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KINEMATICS OF THE HUMAN CADAVER CERVICAL SPINE IN RESPONSE TO SUPERIOR-INFERIOR LOADING OF THE HEAD

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Dynamic Biomechanics Experimental Data

16. Abstract

The primary purpose of the study was to examine the effects of the pre-positioned rotated head on cervical spine injuries produced by a blunt impact to the crown of the head. The superior-inferior direction impact was delivered to an instrumented unrepressurized human cadaver by a free-flying ballistic pendulum striker. In addition, a series of similar tests was conducted on the Hybrid III anthropomorphic test device (dummy surrogate).

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Kinematics of the Human Cadaver Cervical Spine

in Response to Superior-Inferior Loading of the Head

GM Crown Head Impact - Neck

Principal Investigator: Guy S. Nusholtz

Project Final Report

Overview of Problem:

Over the past four years, the University of Michigan Transportation Research Institute (UMTRI) has been engaged in an extensive effort to understand cervical spine response to superior-inferior crown impacts. In the clinic, flexion/compression-type injuries resulting from a superior-inferior crown impact to the head are seen, yet most efforts to reproduce these injuries in the laboratory have failed. Neck injuries do not occur often in automobile collisions when compared to other lesions, but the consequences of such injuries are particularly tragic for the victims when there is neurological involvement resulting in permanent paralysis. A better understanding of neck injury mechanisms may be used to mitigate the damage produced in certain types of collisions. Our present knowledge of neck injury mechanisms is elementary and fundamental, and has been primarily based on clinical observations provided by physicians who had few (if any) details of the injury-producing event. Although these clinical observations have been supplemented by some cadaver experiments, only recently has it been possible to identify specific research problems. Tests conducted at UMTRI prior to this study had shown that when the head is initially positioned in an asymmetric fashion it is possible to generate flexion/compression-type injuries by applying a superior-inferior load to the head. This observation is consonant with certain experimental evidence in the scientific literature. However, only lately has the complex nature of these responses become fully apparent.

Purpose of Study:

Relatively little is known about the kinematic responses of the human neck following a superior-inferior impact to the head. Although the incidence of cervical spine injuries is relatively low when compared to the other types of injury sustained in automobile accidents, the consequences of blunt crown head impacts can be severe and extreme. Some insights into the mechanical behavior of the head/neck/torso system have been obtained from earlier research, but detailed investigations have yet to be conducted. The primary purpose of the study was to examine the effects of the prepositioned rotated head on injuries produced by a superior-inferior crown impact. Also included were a series of tests for the purpose of comparing cadaver responses with those of the Hybrid III anthropomorphic dummy.

Anthropomorphic dummies are used to investigate safety-related problems by industry and government agencies alike. However, the design and construction of present dummy necks may not be adequate for specific analyses of neck injury mechanisms. Furthermore, it may not be possible to pre-configure the neck of any existing dummy with

rotation. These deficiencies were recognized, yet additional tests were conducted using the Hybrid III dummy to provide some measure of experimental repeatability. At the same time, it was hoped that the results provided by the Hybrid III dummy, when compared with those rendered by the cadavers, would provide information to help in the development of better human surrogates. The deficiencies of the human cadaver were also recognized. The investigators were aware that the cadaver is only an approximation of a living human being, and that data obtained from cadaver material may differ from that rendered by the live subject. However, no better human surrogate was/is known to exist.

Research Plan:

The project was divided into three phases: (1) equipment buildup and protocol development; (2) impact testing of cadavers; and (3) analysis and final report.

General Description of the Tests

Two series of tests were conducted. The first (Series A) required the use of a Hybrid III anthropomorphic test device (dummy) and encompassed the equipment buildup and protocol development phase. The second (Series B) required the use of cadaver subjects.

Series A:

Equipment buildup and protocol development included:

(1) Modifying the impact pendulum, as required.

(2) Construction of three floor-mounted camera supports for GM camera equipment.

(3) Constructing lighting racks and cables.

(4) Building a support table and a calibration array, both with incorporated leveling mechanisms.

(5) Complete construction of X-ray equipment for in-place X-ray.

(6) Preparing an experimental protocol, training assistants, performing necessary clerical work (i.e., developing forms, etc.).

(7) Preparing software to transfer film data from UMTRI to GMRL, and to "clean up" the raw data recovered from 16 mm films.

Series B:

(1) Modify the impact pendulum to accommodate photo coverage equipment.

(2) Construction of three floor-mounted camera supports for UMTRI camera equipment.

(3) Prepare software to transfer electronic transducer data from UMTRI to GMRL and to "clean up" the raw data.

The purpose of the Series A tests was three-fold: first, the series assisted in the development of equipment and protocol for the following cadaver tests (Series B); second, the series determined the extent of mechanical (as opposed to biological) variability due to the experimental procedures; and third, the series was used to compare cadaver responses with those produced with the best currently available mechanical human surrogate (the Hybrid III anthropomorphic test device).

Five (5) identical Hybrid III dummy tests (Series A) were proposed. Twenty-two dummy tests were conducted. The dummy was placed supine, but no attempt was made to achieve any particular head and neck configurations for the first group of eleven Hybrid III tests. For the second group of eleven tests, the head was rotated 5-15 degrees for all axes.

Five (5) cadaver tests (Series B) were conducted. The tests were conducted to investigate the effects of head rotation in superior-inferior crown head impacts. In these tests the subject was placed supine and the neck flexed until the cervical spine was straight. The head was rotated by 60 degrees about Z or 5-15 degrees for all axes. The tests were used to confirm initial observations, to obtain more detailed information regarding the contribution of head rotation, and to investigate the contribution of lateral bending in superior-inferior crown impacts.

Test Synopsis:

The central objective of the cadaver experiments was to document the displacement and velocities of the head, neck, and upper thorax and, if necessary, to reproduce these using computer graphics. Likewise, in the Hybrid III experiments, the primary objective was to describe the kinematics of the mechanical components comprising the head, neck, and upper torso of the dummy.

In each test (cadaver or Hybrid III dummy), the subject was placed in the supine position and supported in a relatively friction-free fashion by a number of styrofoam blocks encased in sheets of heavy-duty plastic. The head of the subject was cradled by a noose until an instant prior to the impact. The impact was produced by a 56 kg striker mass freely suspended four to five meters from the ceiling of the laboratory (see Figure 1). The striker was driven into the head of the subject at approximately 5 m/s by a pneumatic cannon. The stroke of the striker was limited to 30 cm, post-impact. The face of the striker was padded with material similar to that found above the driver's seat in an automobile, and hereafter will be referred to as "roof liner" or "1 inch Ensolite A.L."

Subject Positioning:

The tests were conducted with the shoulders of the subject in contact with the supporting material. The neck was straightened, and the subject was carefully positioned in the test configuration. The head of the subject was rotated an amount prescribed for the specific test. The first group of Hybrid III tests did not have the head rotated. The second group of Hybrid III tests had the head rotated 5-15 degrees for all axes. The cadaver tests had either the head rotated 60 degrees about Z or 5-15 degrees for all axes.

In order to obtain a precise measure of head rotation, small wooden dowels, attached to the opposite ends of a single length of inelastic string, two to three meters in length were used in conjunction with a protractor. The dowels were inserted into the ears of the subject, and the mid-point of the string was pulled away from the subject to form an inverted "V." The tip of the "V" was swept through the required angle. Provided the string was kept in tension, and provided the head of the subject was carefully rotated to match the motions of the inverted "V," a precise amount of head rotation was measured. This was verified by the protractor.

Instrumentation:

The three types of instrumentation were used: electronic, photographic, and radiographic. The electronic instrumentation consisted of transducers and associated hardware to measure the velocity of the striker, the applied load, and various accelerations on the head and the spine of the subject. The photographic instrumentation was used to monitor the three-dimensional displacements and velocities of the cervical spine immediately following the impact. Pre- and post-test radiographs were taken. The post-test radiographs were not useful.

Electronic Instrumentation:

The velocity of the striker mass was recorded by an existing remote pick-up. The applied load was monitored using a bi-directional load-cell aligned to record forces in

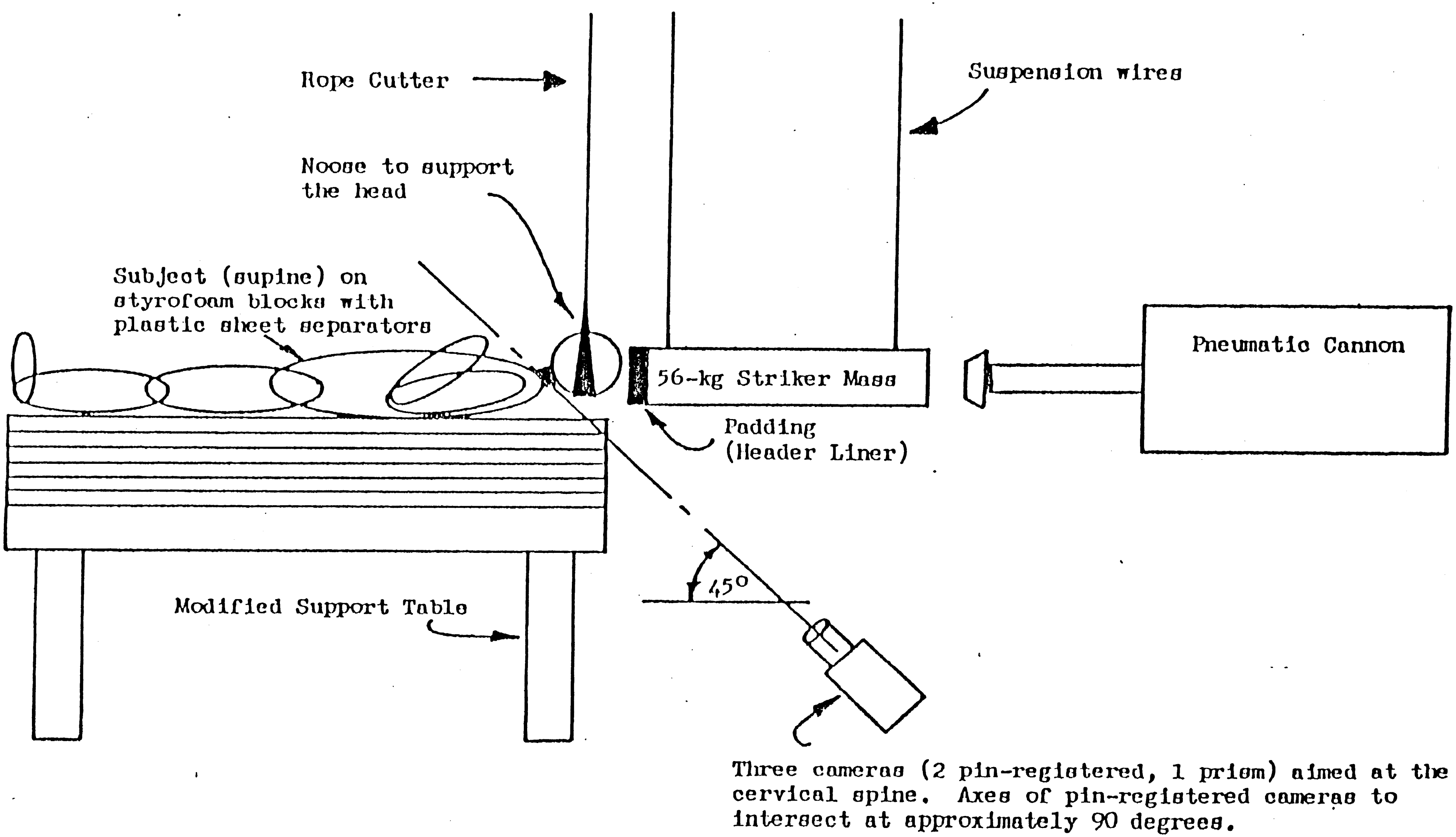


Figure 1 Test Configuration

superior-inferior and anterior-posterior directions for the Hybrid III series, and a uniaxial load cell to record forces in the superior-inferior direction for the cadaver series. An internal triax was used for the Hybrid III, and a nine-accelerometer package was installed at a suitable site on the head of the cadaver subject. In addition, triaxial accelerometers were attached to the thoracic spine of the cadaver at T1, T7, and T12. The surgical procedures employed were identical to those used for earlier tests at HSRI/UMTRI. Twenty-five channels of analog data were recorded using two FM tape recorders. The accelerometers required a total of eighteen channels, and three channels were required to record piston velocity, anteriorly-posteriorly applied load, and superiorly-inferiorly applied load. Four additional channels were recorded to provide an event marker and time base on each FM recording.

Photographic Instrumentation:

Small, spherical, color-coded targets were attached to the skin of the cadaver with Eastman 910 cement. These targets were used to describe the general, three-dimensional kinematics of the head, neck, and upper torso. A photographic target was placed near the face of the striker. A three-dimensional calibration array was constructed. This array was used to calibrate the images produced in the high-speed cameras. The array enclosed a 45x45x60 inch region in space.

A minimum of two high-speed cameras was required to perform three-dimensional reconstructions of displacements. Pin-registered, phase-locked cameras were preferred for this task. The cameras were located beneath the pneumatic piston, tilted toward the subject, with their film planes approximately orthogonal, recording a left-right view of the impact. (Refer to Figure 1). Due to scheduling complications involving these cameras, they were not available for all of the cadaver tests. A rotating prism camera, located to one side of the test, recorded a superior-inferior overview. The pin-registered cameras were operated at 500 feet per second, the prism camera at 1000 feet per second. A Miletus timing unit was used for recording temporal data directly on the film images for some tests.

It was necessary to construct (or modify) a table to support the shoulders of the subject yet provide adequate access to the upper thorax and cervical spine for photographic purposes.

Radiographic Instrumentation:

X-rays were used for two purposes: for positioning the subject prior to impact, and to provide pre- and post-test records of the subject.

Cadaver Material:

The unembalmed cadavers chosen for this project were selected to provide optimum results. All cadavers were male. Cadavers suspected of being infected by communicable diseases were not used in this research project. Osteoporotic cadavers were not used. Any cadaver which was 70 years or older at death was not used unless it was considered to be in exceptional condition. Any cadaver which was less than 21 years old at death was not used. In addition, cadavers which represented the extremes of the normal population were not used. For the purposes of this investigation, an extreme weight was considered to be less than 55 kg or in excess of 110 kg. An extreme height was considered to be less than 165 cm or greater than 190 cm. All cadavers were subjected to radiological examinations to check for the existence of injuries, abnormalities, or surgical modifications. All cadavers were free of damage and abnormalities in the head, neck, and thorax (T1 to T12). Cadavers selected for this research had not been subjected to an autopsy prior to testing. Appropriate measures were taken to ensure that the identities of the cadavers were/will not revealed.

The cadavers were tested as soon after death as possible. Until they were tested, each cadaver was stored at 4 degrees centigrade to retard postmortem degradation of tissues. All personnel who were involved with the handling of the cadavers were given appropriate instructions and signed the required GMRL Affirmation of Ethical Practices form (Appendix B). Appropriate precautions were taken by all personnel to minimize the probability of infection from bacteria associated with the cadaver. All cadavers and dissected body parts were returned to the Department of Anatomy of the University of Michigan Medical School for appropriate disposal.

Subject Preparation and Examination:

The cadavers used in these experiments were obtained from the Anatomy Department of the University of Michigan Medical School in an unembalmed condition. Four mounts for accelerometers were surgically implanted in the UMTRI Anatomy Lab. The cadaver was then moved to the Impact Lab where accelerometers were attached, a number of phototargets were glued to the skin of the cadaver with Eastman 910 cement, and the subject was positioned for the impact. 35 mm color slides were taken to record the initial positioning of the subject prior to impact.

Post-test X-rays, taken immediately following the test before the subject was moved, were not useful, and only used in the first cadaver test. Additional 35 mm color slides were taken to record the final resting position of the subject. An examination of the cadaver was conducted at that time and any anomalies were recorded. Care was taken to provide support for the head and cervical spine before the subject was moved. The cadaver then underwent an autopsy to determine the nature and extent of the injuries produced by the impact. (If time did not permit an autopsy to be performed immediately following the test, the cadaver was returned to the freezer until an autopsy could be performed; however, in no instance did the time between the test and autopsy exceed five days). During the autopsy a permanent record of the observed injuries was maintained.

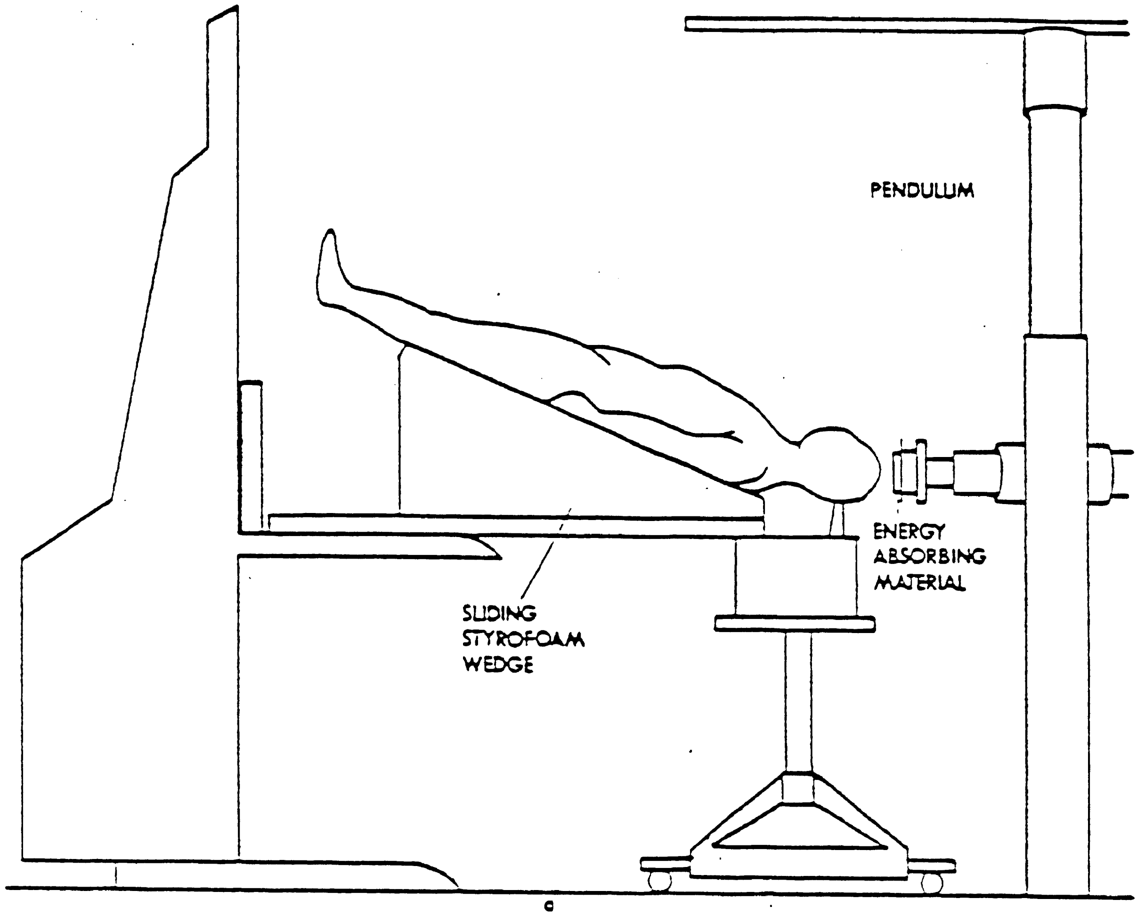
RESULTS

A detailed summary of the contents of the work performed at UMTRI for this study is included here. The data are presented in abbreviated form to show those trends which are felt to be representative of important factors in the response of the cervical spine to crown head impact. Table 1 lists the testing commentary. Table 2 summarizes the Hybrid III testing. Table 3 summarizes the cadaver testing. Table 4 summarizes the anthropometry. Next the cadaver injuries are illustrated with charts and photographs. The appendices include the Hybrid III impedance, spectral coherence, and transducer time-histories, and the cadaver plots of head linear acceleration, angular acceleration, and angular velocity. A data tape in the NHTSA format containing the electromechanical transducer data has also been submitted.

