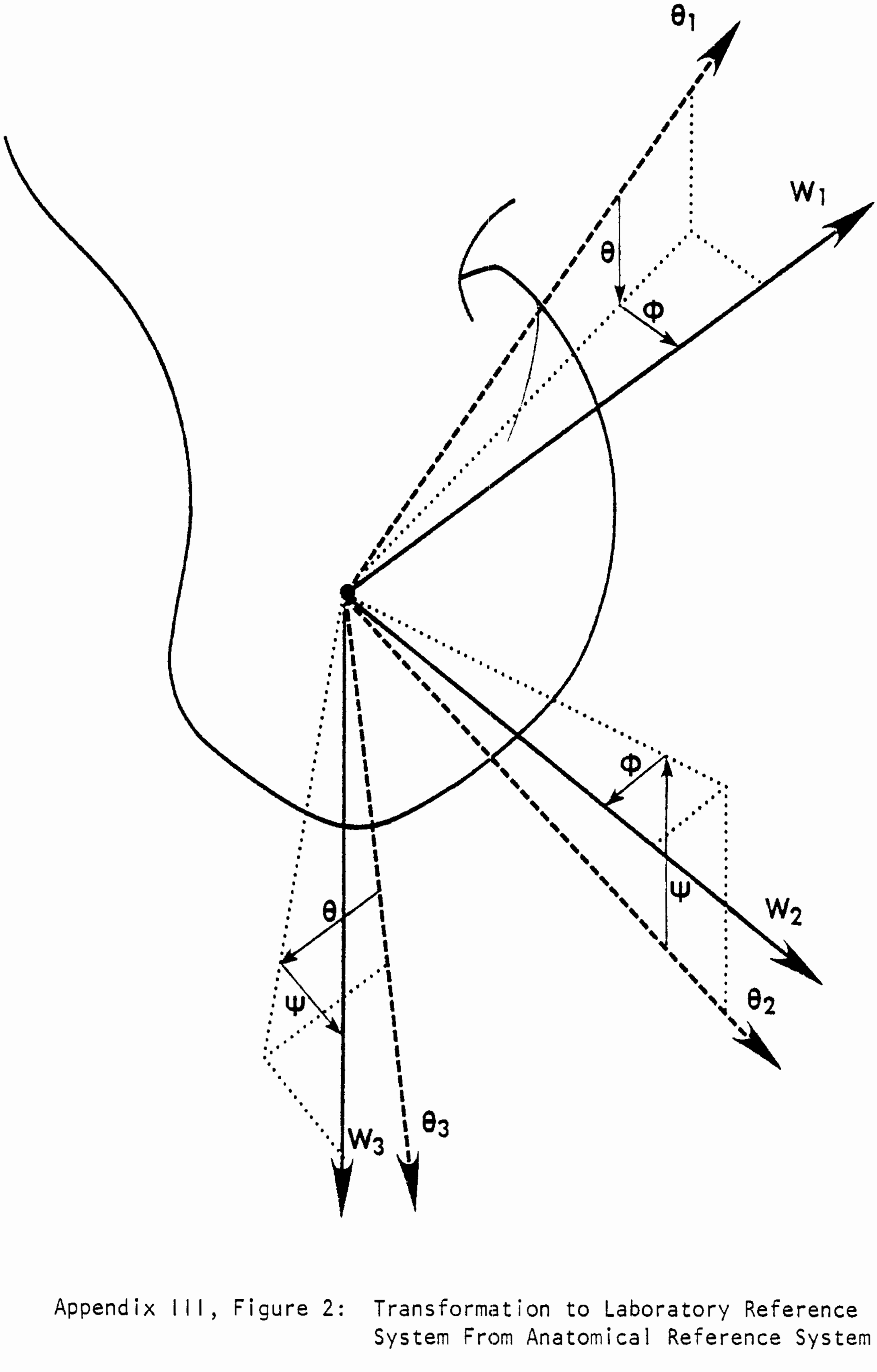
NECK - One angle (α) corresponding to rotation about the 2 axis of the neck coordinate system is measured:



THORAX - Two angles (β,γ) corresponding to rotations of the thorax coordinate system about the 2 and 3 axes, respectively, are measured:



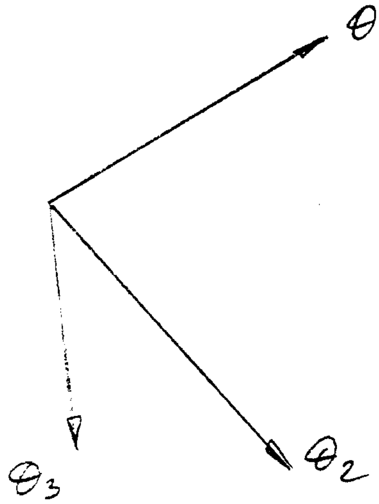
Appendix III, Figure 1: Head Angle Definitions



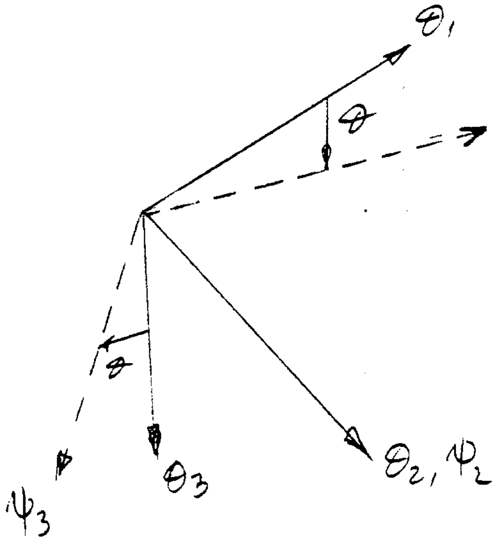
Appendix III, Figure 2: Transformation to Laboratory Reference System From Anatomical Reference System

1. EULER ANGLE TRANSFORMATION FROM HEAD ANATOMICAL FRAME TO LABORATORY REFERENCE FRAME:

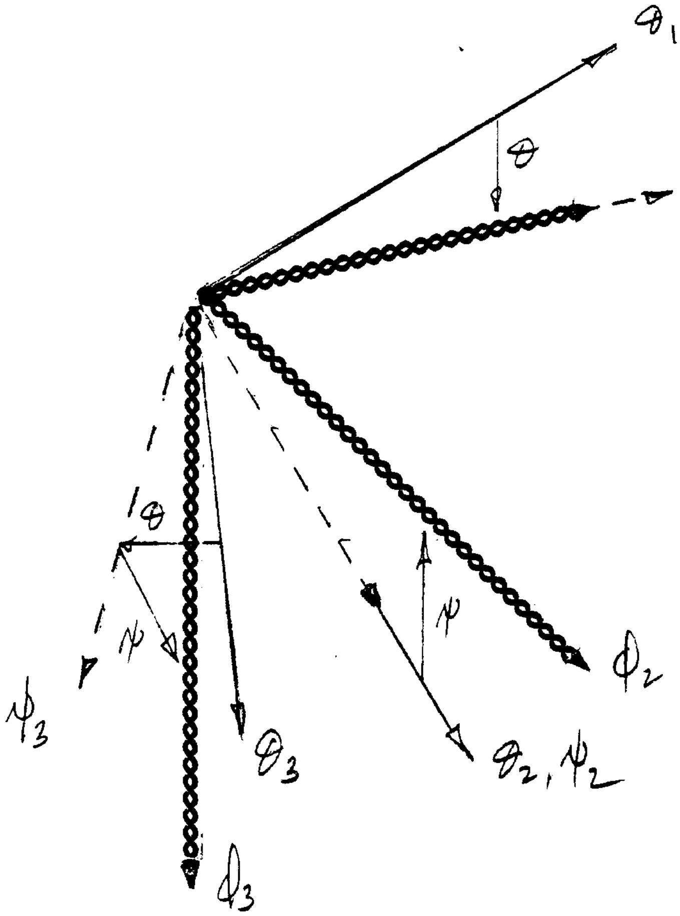
CONSIDER THE FOUR REFERENCE FRAME CONFIGURATIONS W_i, θ_j, ψ_k, AND θ_ℓ WITH BASES $\underset{\sim}{h}_i$, $\underset{\sim}{i}_j$, $\underset{\sim}{j}_k$ AND $\underset{\sim}{k}_\ell$, RESPECTIVELY. THE ANATOMICAL FRAME (θ_ℓ) IS ROTATED THROUGH TWO INTERMEDIATE CONFIGURATIONS (ψ_k, θ_j) UNTIL IT IS FINALLY ALIGNED WITH THE LABORATORY REFERENCE FRAME (W_i).