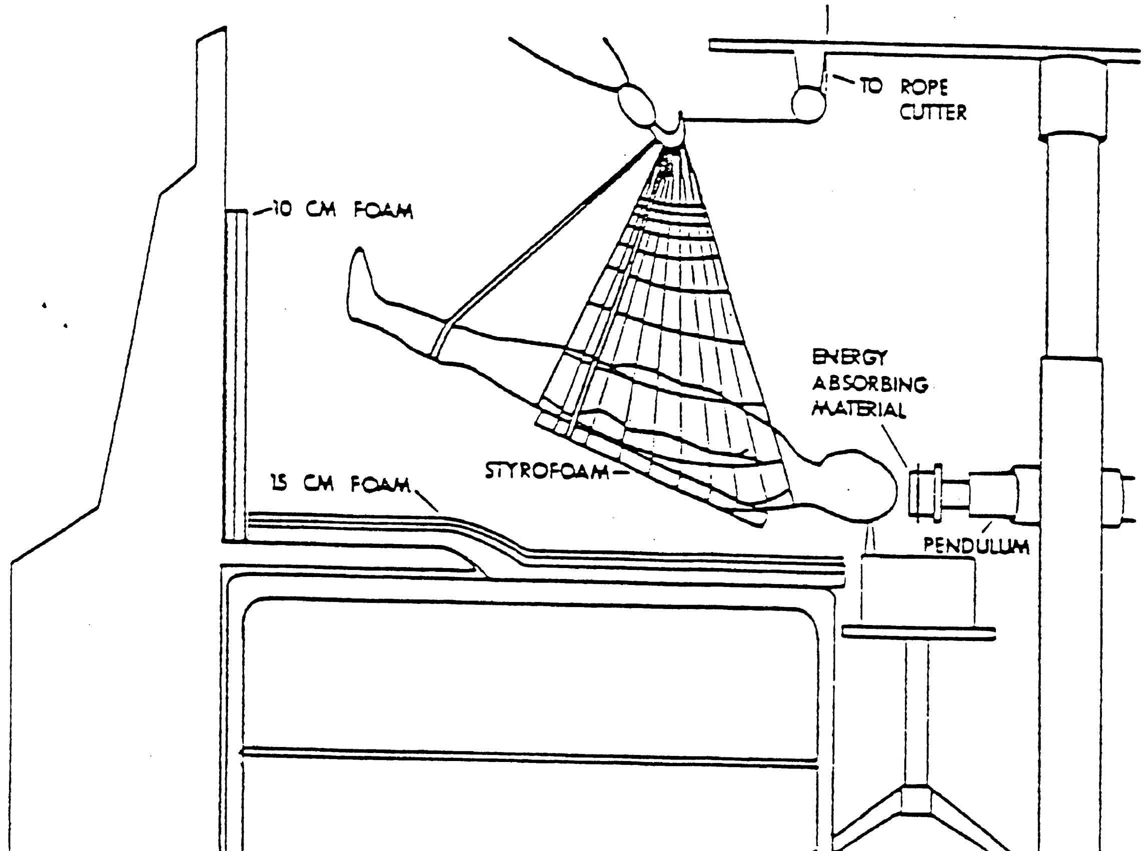
DISCUSSION

The research project being reported in this document, "Kinematics of the Human Cadaver Cervical Spine in Response to Superior-Inferior Loading of the Head," is a continuation of two previously sponsored GM biomechanics studies of cervical spine trauma. The first study, Cervical Spine Injury Research, utilized a linear pendulum to deliver a blow to the crown of the head (Figure 2) and developed procedures and techniques for performing impact experiments designed to obtain the kinematic and injury responses of the cervical spine. The results of that research were reported at the 25th Stapp Car Crash Conference (1). The second study, "Strength and Response of the Human Cadaver Cervical Spine Under Impact Loading," was designed initially to determine the similarities and differences between impacts using the pendulum impact device and impacts utilizing a floor-mounted load platform onto which the subject, suspended overhead in an inverse position, was dropped (Figure 3). The results of the second study research were reported at the 27th Stapp Car Crash Conference (2). In the pendulum tests, the crown of the head is struck in the horizontal direction, while in the floor-mounted load cells tests, the cadaver drops vertically onto the load cell striking first the crown of its head. The testing protocol for the second study was redesigned half way through that project in an attempt to determine the initial positioning factors necessary to produce cervical spine flexion injuries using cadaver drop impact procedures.

The most common neck fracture injury observed in victims of automotive crashes is the so-called "flexion injury." One mechanism for production of these flexion-type injuries commonly reported in the cervical spine trauma literature is that the neck is flexed forward with the head bowing deep into the chest during crash motion. In the first study the motion of the head and neck was restricted primarily to motion in the mid-sagittal plane during impact. This was accomplished through careful pre-impact positioning of the subject. The motion of the neck flexing forward with the head bowing deep into the chest was successfully reproduced in several tests. However, although flexion-type injuries were successfully produced in some tests, extension-type injuries were the predominate injuries overall for those tests, indicating the difficulty of producing flexion-type injuries with that protocol design.


PENDULUM
ENERGY
ABSORBING
MATERIAL
SLIDING
STYROFOAM
WEDGE

a


TO ROPE
CUTTER
10 CM FOAM
ENERGY
ABSORBING
MATERIAL
STYROFOAM
15 CM FOAM
PENDULUM

b

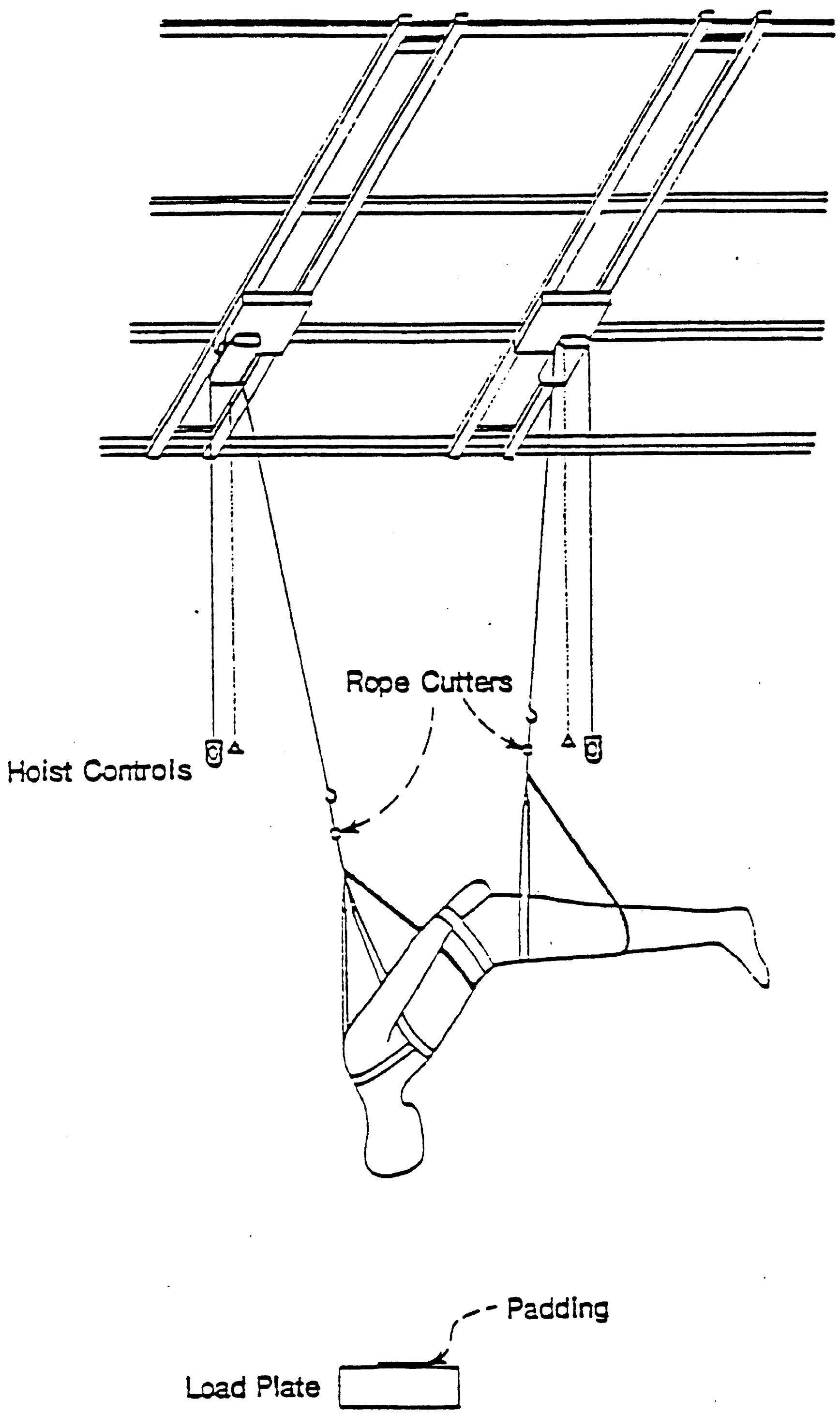


Figure 3: Overhead Hoist System and Restraint Configuration with Cadaveric Subject

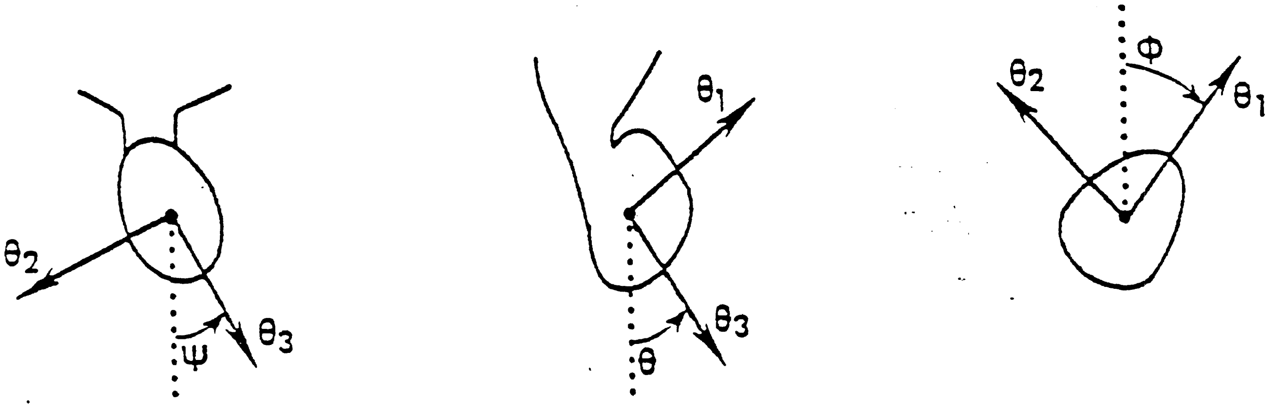
A review of UMTRI data from the first study was performed by GM personnel and concluded that the inability to predominately produce flexion-type injuries was a result of using the linear pendulum impactor. It was also concluded that the pendulum impacts were not representative of the automotive crash environment primarily because of the limited mass of the pendulum (i.e. 56 kg). The second study was designed to remedy this problem by dropping the cadaver subject in an inverted position onto a load plate. However, the force time-histories as well as the injuries produced were similar to those of the pendulum tests in the first study. These data were reviewed by UMTRI personnel who then concluded that the initial positioning of the test subject was the critical factor that needed to be adjusted to produce flexion-type injuries. However, it was not known at that time which positioning factors or which collection of positioning factors were important. Therefore, an impact test protocol was designed in which the initial positioning factors of the three body regions believed to be involved in cervical spine injuries (i.e. the head, neck, and thorax) were represented by three angles for each body region. The testing protocol required the adjustment of all nine of those angles from between five and twenty degrees (Figure 4). An initial configuration was chosen and drop-tests in that configuration repeatedly produced flexion-type injuries.

A critical review of all the UMTRI and other cervical spine data was performed by GM scientists shortly after the completion of the second study. Their conclusions were then used to design the research project being reported in this document. After that review, it was concluded that: 1) The body weight and age range used in previous UMTRI studies produced too much scatter in the data. A more limited weight and age range should be used. 2) A pendulum impactor would deliver the blow to the crown of the head. The subject would be placed on a table with a sliding plastic surface underneath him/her. 3) Head rotation was the most important parameter associated with flexion injury; and 4) High-speed photogrammetry would be the most appropriate method to obtain the kinematic response of the cervical spine to superior-inferior (S-I) impact. The study was designed to monitor the motion of the cervical spine on film using targets attached to the skin of the head, neck, and shoulder in the area of the posterior cervical spine. Similar testing was to be performed on the Hybrid III anthropomorphic test device. In addition, it was decided that auxilliary data would be obtained by means of accelerometers mounted on the skull and the spine. These acceleration data could later be used to complement the film analysis.

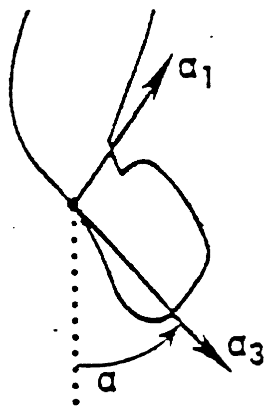
The protocol designed in consultation with GM personnel was used on the first two subjects. Although some of the damage patterns were different from what had been observed in previous studies, the head rotation did not produce the flexion-type injuries. It was, therefore, necessary to redesign the impact testing protocol. The first two cadaver subjects tested for the project being reported here were positioned with the head rotated 60 degrees. However, the gross pathological investigation revealed that cervical spine flexion injuries had not been produced during the crown head impact testing. In consultation with the GM contract technical monitor, it was decided to utilize the nine-angle positioning system developed during the earlier study while maintaining the table support system for the subject and a pendulum impactor as the energy source. Using this configuration, flexion injuries similar to those produced in the drop tests of the earlier study were produced during the crown head impacts. Thus, the conclusion derived from the previous study that a

Figure 4: Translation of Instrumentation Frame Angles to Laboratory Frame Angles

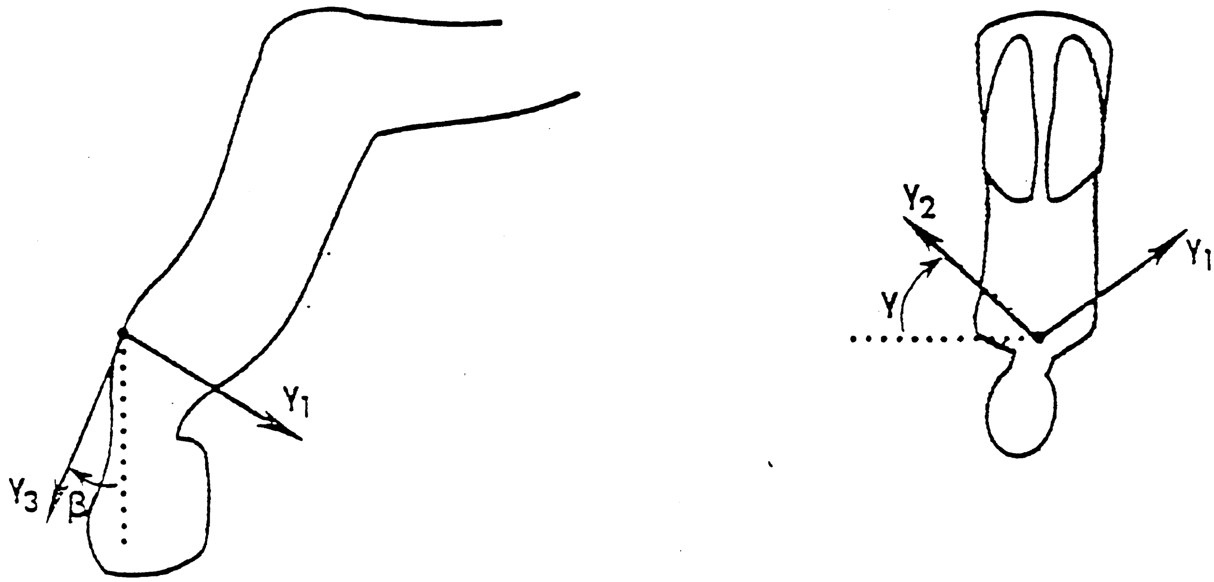
HEAD - Three angles (ψ, θ, ϕ) corresponding to rotations of the head coordinate system about the 1,2, and 3 axes, respectively, are used:



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



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



pendulum impactor could replicate load plate drop impacts seemed to be confirmed.

Review of the films indicated that the motion of the skin targets was significantly independent of the motion of the cervical spine. This was a result of what seemed to be a wave propagation in the soft tissues from the head along the neck as a result of the impact. Therefore, comparison of the motion of the neck of the crown-head cadaver impacts to the motion of the neck of the Hybrid III crown-head impacts would be difficult.

An initial analysis of the transducer time-histories included the data from the first two cadaver tests and the initial set of Hybrid III tests before the project was moved in another direction by GM. Examination of the transfer function relationships of either mechanical impedance of force divided by velocity or direct transfer functions of one transducer signal divided by another (such as impact force divided by different accelerations, e.g. head accelerations, spinal accelerations) for various transducer outputs for the Hybrid III dummy indicated that the Hybrid III dummy response was very repeatable between tests for this test configuration. These comparisons showed that the transfer functions were the same for each impact except at certain frequencies in which the two compared signals were not coherent as indicated by the spectral coherence plots. Non-coherence at a frequency indicates that the points being compared cannot be separated from noise in the system at that frequency.

The first two cadaver tests were examined for similarities and differences using the transfer function procedure. In particular, comparisons were made of force divided by head velocity, force divided by spinal velocity, and head acceleration divided by spinal acceleration. Although there were obvious differences between these two cadaver tests, there were greater differences between each of these two cadaver tests and any of the Hybrid III tests. The dummy responds in a significantly different manner than the cadaver. This is illustrated by Figure 5 which shows that the cadaver impedance was consistently less than that of the Hybrid III in the low-frequency range, indicating that the cadaver neck is significantly less stiff than the dummy neck in the superior-inferior direction.

CONCLUSION

1. Rotation of the head as a single parameter does not seem to produce flexion injury of the cervical spine upon crown head S-I impact.

2. Photographic coverage of the neck skin (and other skin targets) during S-I impact to the crown of the head needs to address the independent motion of the skin in the adequate characterization of cervical spine motion.