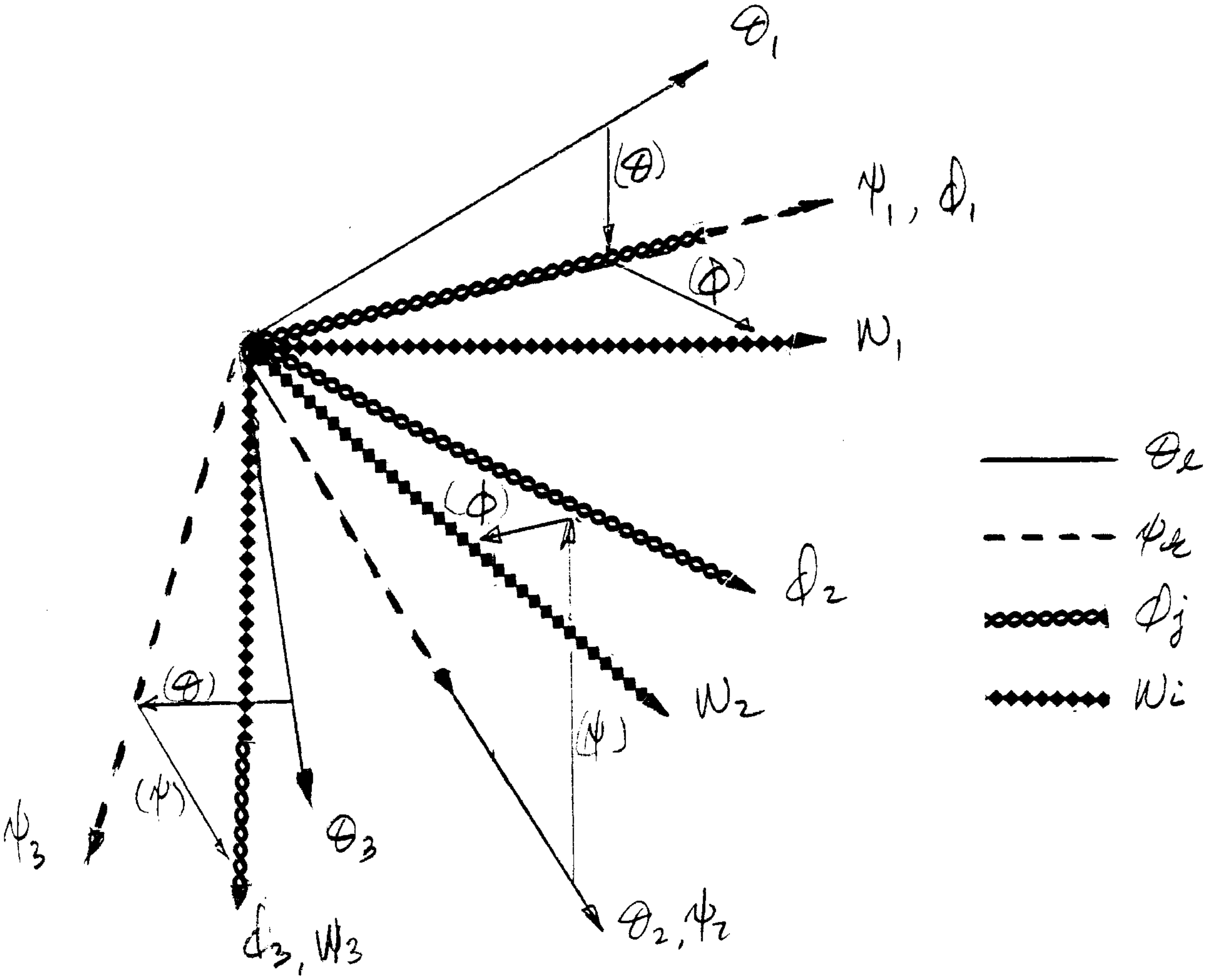
ROTATE ABOUT THE θ_2 AXIS THROUGH THE ANGLE θ TO OBTAIN THE ψ_k CONFIGURATION:



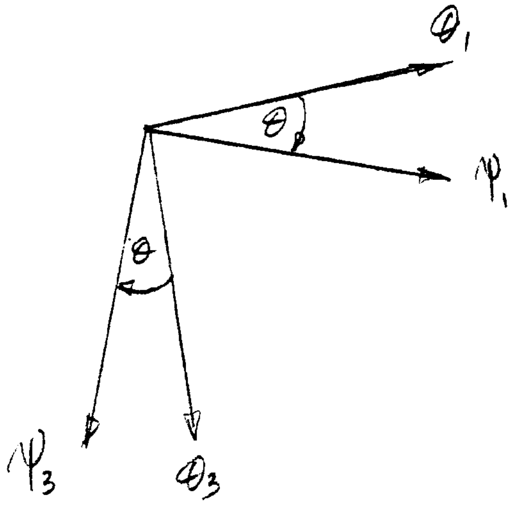
ROTATE THIS SYSTEM ABOUT THE ψ_2 AXIS THROUGH THE ANGLE ψ TO OBTAIN THE Φ_j CONFIGURATION:



ROTATE THIS SYSTEM ABOUT THE Φ_3 AXIS THROUGH THE ANGLE ϕ TO OBTAIN THE W_i (REFERENCE) CONFIGURATION:

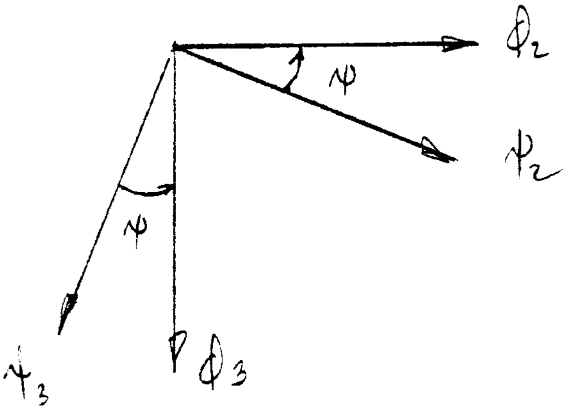


THE DIRECTION COSINE MATRICIES ASSOCIATED WITH EACH TRANSFORMATION ARE THE FOLLOWING:



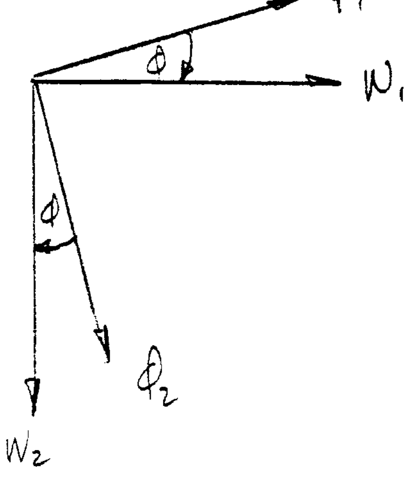
$$\begin{bmatrix} \underset{\sim}{j}_1 \\ \underset{\sim}{j}_2 \\ \underset{\sim}{j}_3 \end{bmatrix} = \begin{bmatrix} \cos\theta & 0 & \sin\theta \\ 0 & 1 & 0 \\ -\sin\theta & 0 & \cos\theta \end{bmatrix} \cdot \begin{bmatrix} \underset{\sim}{k}_1 \\ \underset{\sim}{k}_2 \\ \underset{\sim}{k}_3 \end{bmatrix}$$

$$\underset{\sim}{j}_k = \theta_{kl} \underset{\sim}{k}_l$$



$$\begin{bmatrix} \underset{\sim}{i}_1 \\ \underset{\sim}{i}_2 \\ \underset{\sim}{i}_3 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\psi & -\sin\psi \\ 0 & \sin\psi & \cos\psi \end{bmatrix} \cdot \begin{bmatrix} \underset{\sim}{j}_1 \\ \underset{\sim}{j}_2 \\ \underset{\sim}{j}_3 \end{bmatrix}$$