3. Transfer function analysis based upon accelerometer signals is a useful technique for characterizing the response of the cadaver and comparing it to the Hybrid III.

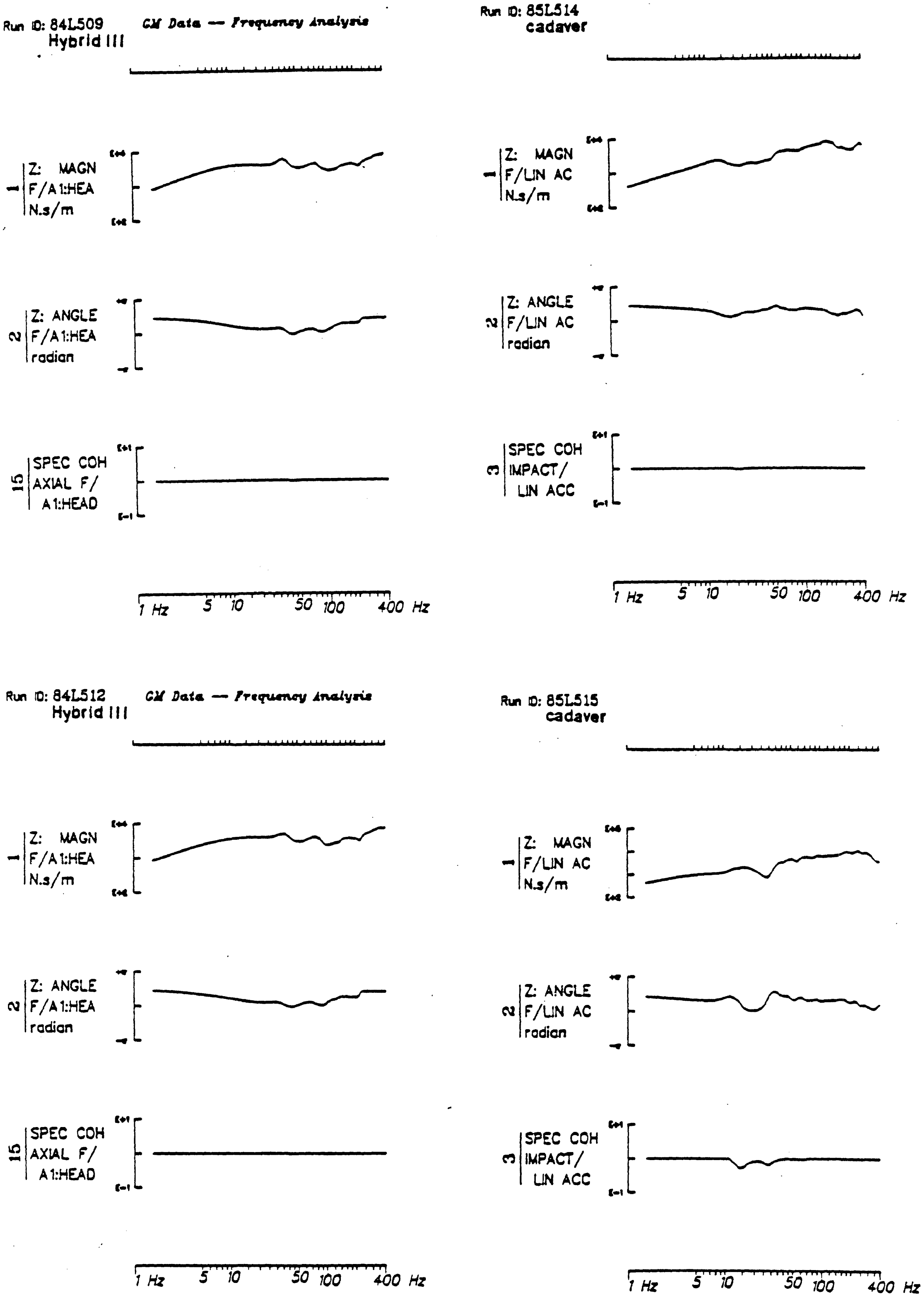


FIGURE 5: MECHANICAL IMPEDANCE

RECOMMENDATIONS FOR FUTURE RESEARCH

UMTRI now has a sizable collection of cervical spine trauma data and UMTRI researchers have gained extensive experience in addressing the cervical spine response of human surrogates to head impact using a number of different analytical procedures including both time-history and frequency domain analysis. Although some analysis was performed for each of the research projects these UMTRI historical data entailed, to date there has not been a comprehensive analysis of these data which cover all twenty-five cervical spine trauma tests. In addition, UMTRI has improved its analytical procedures and more sophisticated analyses of data are now available. Therefore, it is recommended that UMTRI reformat all of the data obtained from its cervical spine trauma studies in such a way that all the time-histories are readily comparable. Statistical analysis of appropriate parameters could then be performed to evaluate impact parameters (especially time-history descriptors) as injury predictors. In addition, transfer function analysis could be used to characterize and describe the response of the cervical spine to head impact.

Because of the complexity of the cervical fracture problem, each GM project monitor had his own "idea" of what should be done. We have traveled a serpentine pathway, due to the changing ideas with each successive project monitor, a time consuming, money intensive pathway. Stability via a permanent GM project monitor will be most effective for research productivity.

ACKNOWLEDGEMENTS

We express our appreciation here to Jim Walton for his technical assistance in developing the experimental protocol and participating in the experiments and to John Melvin for his advice and technical guidance. We especially thank Nabih Alem for his work on the analysis of the data as well as on the development of software used to produce the output plots. In addition we wish to acknowledge the technical assistance of Richard J. Lehman, Bryan R. Suggitt, Jean Brindamour, Marvin Dunlap, Steven Richter, and Wendy Gould in the performance of this work.

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2. Nusholtz, G.S., et al. 1983. Cervical Spine Injury Mechanisms. 27th Stapp Car Crash Conference Proceedings, pp. 179-198.

TEST NO.	COMMENTS HYBRID III IMPACTS
84L502	Not digitized at J.Walton's request: Z-force clipped. Velocity estimated.*
84L503	Gain on axial force 50 from 500 Gain on RL shear 250 from 50 Gain on CW MOM 250 from 150 ; Velocity estimated.
84L504	Same gains as 84L503; Velocity estimated.
84L505	Gain on VRT LOAD 100 from 50 ; Velocity estimated.
84L506	3300 Taperecorder malfunction; table flipped ; Velocity estimated.
84L507	Brake froze slow launch of pendulum; velocity estimated to be 2.5 m/s
84L508	Table lifted a little ; velocity estimated.
84L509	No problems; velocity estimated.
84L510	Rope secured table flipped ; velocity estimated.
84L511	Table flipped onto its side ; velocity estimated.
84L512	Table flipped onto its side ; velocity estimated.
84L513	Table flipped onto its side ; velocity estimated.
86L519	No problems
86L520	No problems
86L521	Front-view camera malfunction; loss of cannon pressure produces velocity of 2.0 m/s
86L522	Front-view camera malfunction
86L524	Pendulum acceleration cable broke
86L525	Pendulum stringpot being repaired; signal not recorded
86L526	Pendulum stringpot being repaired; signal not recorded
86L527	Pendulum acceleration signal inverted and clipped
86L528	Pendulum acceleration signal inverted
86L529	No problems
86L530	No problems

*Velocity probe malfunction.

TEST NO.	COMMENTS CADAVER IMPACTS
85L513	No GM cameras; T7 PA amp malfunction
85L515	In-place x-rays did not provide useful information
85L516	T7 mount was attached to T6
85L517	2.5 cm Ensolite plus roofliner
85L518	2.5 cm Ensolite plus roofliner

Table 2: GM Crown Head Impact - Neck
Hybrid III Dummy Impact Summary

SERIES A: NO HEAD ROTATION

Test No.	Axial Force lbs	HIC	RESULTANT Head Acceleration g	Spinal Acceleration g	Neck Force lbs	Neck Moment ft lbs	Velocity m/s
84L503	3500	-	237	32	3235	73	5:5*
84L504	3400	-	218	29	3074	70	5.5*
84L505	3400	-	222	27	3162	70	5.5*
84L507	2500	-	142	19	2275	49	2.5*
84L508	3800	-	271	33	3491	89	5.5*
84L509	3500	-	242	28	3191	76	5.5*
84L510	3600	-	260	33	3319	93	5.5*
84L511	3600	-	260	32	3259	88	5.5*
84L512	3600	-	258	32	3208	91	5.5*
84L513	3600	-	251	7	3265	70	5.5*

*Velocity probe malfunction. These values are estimated from initial condition parameters and should be within 10% of the actual values.

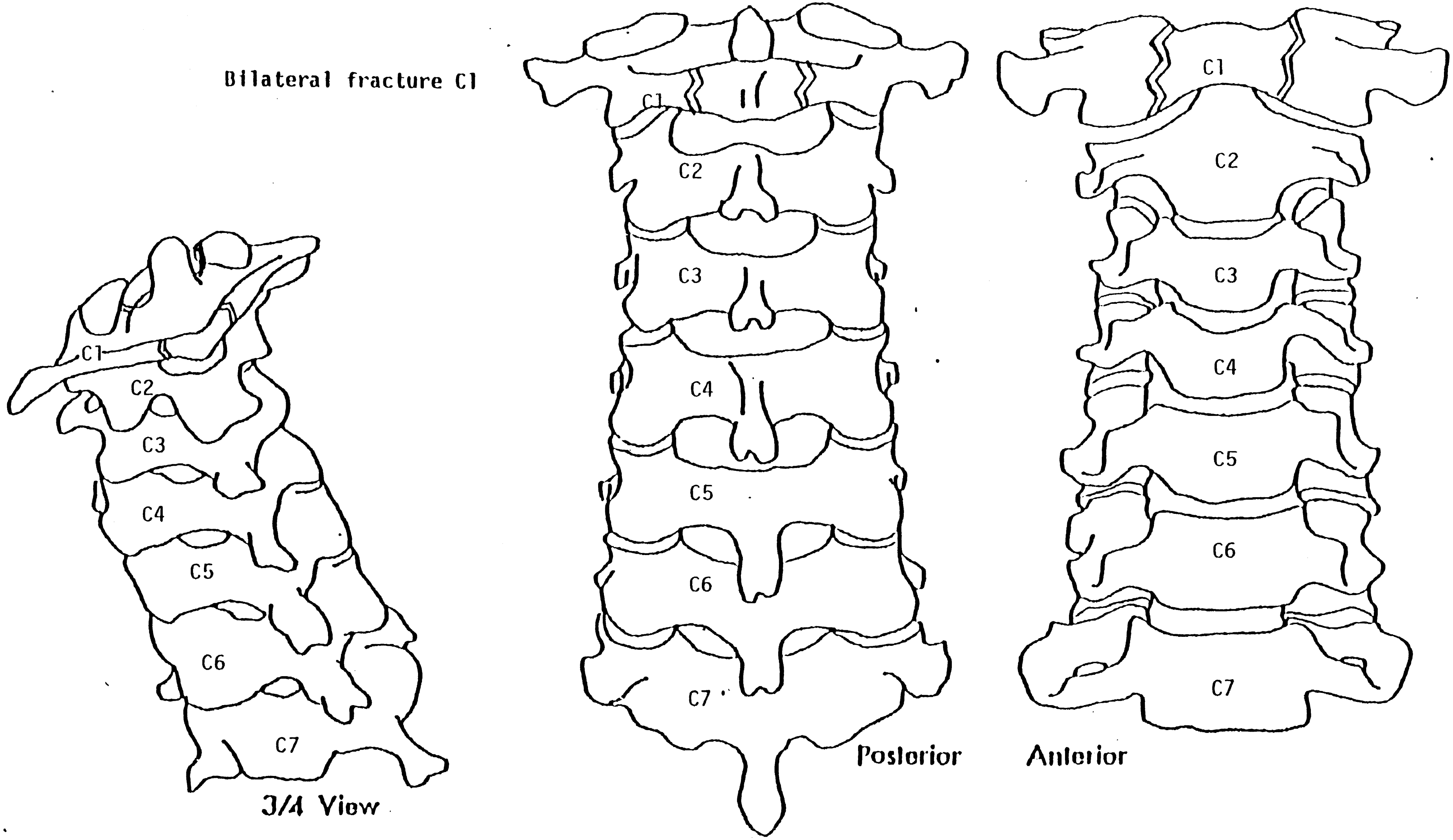
SERIES A: 5-15 DEGREES ROTATION OF HEAD FOR ALL AXES

Test No.	Axial Force lbs	HIC	RESULTANT Head Acceleration	Spinal Acceleration g	Neck Force lbs g	Neck Moment ft lbs	Velocity m/s
86L519	2100	158	77	34	1603	120	3.7
86L520	4000	155	77	20	1575	64	3.6
86L521	840	17	20	6	725	34	2.0
86L522	2900	382	125	29	2060	76	4.8
86L524	3300	485	143	29	2244	82	4.9
86L525	3100			36	1947	42	5.3
86L526	3300	403	125	25	2238	77	5.2
86L527	4900	629	153	30	3145	78	5.5
86L528	3300	499	143	26	2185	138	4.9
86L529	3500	534	143	31	2426	124	5.2
86L530	3200	511	143	26	1910	162	5.0

Table 3: GM Crown Head Impact - Neck Cadaver Impact Summary

Test No.	Peak Force lbs	Impact Velocity m/s	Neck Injuries	Other Injuries
	ROOF LINER AND 60 DEGREES ROTATION OF HEAD ABOUT Z			
84L514	3000	5.7	Bilateral fracture C1 Flexion-compression damage C6-C7 (inter-spinous ligaments) Crush fracture T1 and T2	
84L515	2400	5.6	Extension-compression damage C3,C4,C5, and C6	Two hematomas left frontal lobe of brain. One anterior and one posterior.
	ROOF LINER AND 5-15 DEGREES ROTATION OF HEAD FOR ALL ANGLES			
84L516	2600	5.5	Subluxation C5 over C6	
	ROOF LINER PLUS 2.5 CM ENSOLITE AND 5-15 DEGREES ROTATION OF HEAD FOR ALL ANGLES			
84L517	1100	5.5	Flexion-compression damage C5-C6 Flexion-compression damage C7-T1	
84L518	1200	5.7	Flexion-compression damage C5-C6	

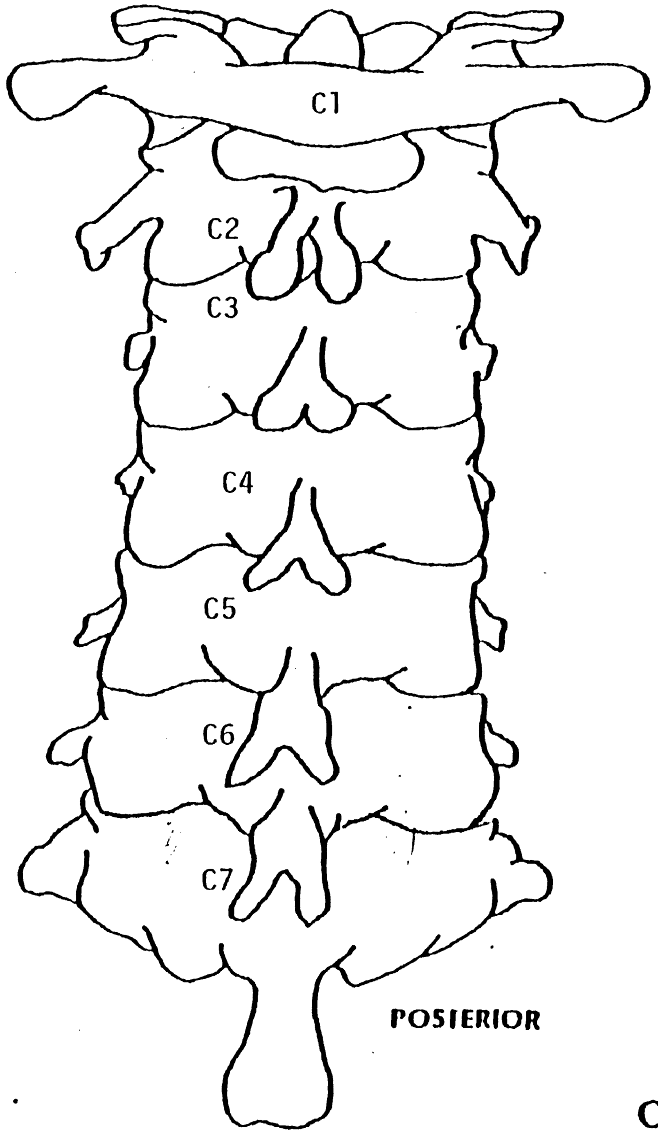
Bilateral fracture C1



CERVICAL VERTEBRAE

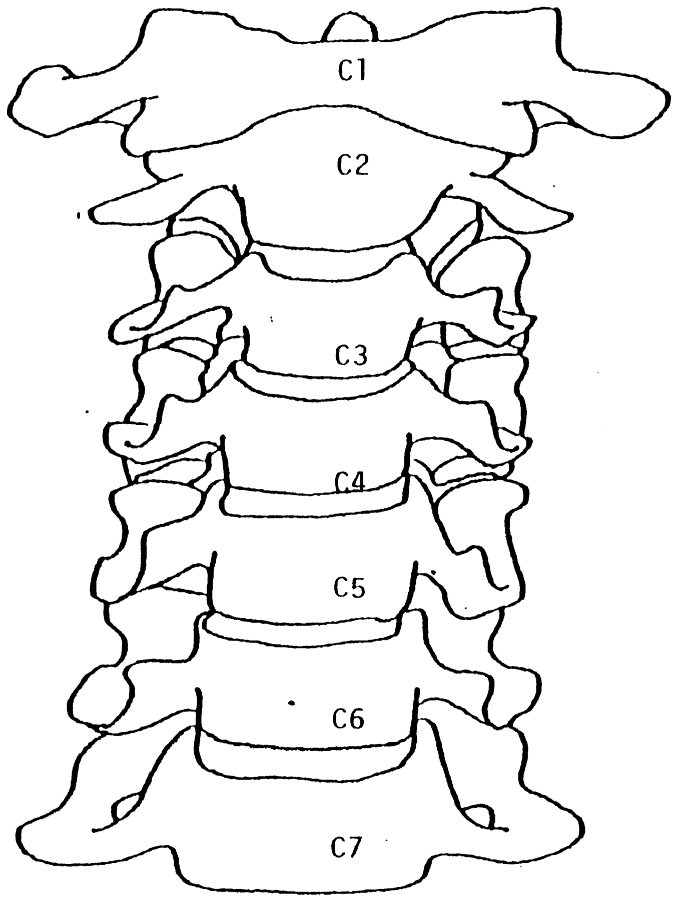
Test No. 85L514

TEST NO. 85L514



POSTERIOR

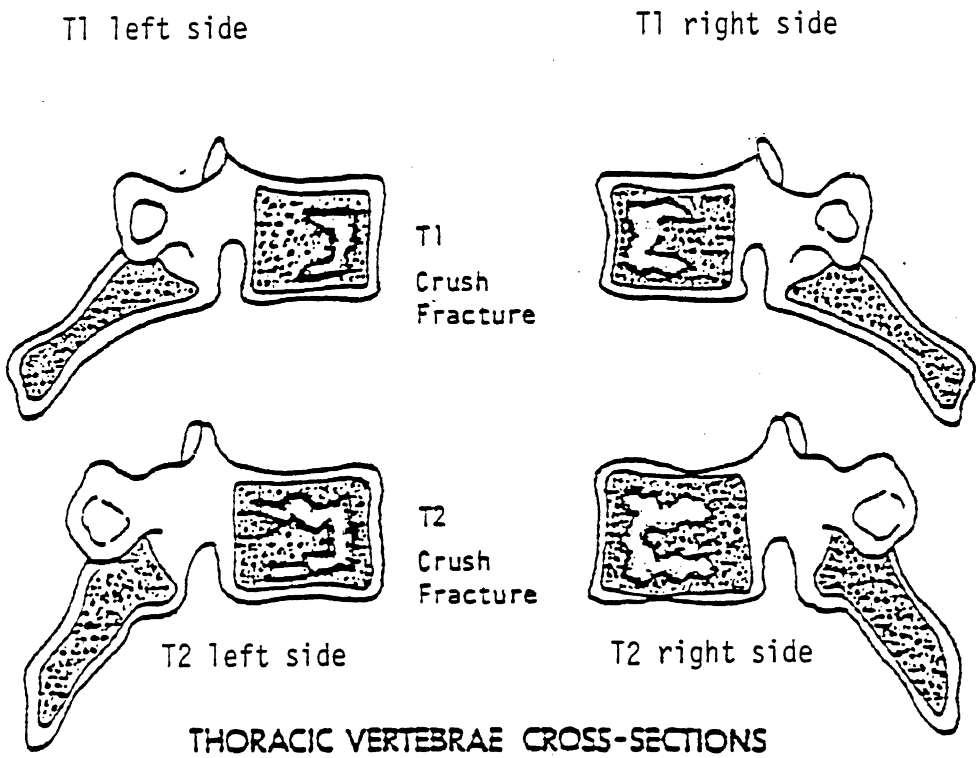
C6-C7
Interspinous
ligaments are
hemorrhagic



ANTERIOR

CERVICAL VERTEBRAE

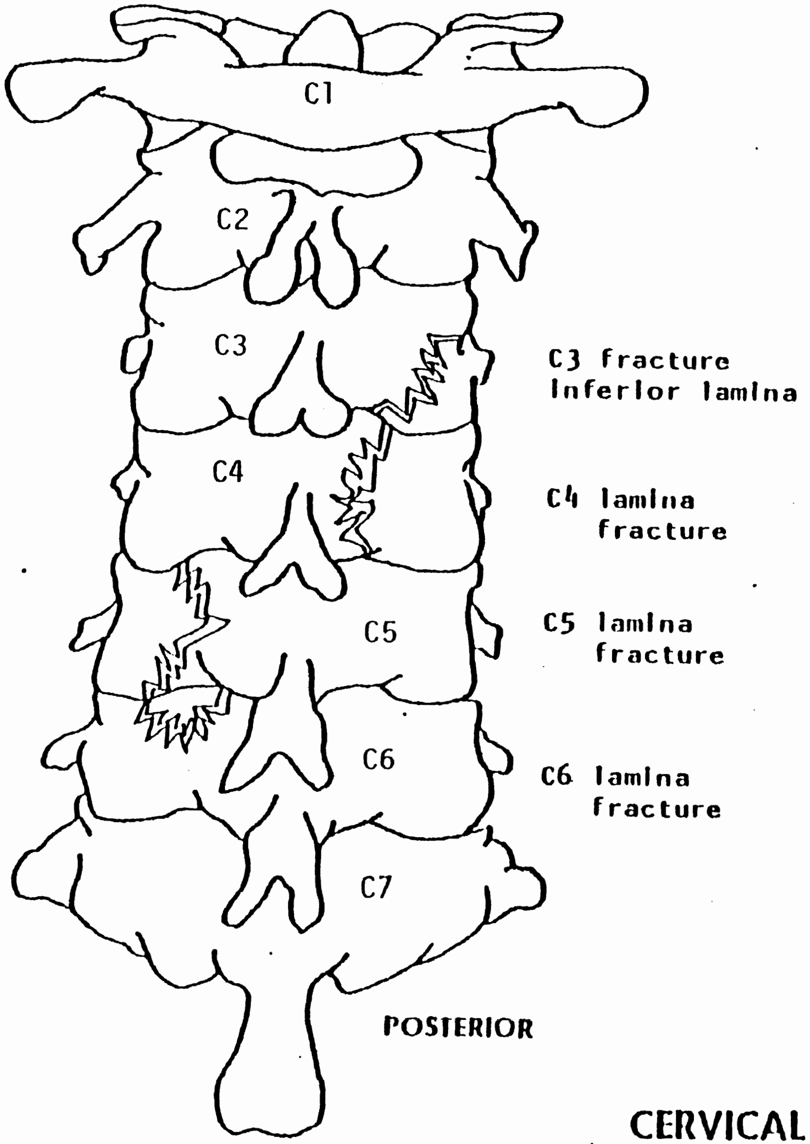
TEST NO. 85L514



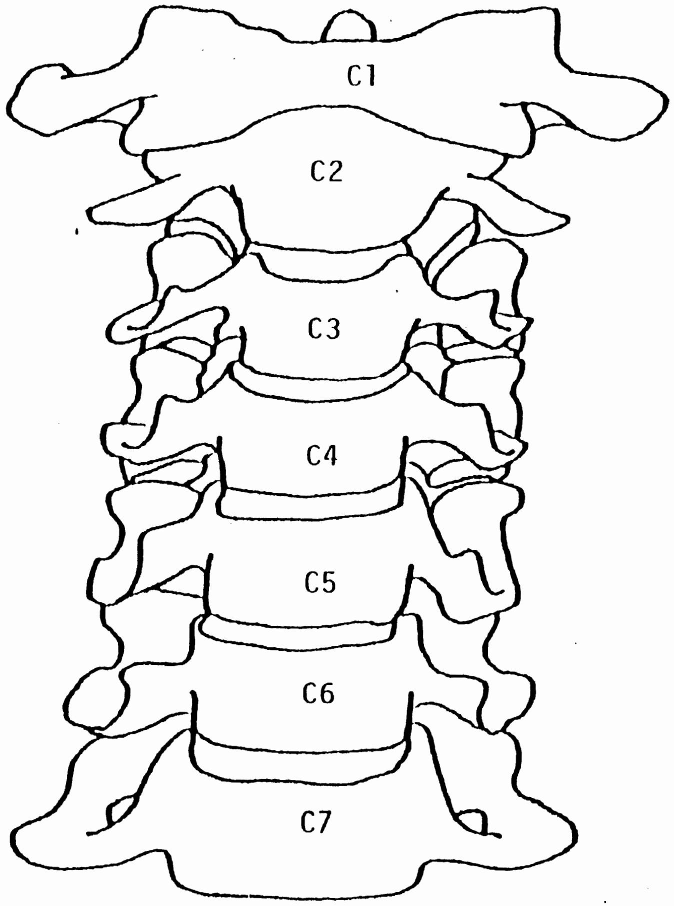
T1-T12 interspinous ligaments are hemorrhagic