$$\underset{\sim}{i}_j = \psi_{jk} \underset{\sim}{j}_k$$



$$\begin{bmatrix} \underset{\sim}{h}_1 \\ \underset{\sim}{h}_2 \\ \underset{\sim}{h}_3 \end{bmatrix} = \begin{bmatrix} \cos\phi & \sin\phi & 0 \\ -\sin\phi & \cos\phi & 0 \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} \underset{\sim}{i}_1 \\ \underset{\sim}{i}_2 \\ \underset{\sim}{i}_3 \end{bmatrix}$$

$$\underset{\sim}{h}_i = \phi_{ij} \underset{\sim}{i}_j$$

THE OVERALL TRANSFORMATION FROM THE ANATOMICAL FRAME ($\theta_1, \theta_2, \theta_3$ WITH BASIS $\underset{\sim}{k}_1, \underset{\sim}{k}_2, \underset{\sim}{k}_3$) TO THE LABORATORY REFERENCE FRAME (W_1, W_2, W_3 WITH BASIS $\underset{\sim}{h}_1, \underset{\sim}{h}_2, \underset{\sim}{h}_3$) IS

$$\underset{\sim}{h}_i = \phi_{ij} \psi_{jk} \theta_{kl} \underset{\sim}{k}_l$$

WHERE ϕ_{ij}, ψ_{jk}, AND θ_{kl} ARE THE DIRECTION COSINE MATRICIES CORRESPONDING TO THE THREE ROTATIONS.

IN MATRIX FORM, THIS TRANSFORMATION IS

$$\begin{bmatrix} \underset{\sim}{h}_1 \\ \underset{\sim}{h}_2 \\ \underset{\sim}{h}_3 \end{bmatrix} = \begin{bmatrix} \cos\phi & \sin\phi & 0 \\ -\sin\phi & \cos\phi & 0 \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\psi & -\sin\psi \\ 0 & \sin\psi & \cos\psi \end{bmatrix} \cdot \begin{bmatrix} \cos\theta & 0 & \sin\theta \\ 0 & 1 & 0 \\ -\sin\theta & 0 & \cos\theta \end{bmatrix} \cdot \begin{bmatrix} \underset{\sim}{k}_1 \\ \underset{\sim}{k}_2 \\ \underset{\sim}{k}_3 \end{bmatrix}$$

CARRYING OUT THE MATRIX MULTIPLICATION, THE EULER MATRIX IS

$$\begin{bmatrix} \underset{\sim}{h}_1 \\ \underset{\sim}{h}_2 \\ \underset{\sim}{h}_3 \end{bmatrix} = \begin{bmatrix} \cos\phi\cos\theta + \sin\phi\sin\psi\sin\theta & \sin\phi\sin\psi & \cos\phi\sin\theta - \sin\phi\sin\psi\cos\theta \\ -\sin\phi\cos\theta + \cos\phi\sin\psi\sin\theta & \cos\phi\cos\psi & -\sin\phi\sin\theta - \cos\phi\sin\psi\cos\theta \\ -\cos\psi\sin\theta & \sin\psi & \cos\psi\cos\theta \end{bmatrix} \cdot \begin{bmatrix} \underset{\sim}{k}_1 \\ \underset{\sim}{k}_2 \\ \underset{\sim}{k}_3 \end{bmatrix}$$

EXPRESSING THIS MATRIX IN EQUATION FORM, WE OBTAIN THE SET OF EQUATIONS DESCRIBING THE ANATOMICAL BASIS IN TERMS OF THE LABORATORY REFERENCE BASIS FOR THE SUBJECT IN ITS INITIAL POSITION (IMMEDIATELY PRIOR TO CONTACT):

$$\underset{\sim}{h}_1 = (\cos\phi\cos\theta + \sin\phi\sin\psi\sin\theta)\cdot\underset{\sim}{k}_1 + (\sin\phi\cos\psi)\cdot\underset{\sim}{k}_2 + (\cos\phi\sin\theta - \sin\phi\sin\psi\cos\theta)\cdot\underset{\sim}{k}_3$$

$$\underset{\sim}{h}_2 = (-\sin\phi\cos\theta + \cos\phi\sin\psi\sin\theta)\cdot\underset{\sim}{k}_1 + (\cos\phi\cos\psi)\cdot\underset{\sim}{k}_2 + (-\sin\phi\sin\theta - \cos\phi\sin\psi\cos\theta)\cdot\underset{\sim}{k}_3$$

$$\underset{\sim}{h}_3 = (-\cos\psi\sin\theta)\cdot\underset{\sim}{k}_1 + (\sin\psi)\cdot\underset{\sim}{k}_2 + (\cos\psi\cos\theta)\cdot\underset{\sim}{k}_3$$