THORACIC VERTEBRAE CROSS-SECTIONS
MEDIAL SURFACES
Accelerometer mount was on C7

TEST NO. 85L515

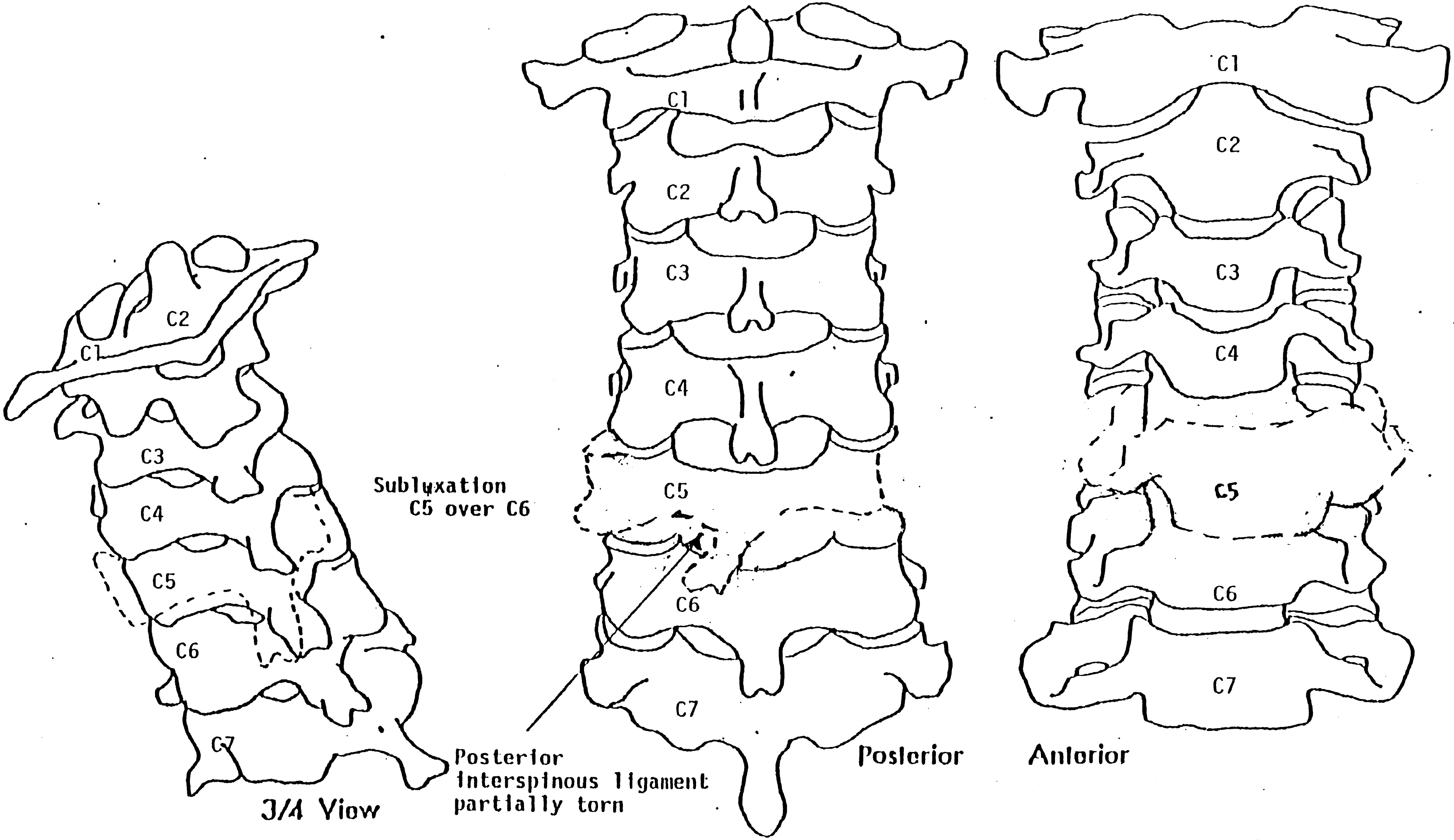


POSTERIOR



ANTERIOR

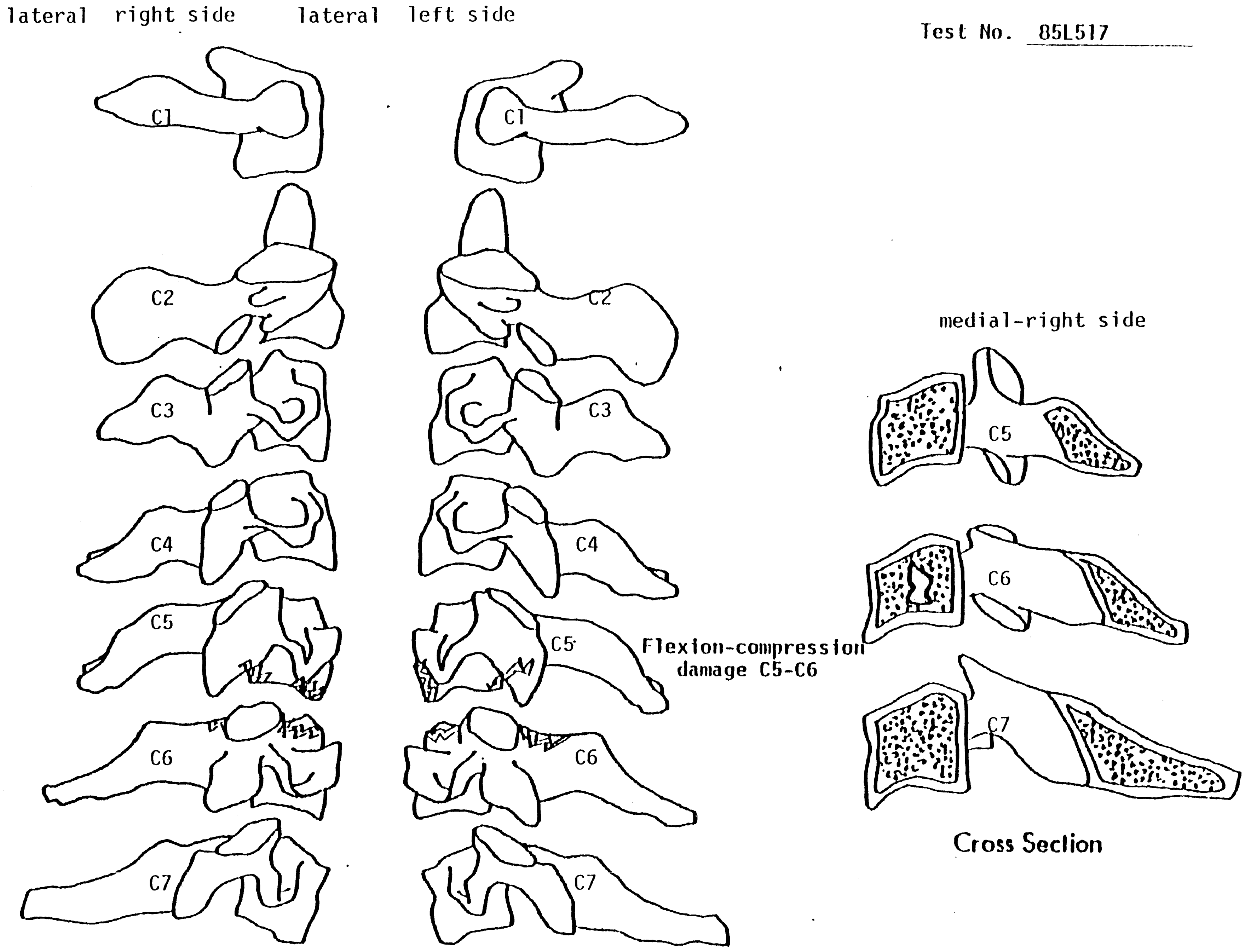
CERVICAL VERTEBRAE



CERVICAL VERTEBRAE

Test No. 051516

Test No. 85L517

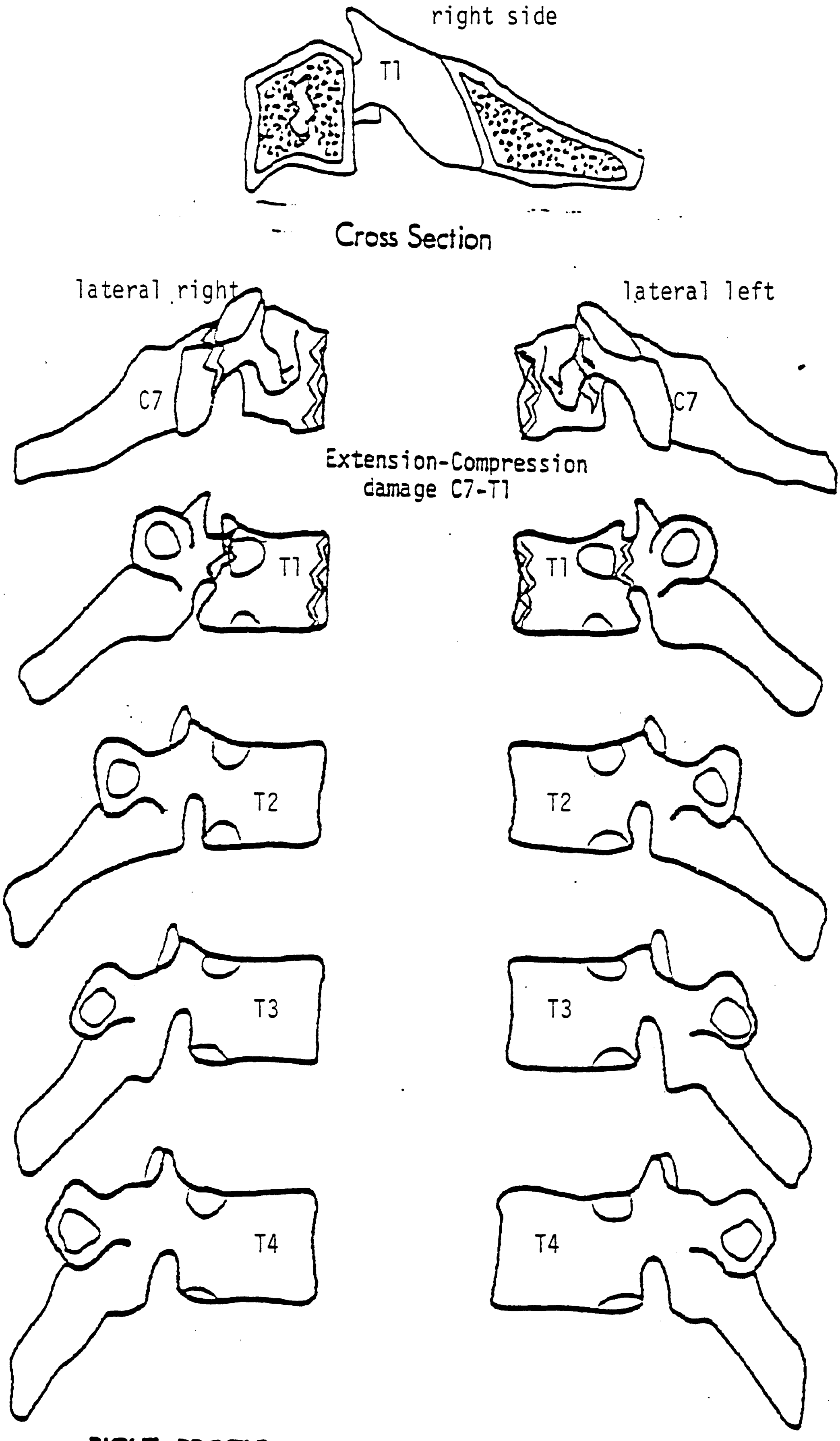


Right Profile

Left Profile

Cross Section

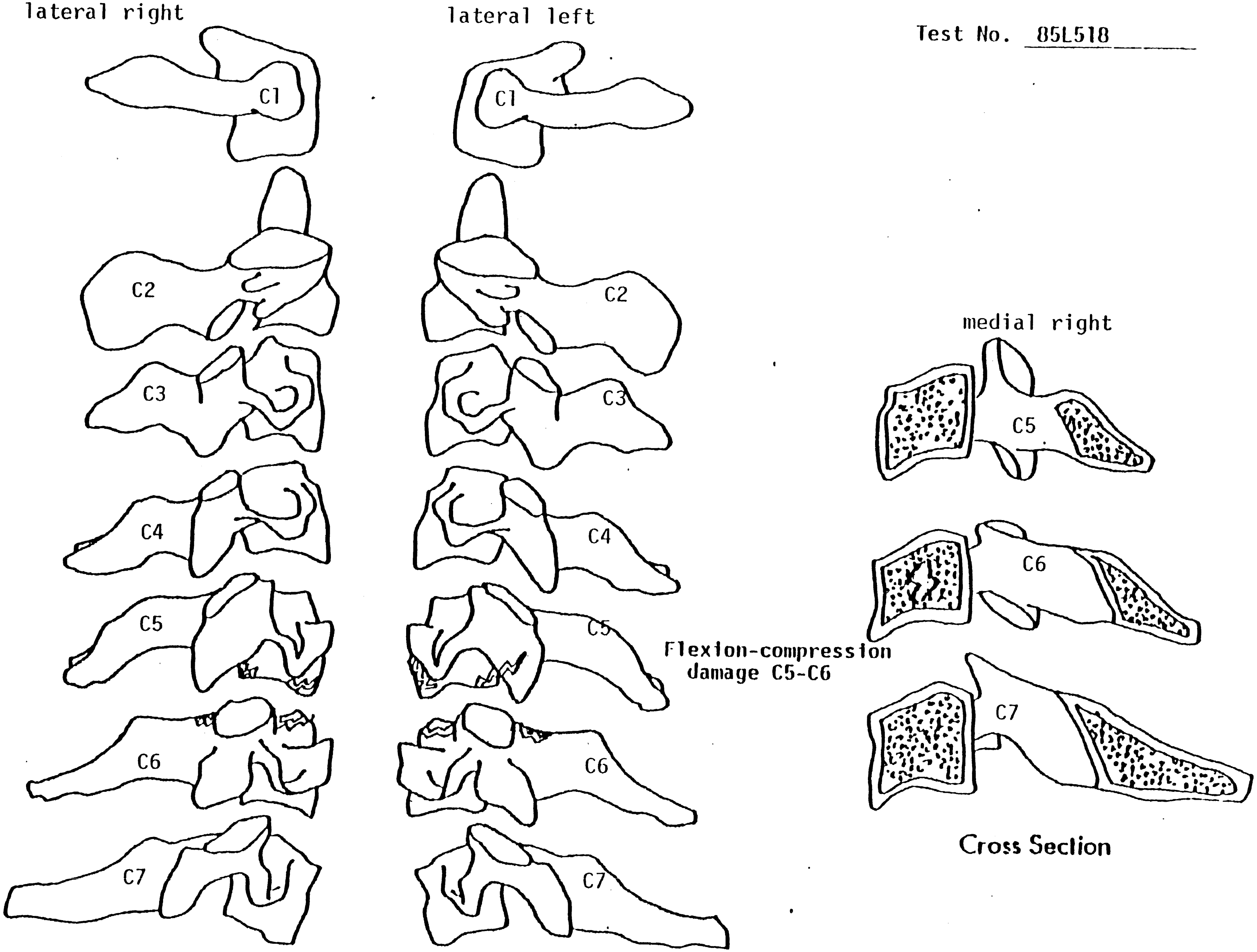
TEST NO. 85L517



RIGHT PROFILE

LEFT PROFILE

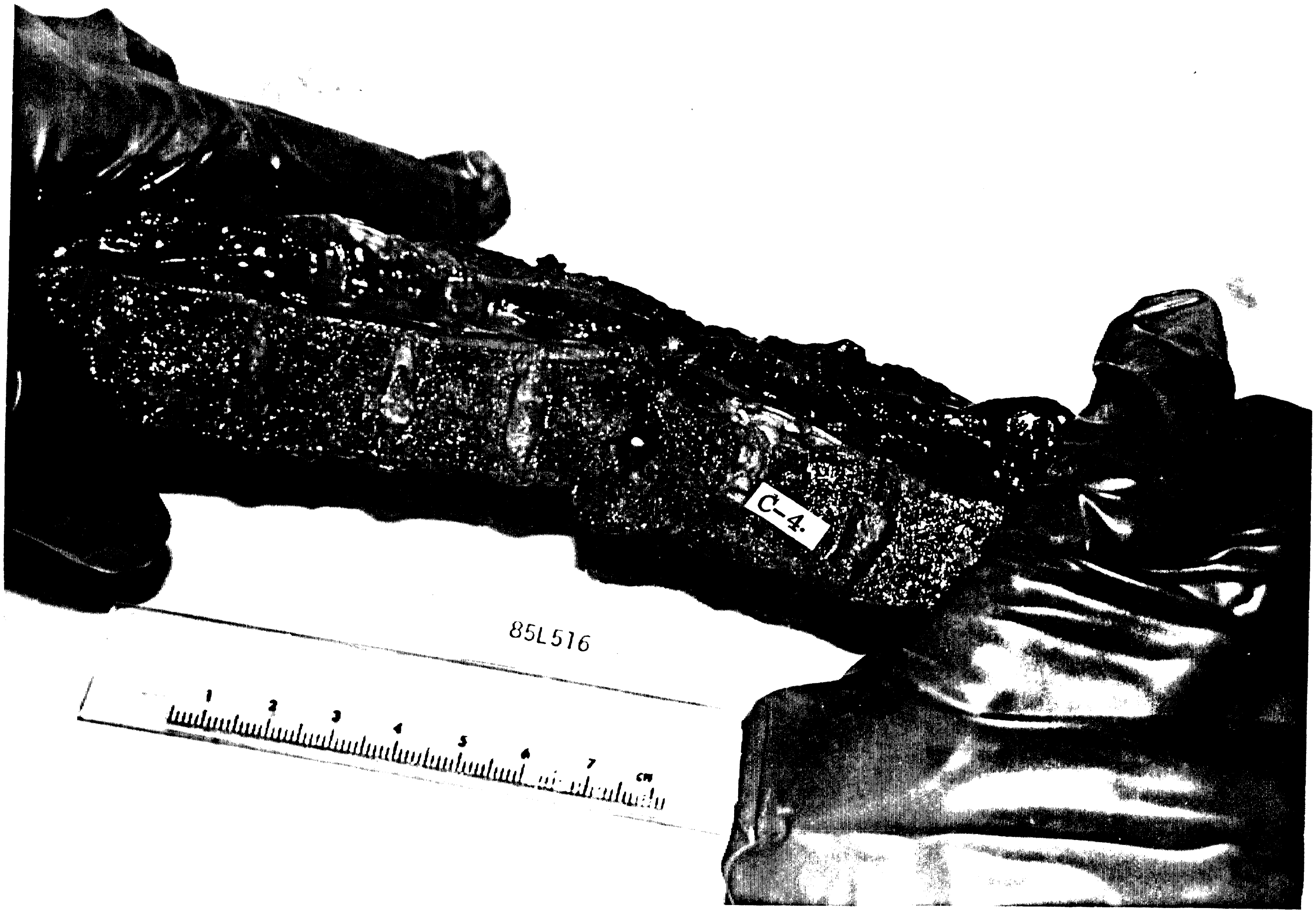
Test No. 85L518

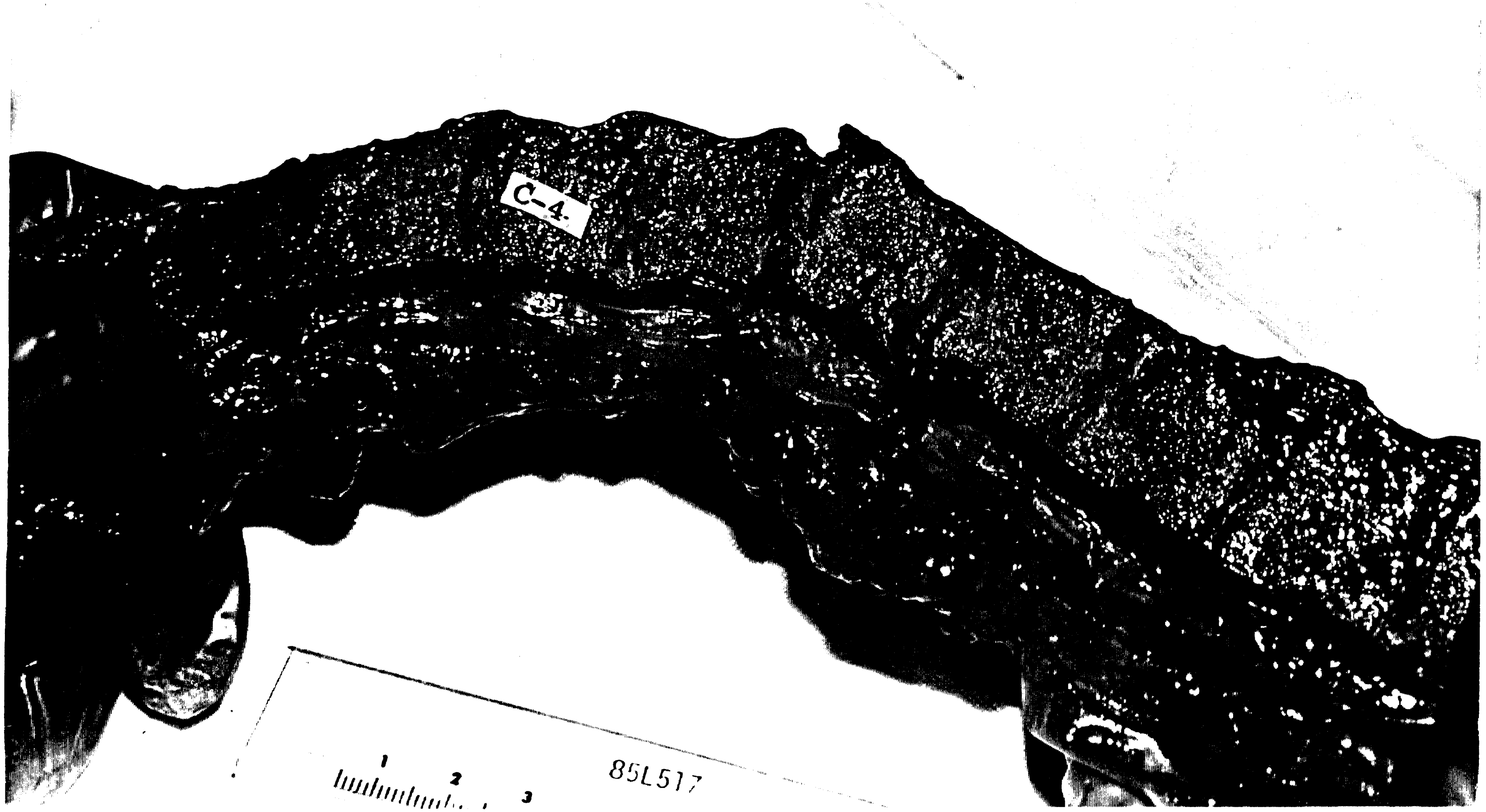


Right Profile

Left Profile

Cross Section


C-4.
85L516
1 2 3 4 5 6 7 cm


C-4.
1
2
3
85L517

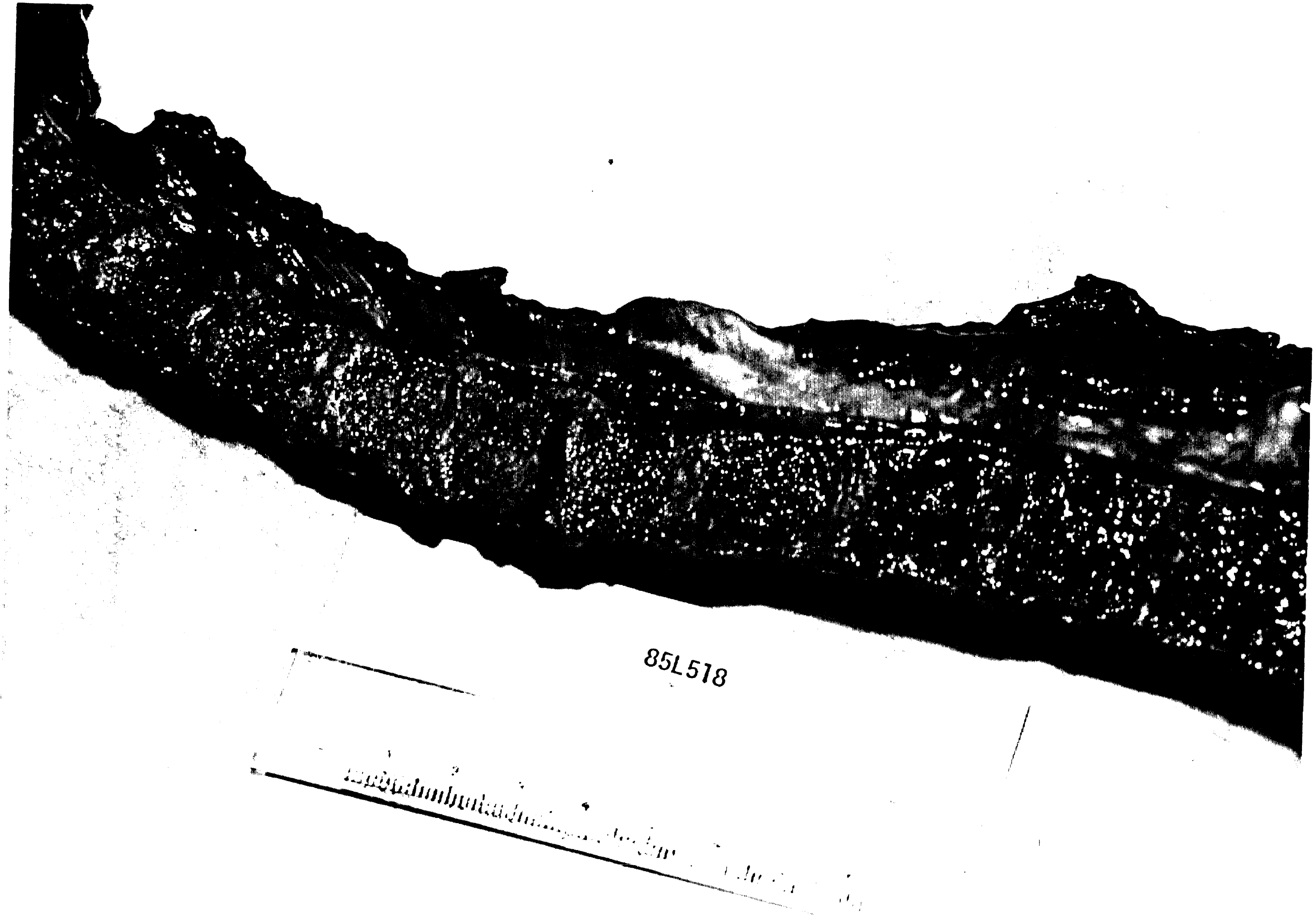
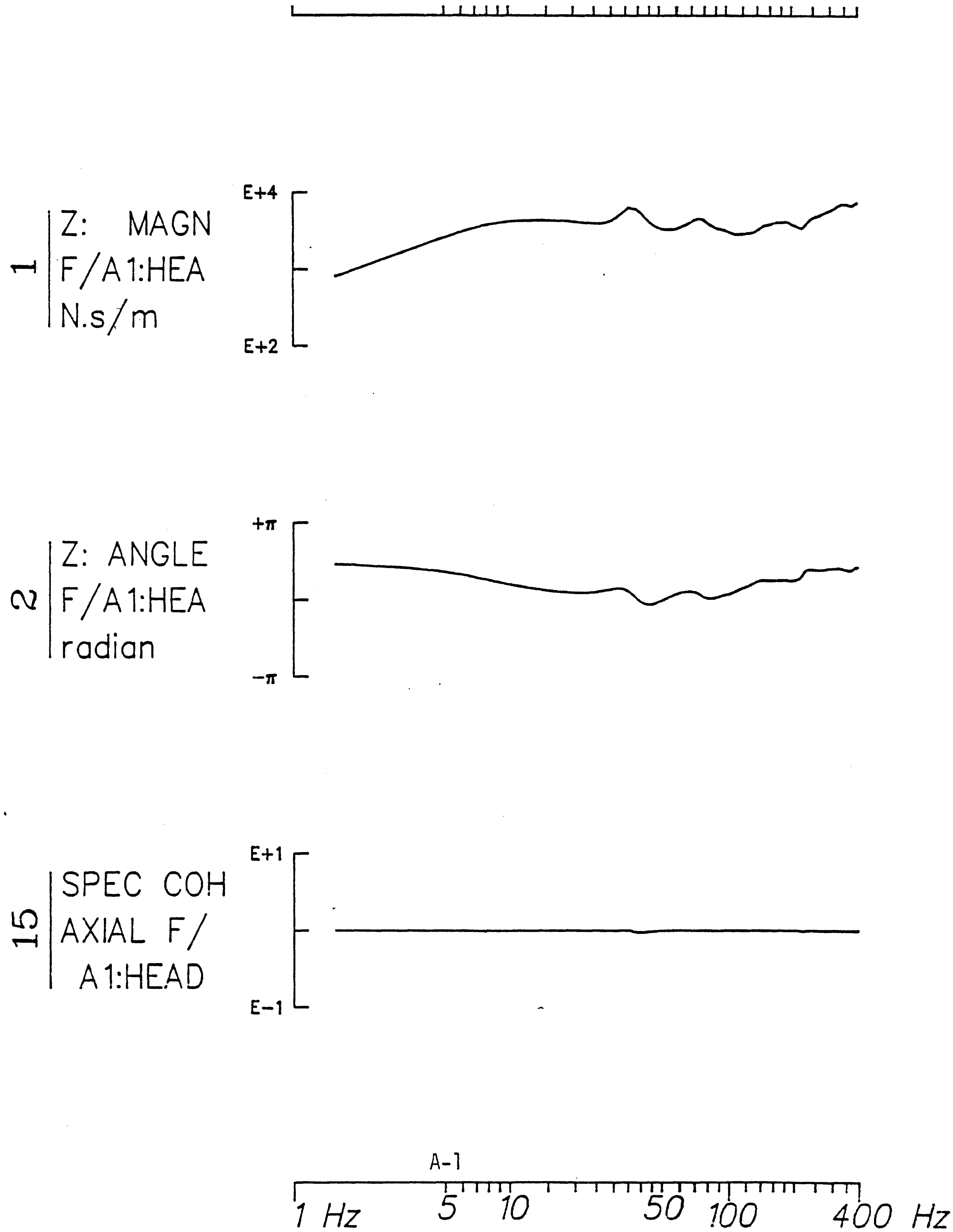

85L518

Table 4: Anthropometry Summary

PARAMETER	84L514	84L515	84L516	84L517	84L518	MEAN	STDEV
Age (yrs)	64	67	57	65	64	63.4	3.78
Stature (cm)	170.2	168.4	173.8	186.3	174.3	174.6	6.99
Weight (kg)	80.5	83.1	65.9	108.0	63.5	80.2	17.78
Head Circumference (cm)	55.5	56.0	57.0	63.8	56.0	57.7	3.48
Head length (cm)	19.5	20.3	14.8	20.7	19.6	19.0	2.39
Head breadth (cm)	16.0	15.5	20.6	16.6	14.5	16.6	2.34
Menton-Vertex (cm)	24.5	21.5	23.4	22.3	23.6	23.1	1.17
Menton-Suprasternale (cm)	9.5	9.1	11.5	9.4	7.2	9.3	1.53
Neck circumference 1 (cm)	46.5	55.0	34.0	44.0	35.5	43.0	8.58
Neck circumference 2 (cm)	42.5	41.0	35.5	42.0	36.8	39.6	3.19
Neck circumference 3 (cm)	45.0	40.0	38.0	41.0	38.0	40.4	2.88
Acromion height (cm)	19.0	24.7	27.3	24.0	25.1	24.0	3.07
Suprasternale height (cm)	34.0	30.6	34.9	31.7	30.8	32.4	1.94
Substernale height (cm)	46.5	49.4	51.5	41.7	52.5	48.3	4.36
Substernale circumference (cm)	107.3	108.0	89.5	101.6	80.3	97.3	12.07
Axilliary breadth (cm)	34.0	33.0	29.6	39.0	29.0	32.9	4.02
Chest breadth (cm)	35.0	32.3	30.4	39.5	29.8	33.4	3.97

APPENDICES

Run ID: 84L503 ***GM Data frequency analysis***



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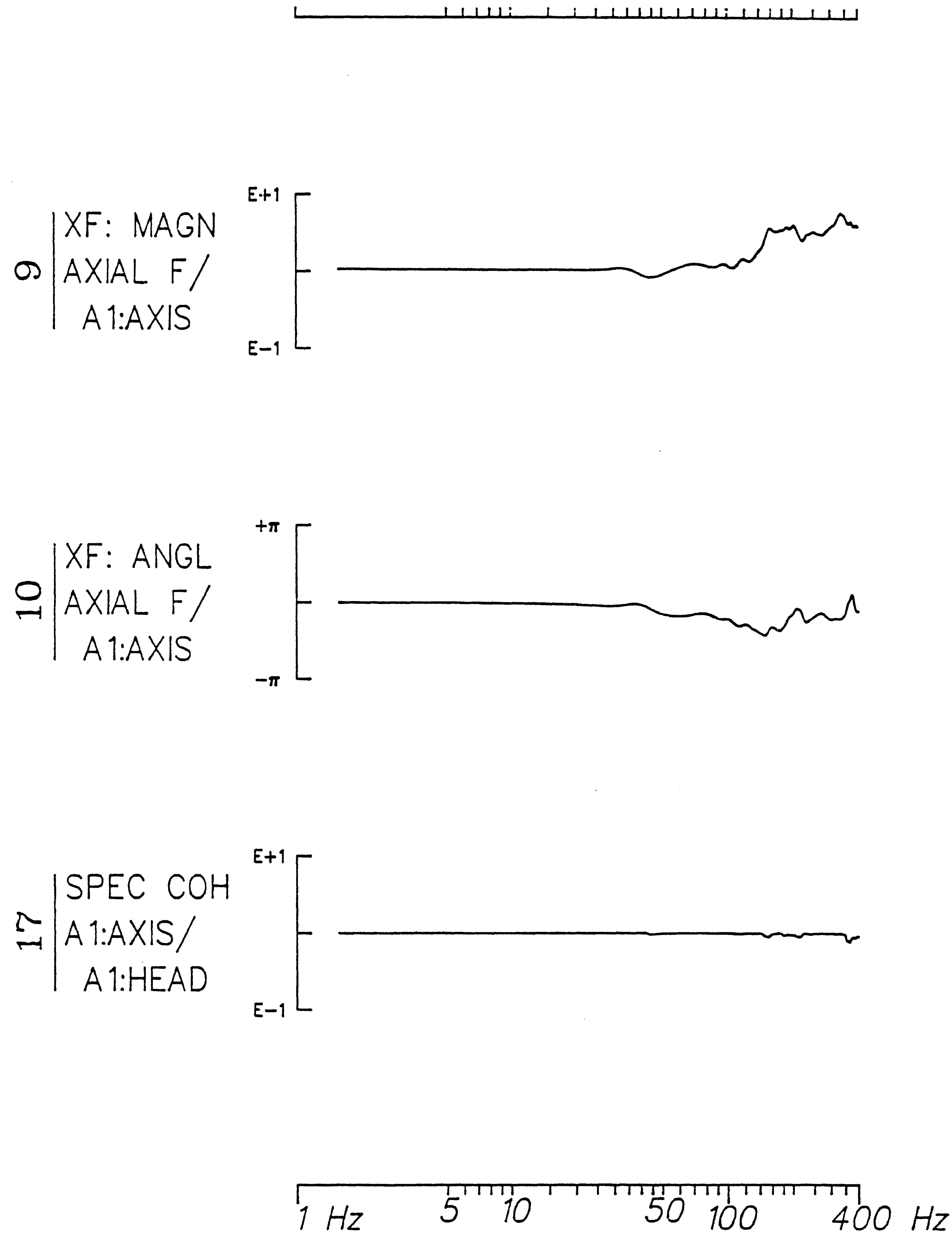

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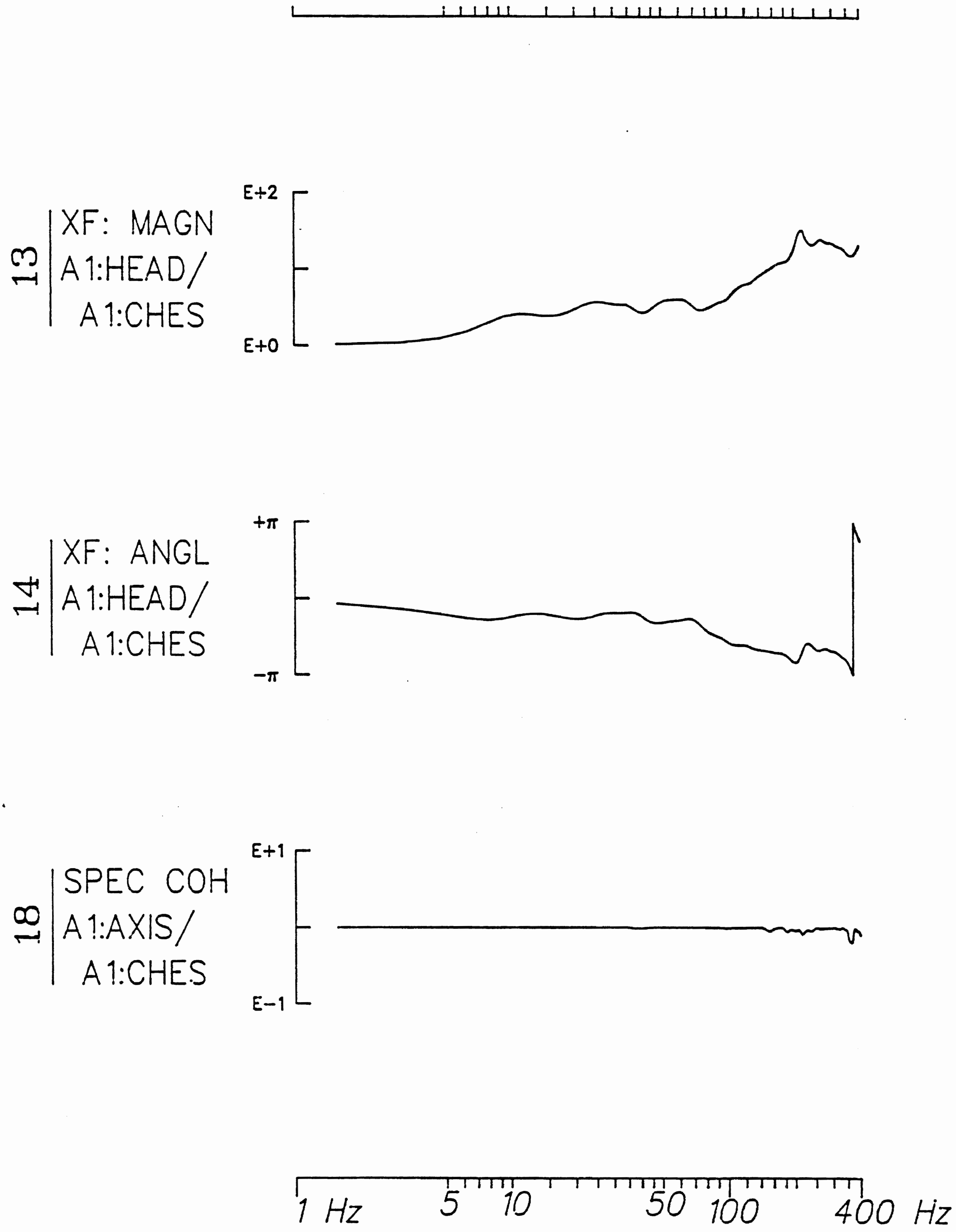

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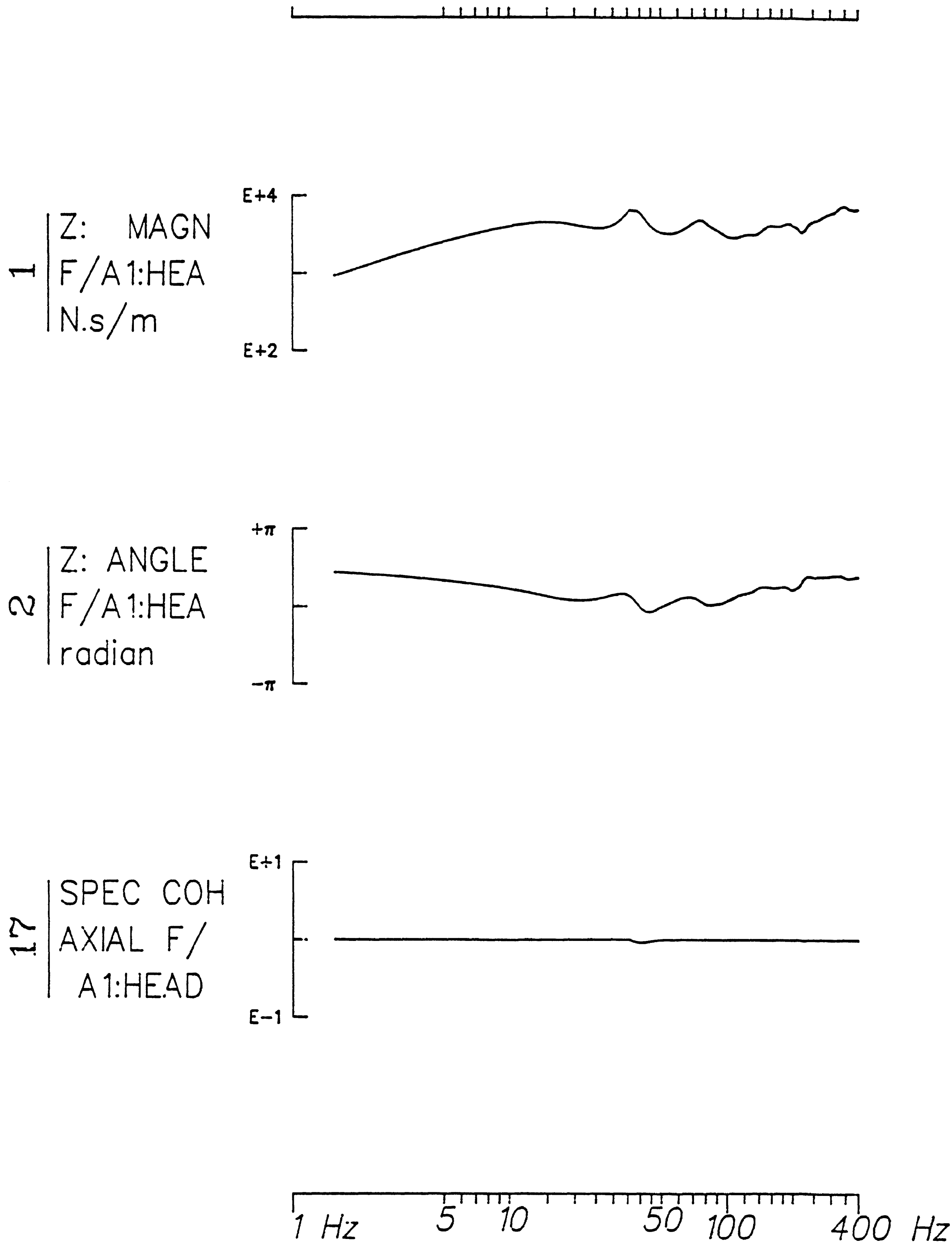

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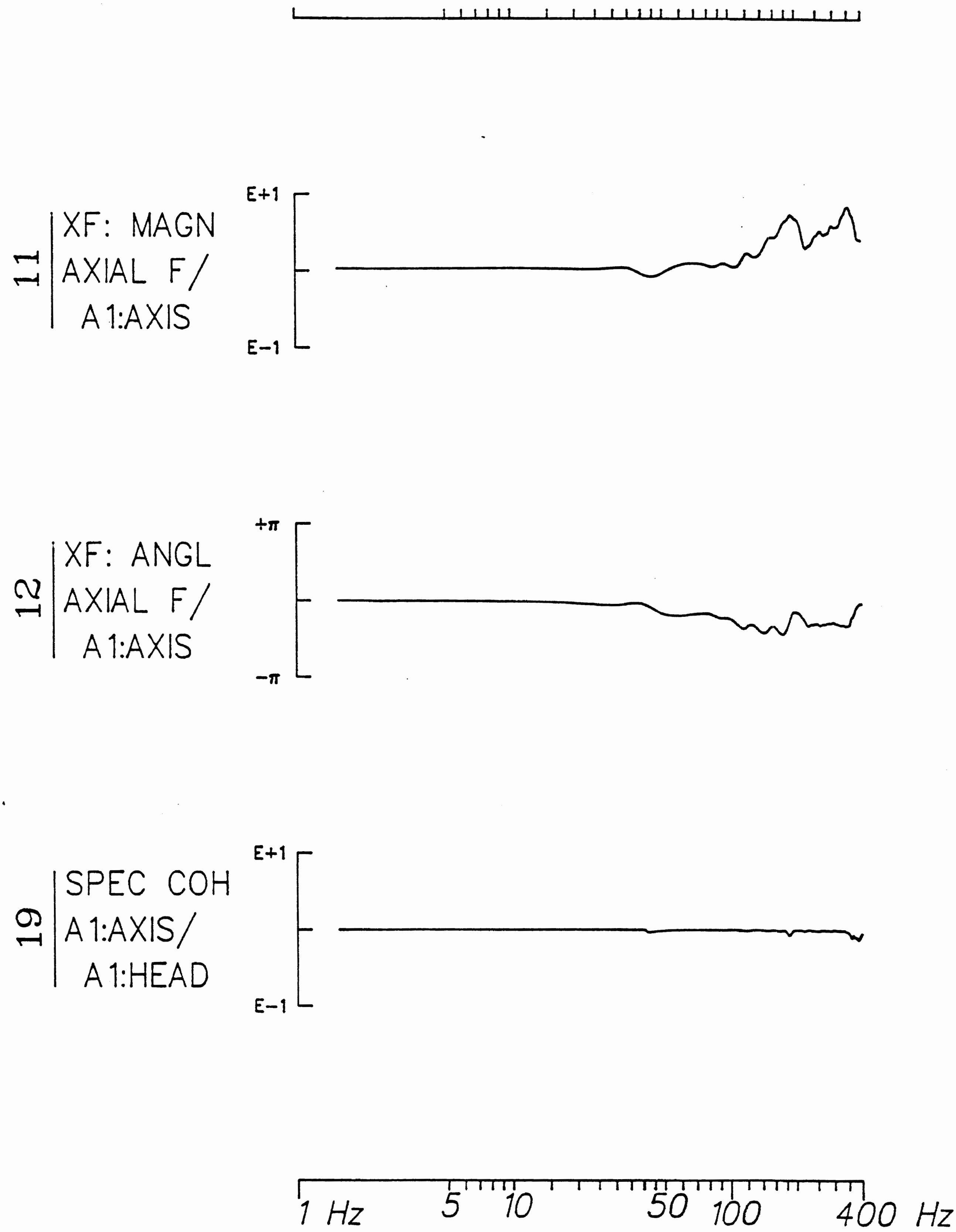

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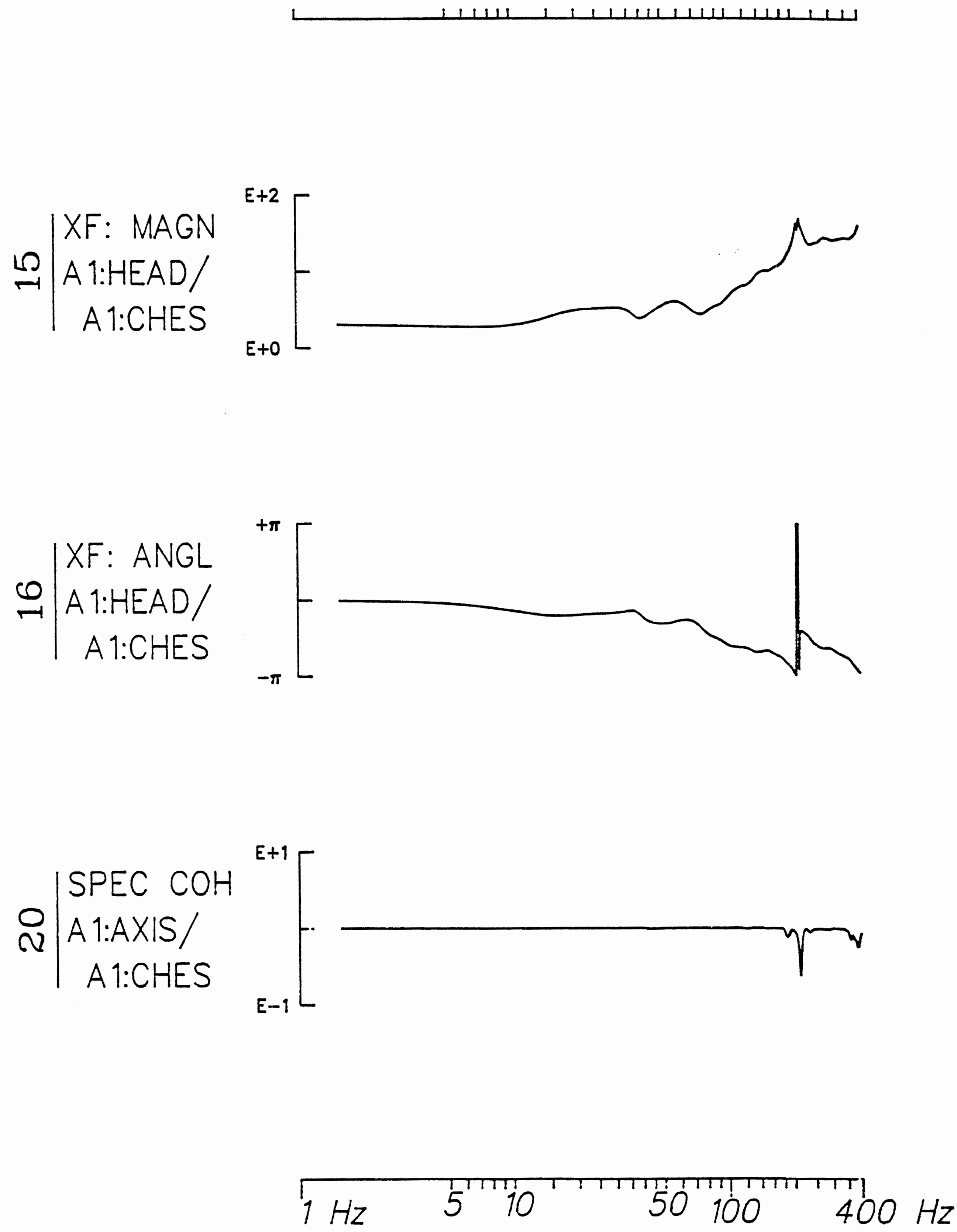