THE INITIAL POSITION OF THE HEAD IN THE LABORATORY REFERENCE FRAME HAS BEEN DETERMINED BY TAKING MEASUREMENTS IN THE ANATOMICAL FRAME AND TRANSFORMING THEM BY THE EULER ANGLE METHOD. IT IS ALSO DESIRED, FOR MEANS OF KINEMATIC ANALYSIS, TO SPECIFY THE INITIAL VELOCITY OF THE HEAD IN THE ANATOMICAL REFERENCE FRAME. THIS QUANTITY, HOWEVER, IS MEASURED IN THE LABORATORY REFERENCE SYSTEM. THE EULER ANGLE MATRIX MAY ALSO BE USED TO TRANSFORM FROM THE ANATOMICAL SYSTEM TO THE LABORATORY SYSTEM (SINCE THE TRANSFORMATION IS ORTHOGONAL) BY TAKING THE TRANSPOSE OF THE EULER MATRIX. RECALL THE TRANSFORMATION FROM THE ANATOMICAL SYSTEM TO THE LABORATORY SYSTEM:

$$\underset{\sim}{h}_i = \phi_{ij}\,\psi_{jk}\,\theta_{kl}\,\underset{\sim}{k}_l .$$

TRANSPOSING THE MATRICIES, $\phi^T = \phi_{ji}$, $\psi^T = \psi_{kj}$; AND $\theta^T = \theta_{lk}$. THE INVERSE TRANSFORMATION IS THEREFORE

$$\underset{\sim}{k}_l = \theta_{lk}\,\psi_{kj}\,\phi_{ji}\,\underset{\sim}{h}_i .$$

THE RESULTING INVERSE MATRIX IS

$$\begin{bmatrix} \underset{\sim}{k}_1 \\ \underset{\sim}{k}_2 \\ \underset{\sim}{k}_3 \end{bmatrix} = \begin{bmatrix} \cos\theta\cos\phi + \sin\theta\sin\psi\sin\phi & -\cos\theta\sin\phi + \sin\theta\sin\psi\cos\phi & -\sin\theta\cos\psi \\ \cos\psi\sin\phi & \cos\psi\cos\phi & \sin\psi \\ \sin\theta\cos\phi - \cos\theta\sin\psi\sin\phi & -\sin\theta\sin\phi - \cos\theta\sin\psi\cos\phi & \cos\theta\cos\psi \end{bmatrix} \cdot \begin{bmatrix} \underset{\sim}{h}_1 \\ \underset{\sim}{h}_2 \\ \underset{\sim}{h}_3 \end{bmatrix}$$

FOR WHICH THE ASSOCIATED EQUATIONS ARE

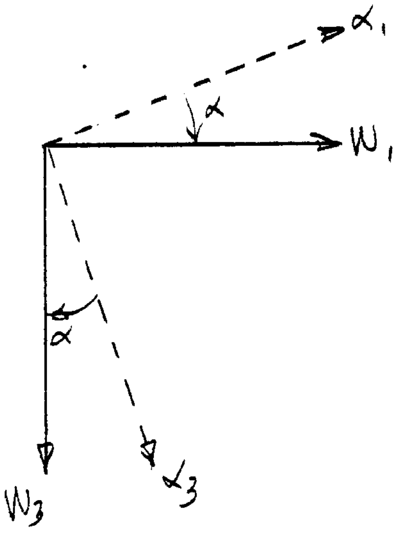
$$\underset{\sim}{k}_1 = (\cos\theta\cos\phi + \sin\theta\sin\psi\sin\phi)\,\underset{\sim}{h}_1 + (-\cos\theta\sin\phi + \sin\theta\sin\psi\cos\phi)\cdot\underset{\sim}{h}_2 + (-\sin\theta\cos\psi)\cdot\underset{\sim}{h}_3$$

$$\underset{\sim}{k}_2 = (\cos\psi\sin\phi)\,\underset{\sim}{h}_1 + (\cos\psi\cos\phi)\,\underset{\sim}{h}_2 + (\sin\psi)\,\underset{\sim}{h}_3$$

$$\underset{\sim}{k}_3 = (\sin\theta\cos\phi - \cos\theta\sin\psi\sin\phi)\cdot\underset{\sim}{h}_1 + (-\sin\theta\sin\phi - \cos\theta\sin\psi\cos\phi)\,\underset{\sim}{h}_2 + (\cos\theta\cos\psi)\,\underset{\sim}{h}_3$$