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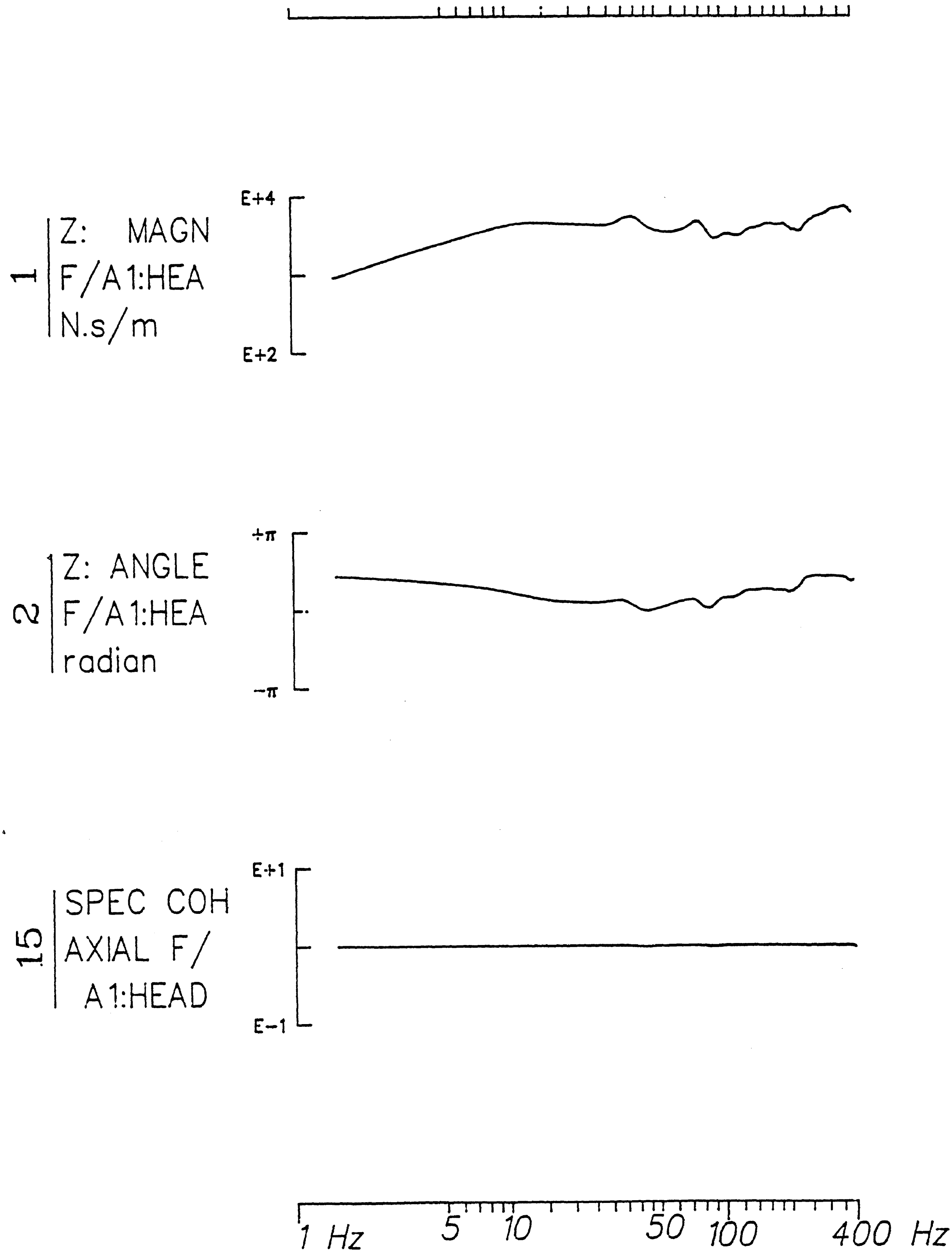

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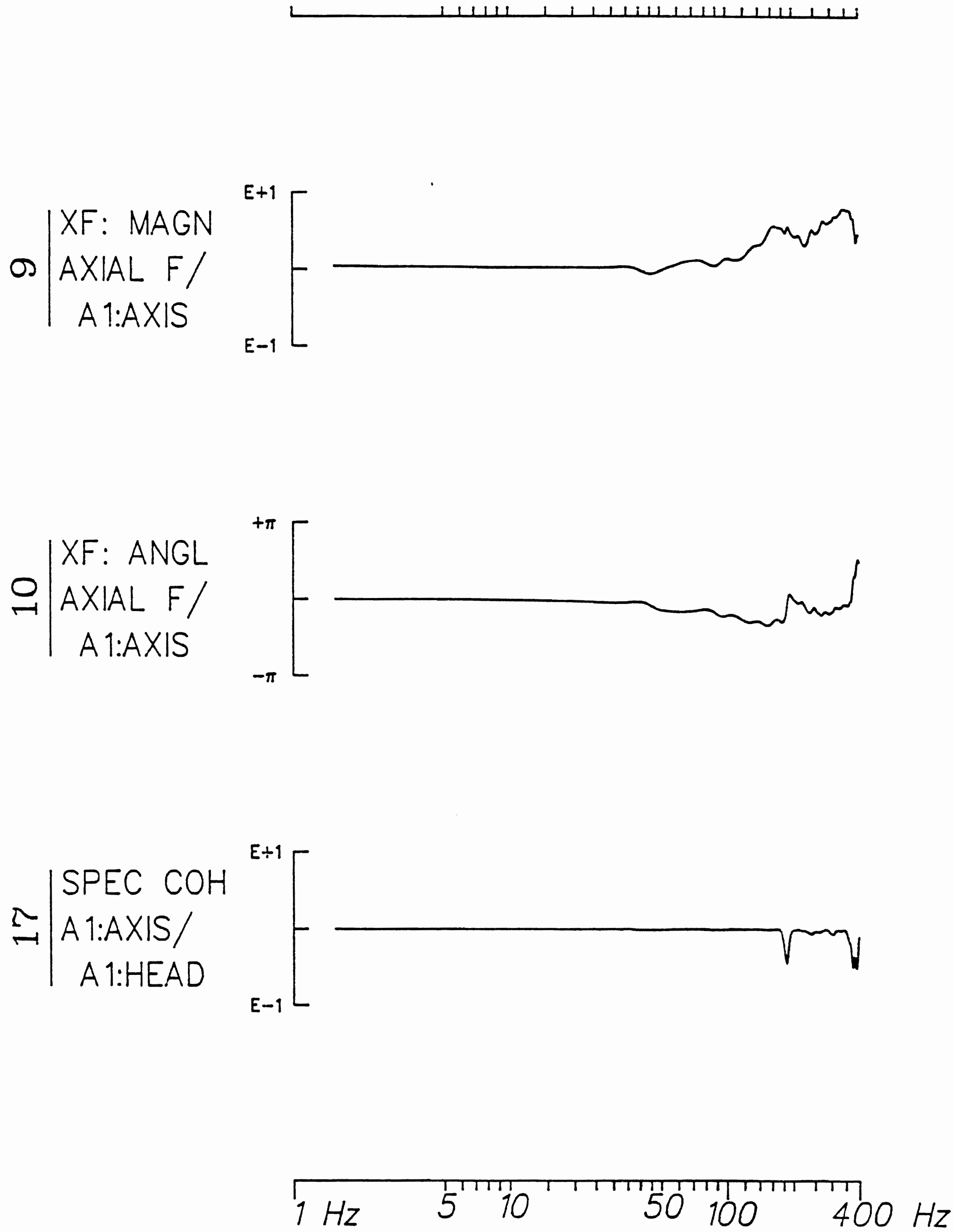

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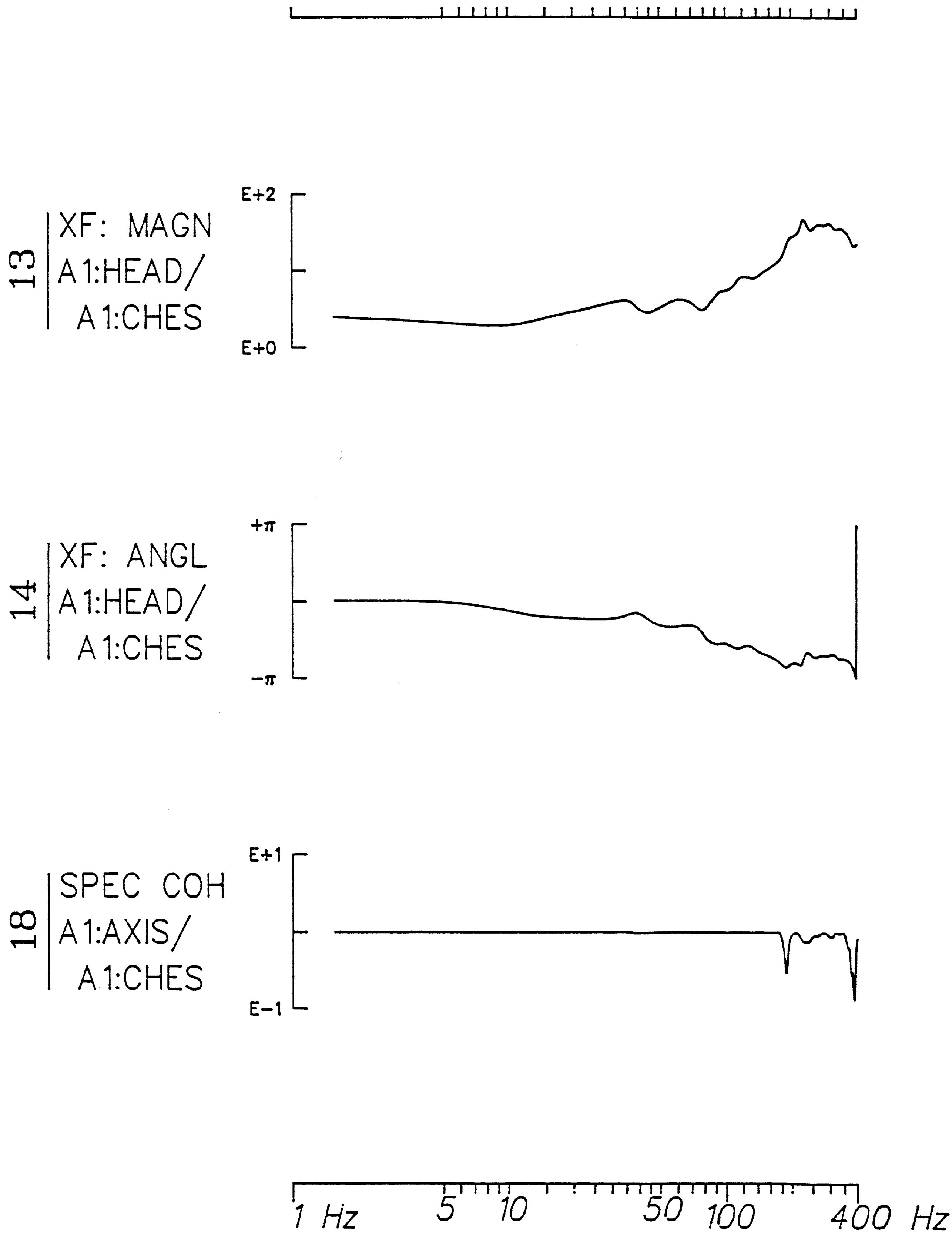

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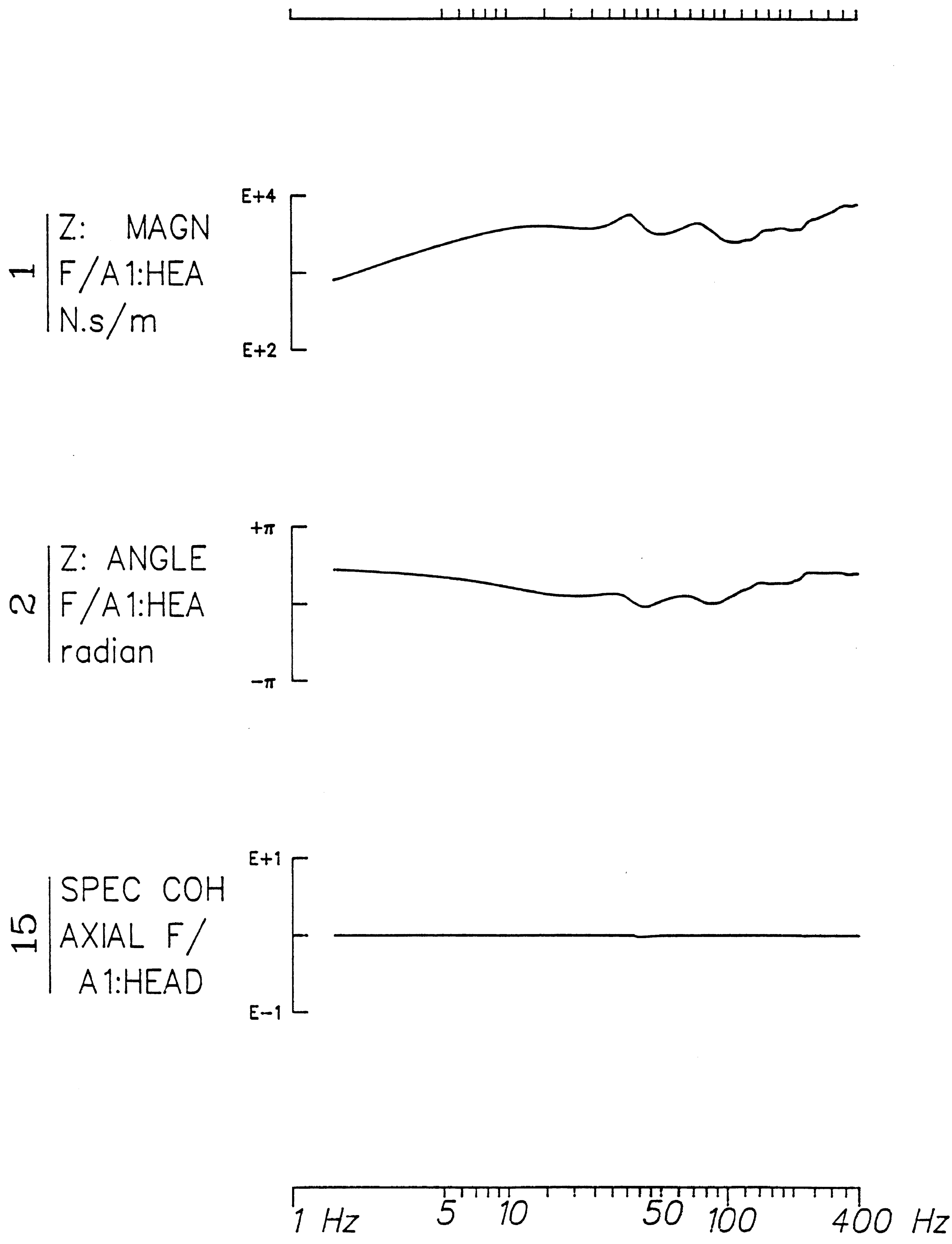

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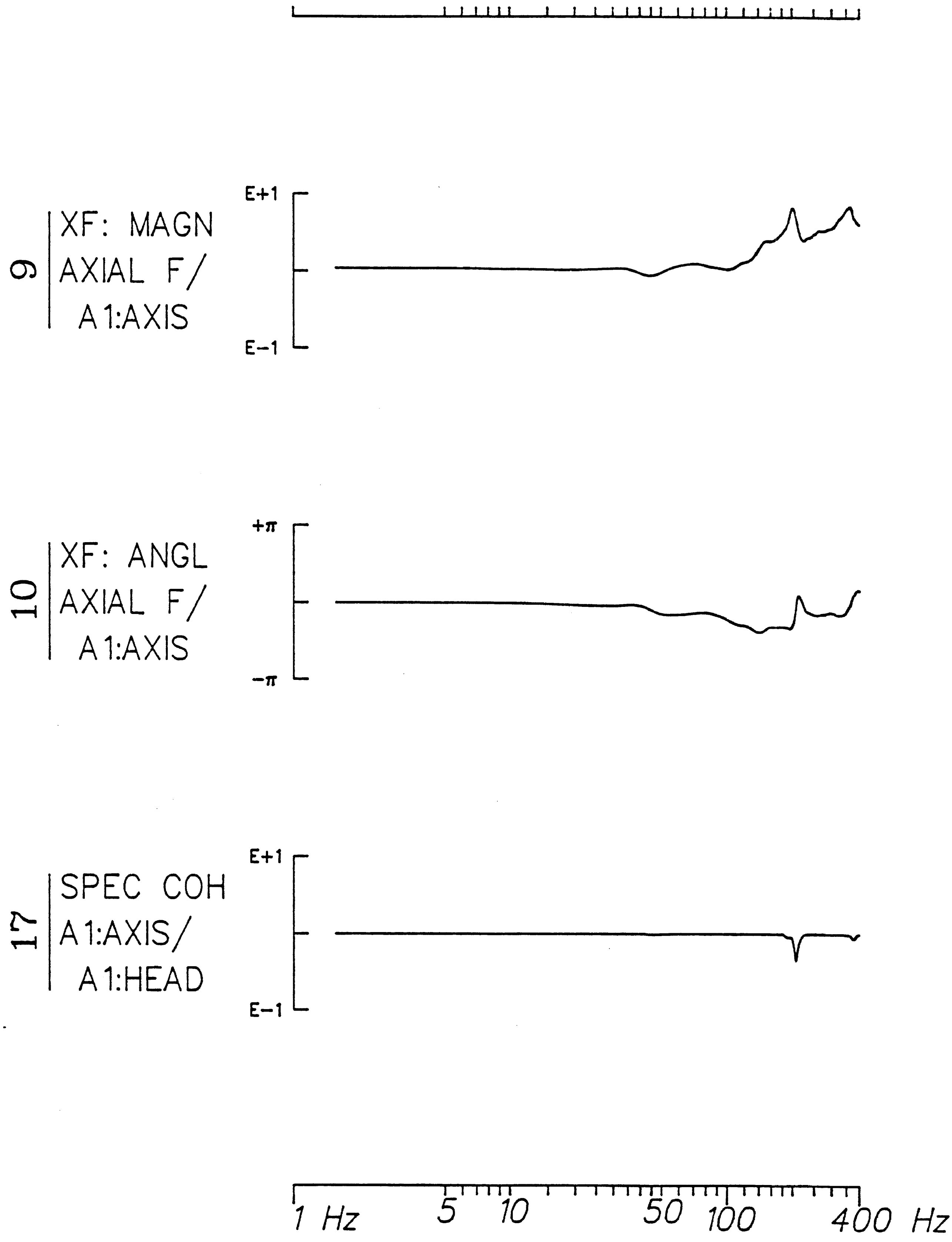