2. EULER ANGLE TRANSFORMATION FROM NECK ANATOMICAL FRAME TO LABORATORY REFERENCE FRAME:

ONLY ONE ANGLE (α) IS MEASURED, WHICH REPRESENTS THE ANGLE THE AXIS OF THE NECK MAKES WITH THE VERTICAL. CONSIDER TWO REFERENCE SYSTEMS W_i AND α_i WITH BASES $\underset{\sim}{h}_i$ AND $\underset{\sim}{i}_j$, RESPECTIVELY. THE ANATOMICAL FRAME α_i IS ROTATED THROUGH ONE ANGLE TO ALIGN THE 3 AXIS WITH THAT OF THE LABORATORY REFERENCE FRAME:



($\alpha_2 = W_2$)

THE DIRECTION COSINE MATRIX ASSOCIATED WITH THE TRANSFORMATION IS

THE DIRE

$$\begin{bmatrix} \underset{\sim}{h}_1 \\ \underset{\sim}{h}_2 \\ \underset{\sim}{h}_3 \end{bmatrix} \quad \begin{bmatrix} \cos\alpha & 0 & \sin\alpha \\ 0 & 1 & 0 \\ -\sin\alpha & 0 & \cos\alpha \end{bmatrix} \begin{bmatrix} \underset{\sim}{i}_1 \\ \underset{\sim}{i}_2 \\ \underset{\sim}{i}_3 \end{bmatrix}$$

AND THE ASSOCIATED EQUATIONS ARE

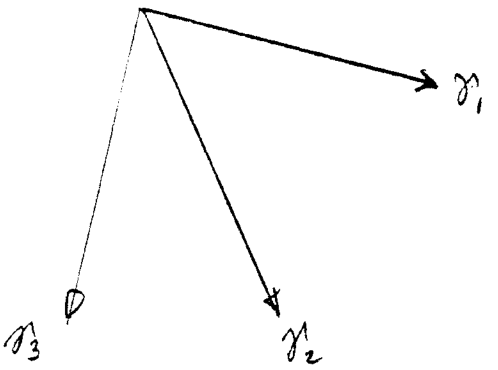
$$\underset{\sim}{h}_1 = \cos\alpha\, \underset{\sim}{i}_1 + \sin\alpha\, \underset{\sim}{i}_2$$

$$\underset{\sim}{h}_2 = \underset{\sim}{i}_2$$

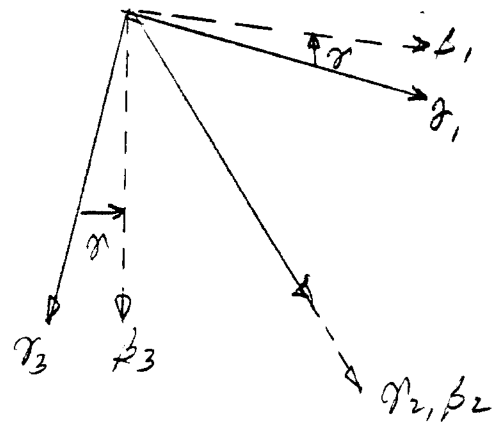
$$\underset{\sim}{h}_3 = -\sin\alpha\, \underset{\sim}{i}_1 + \cos\alpha\, \underset{\sim}{i}_3$$

3. EULER ANGLE TRANSFORMATION FROM THORACIC ANATOMICAL FRAME TO LABORATORY REFERENCE FRAME

TWO ANGLES (β, γ) ARE MEASURED. CONSIDER THREE SYSTEMS W_i, β_j, AND γ_k WITH BASES $\underset{\sim}{h}_i$, $\underset{\sim}{i}_j$, AND $\underset{\sim}{j}_k$, RESPECTIVELY. THE ANATOMICAL FRAME γ'_k IS ROTATED THROUGH ONE INTERMEDIATE CONFIGURATION TO ALIGN IT WITH THE LABORATORY REFERENCE FRAME W_i.

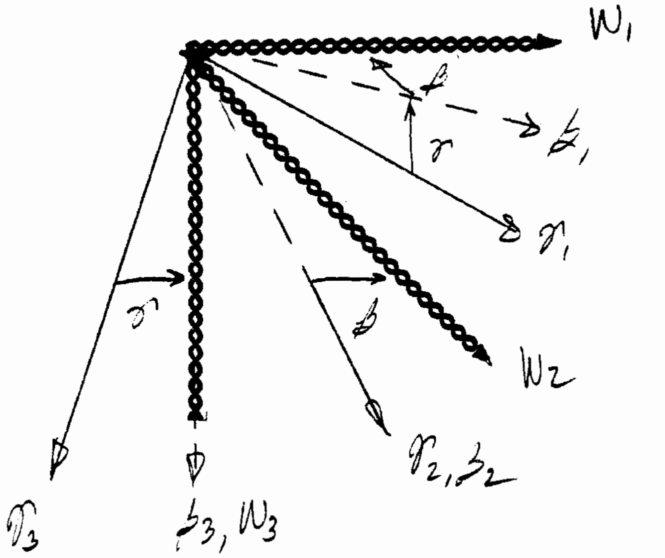


ROTATE THIS SYSTEM THROUGH THE ANGLE γ ABOUT THE γ_2 AXIS TO OBTAIN THE β_j CONFIGURATION:



ROTATE THIS SYSTEM THROUGH THE ANGLE β ABOUT THE β_3 AXIS TO OBTAIN THE LABORATORY REFERENCE CONFIGURATION:

$$\underset{\sim}{i}_j = \gamma_{jk}\,\underset{\sim}{j}_k$$



$$\underset{\sim}{h}_i = \beta_{ij}\, \underset{\sim}{i}_j$$

THE OVERALL TRANSFORMATION IS $\underset{\sim}{h}_i = \beta_{ij}\, \gamma_{jk}\, \underset{\sim}{j}_k$, CORRESPONDING TO THE MATRIX EQUATION

$$\begin{bmatrix} \underset{\sim}{h}_1 \\ \underset{\sim}{h}_2 \\ \underset{\sim}{h}_3 \end{bmatrix} = \begin{bmatrix} \cos\gamma & 0 & -\sin\gamma \\ 0 & 1 & 0 \\ \sin\gamma & 0 & \cos\gamma \end{bmatrix} \cdot \begin{bmatrix} \cos\beta & -\sin\beta & 0 \\ \sin\beta & \cos\beta & 0 \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} \underset{\sim}{j}_1 \\ \underset{\sim}{j}_2 \\ \underset{\sim}{j}_3 \end{bmatrix}$$

THE OVERALL EULER MATRIX IS

$$\begin{bmatrix} \underset{\sim}{h}_1 \\ \underset{\sim}{h}_2 \\ \underset{\sim}{h}_3 \end{bmatrix} = \begin{bmatrix} \cos\gamma\cos\beta & -\cos\gamma\sin\beta & -\sin\gamma \\ \sin\beta & \cos\beta & 0 \\ \sin\gamma\cos\beta & -\sin\gamma\sin\beta & \cos\gamma \end{bmatrix} \cdot \begin{bmatrix} \underset{\sim}{j}_1 \\ \underset{\sim}{j}_2 \\ \underset{\sim}{j}_3 \end{bmatrix}$$

AND THE ASSOCIATED EQUATIONS ARE

$$\underset{\sim}{h}_1 = \cos\gamma\cos\beta\, \underset{\sim}{j}_1 - \cos\gamma\sin\beta\, \underset{\sim}{j}_2 - \sin\gamma\, \underset{\sim}{j}_3$$

$$\underset{\sim}{h}_2 = \sin\beta\, \underset{\sim}{j}_1 + \cos\beta\, \underset{\sim}{j}_2$$

$$\underset{\sim}{h}_3 = \sin\gamma\cos\beta\, \underset{\sim}{j}_1 - \sin\gamma\sin\beta\, \underset{\sim}{j}_2 + \cos\gamma\, \underset{\sim}{j}_3$$