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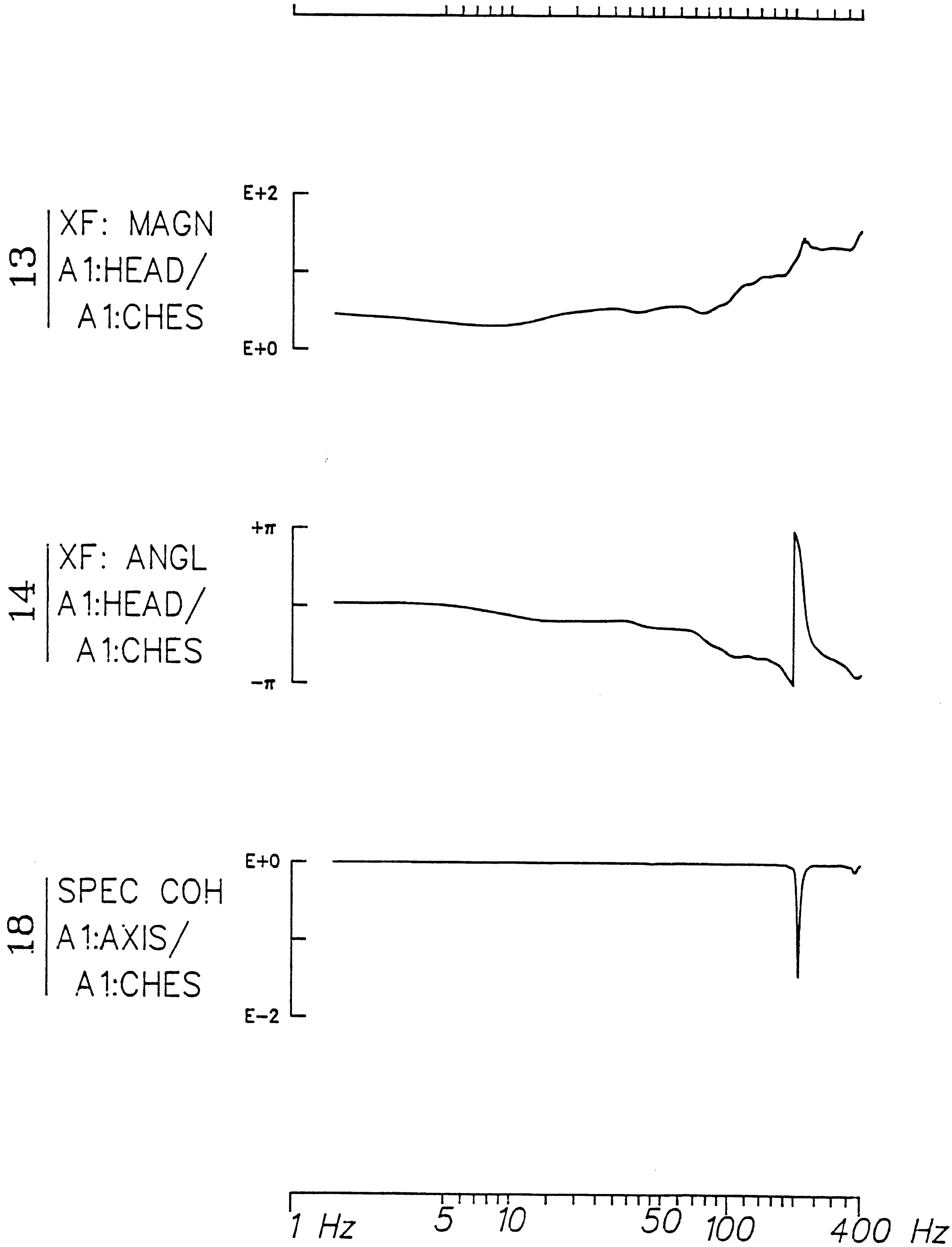

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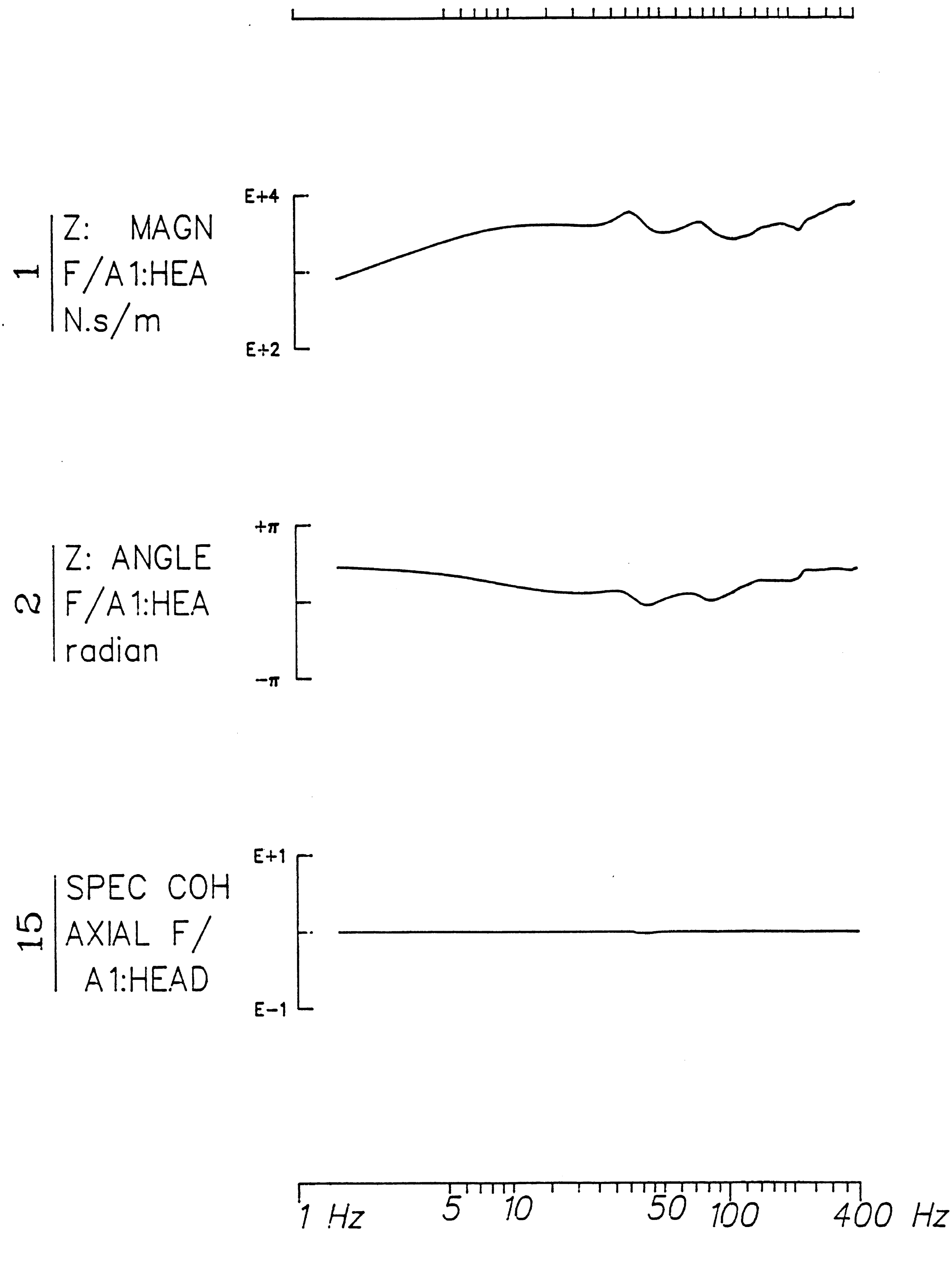

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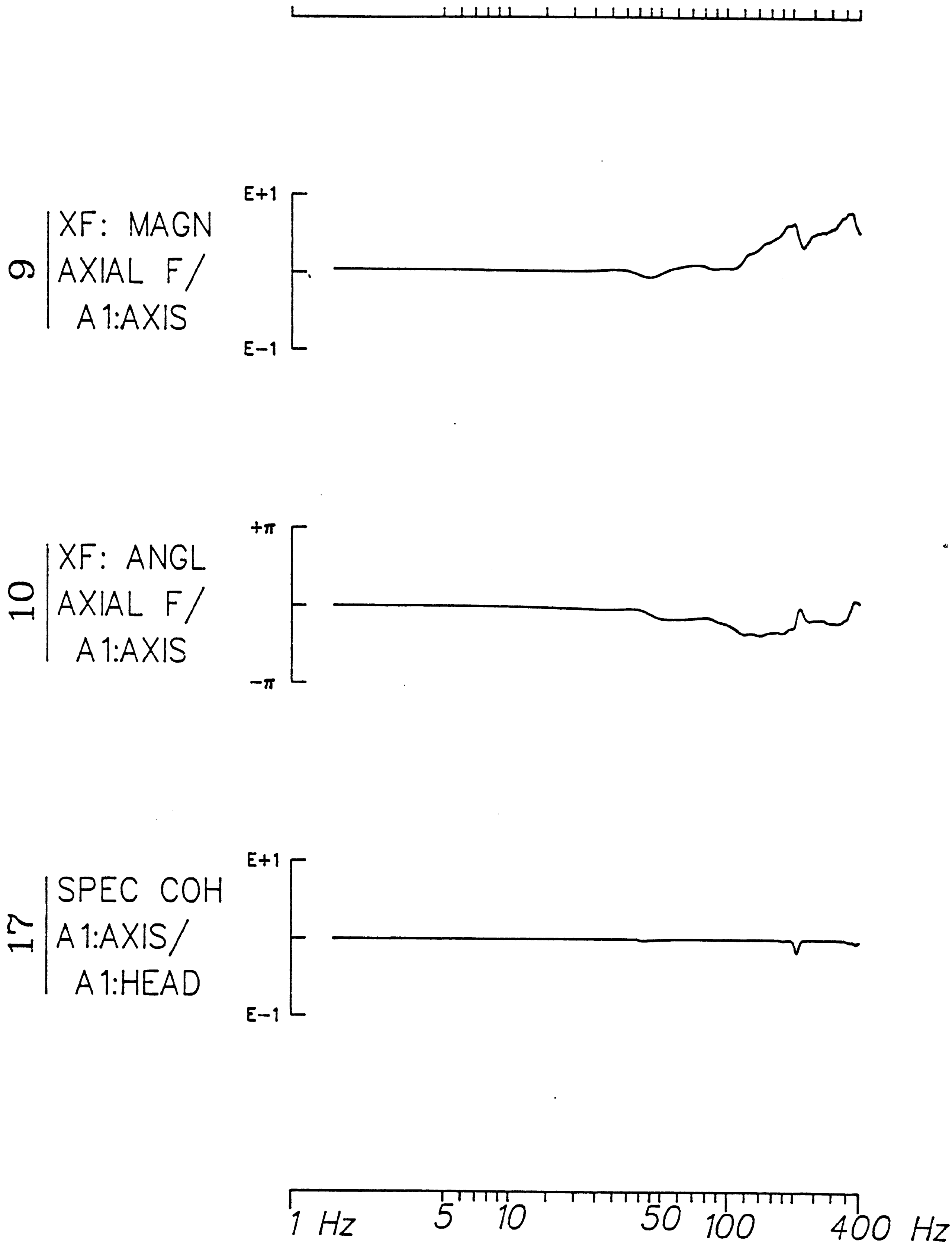

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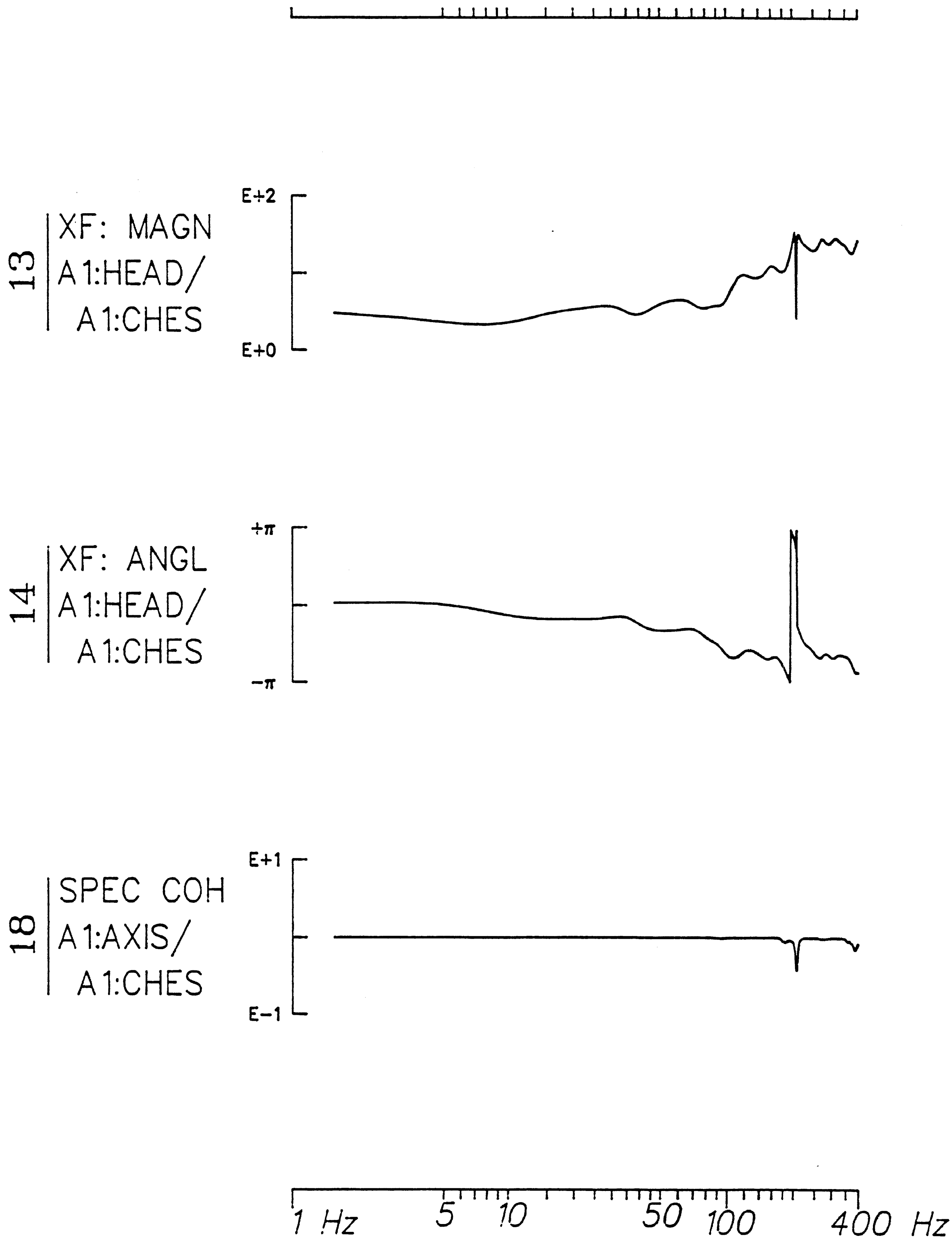

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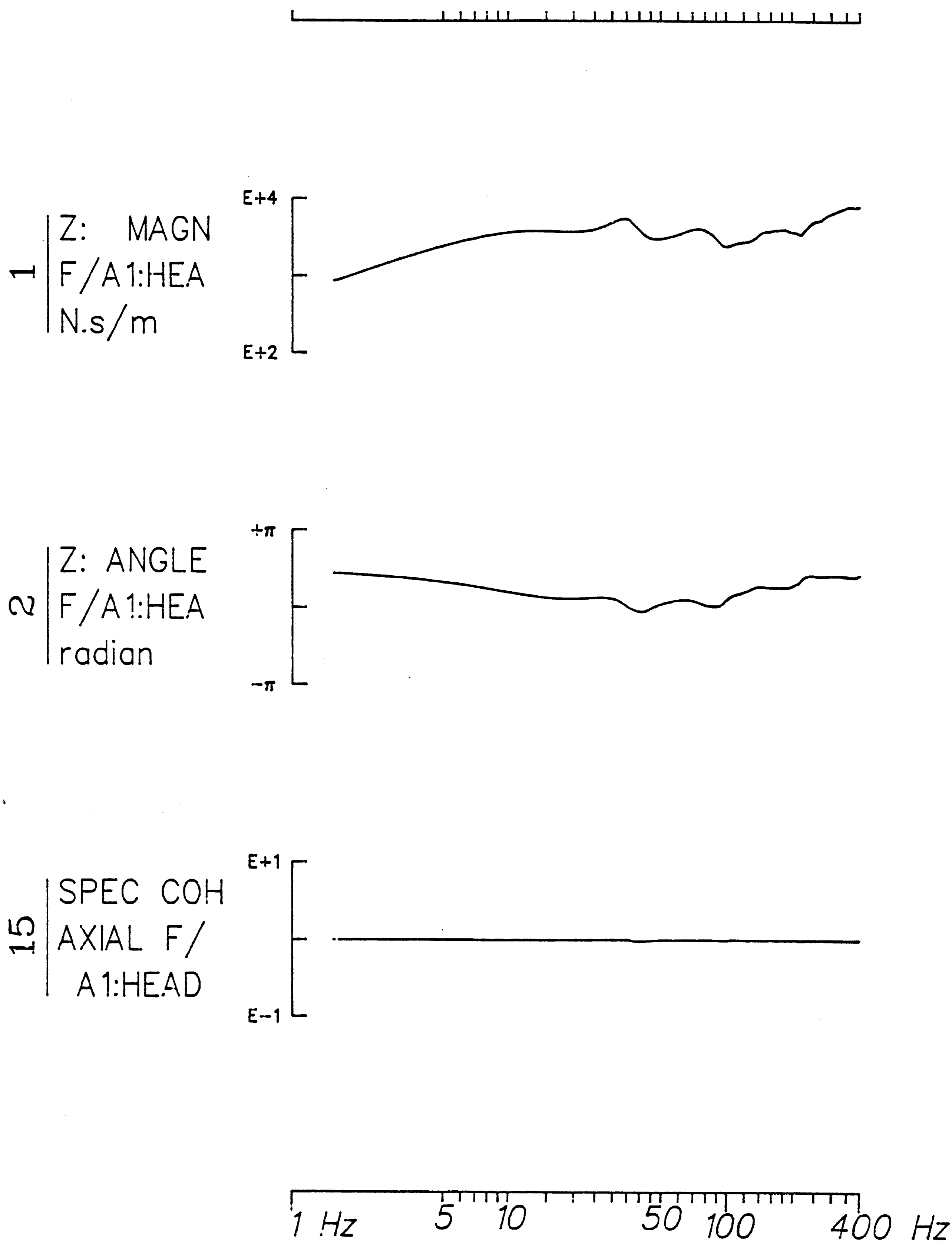

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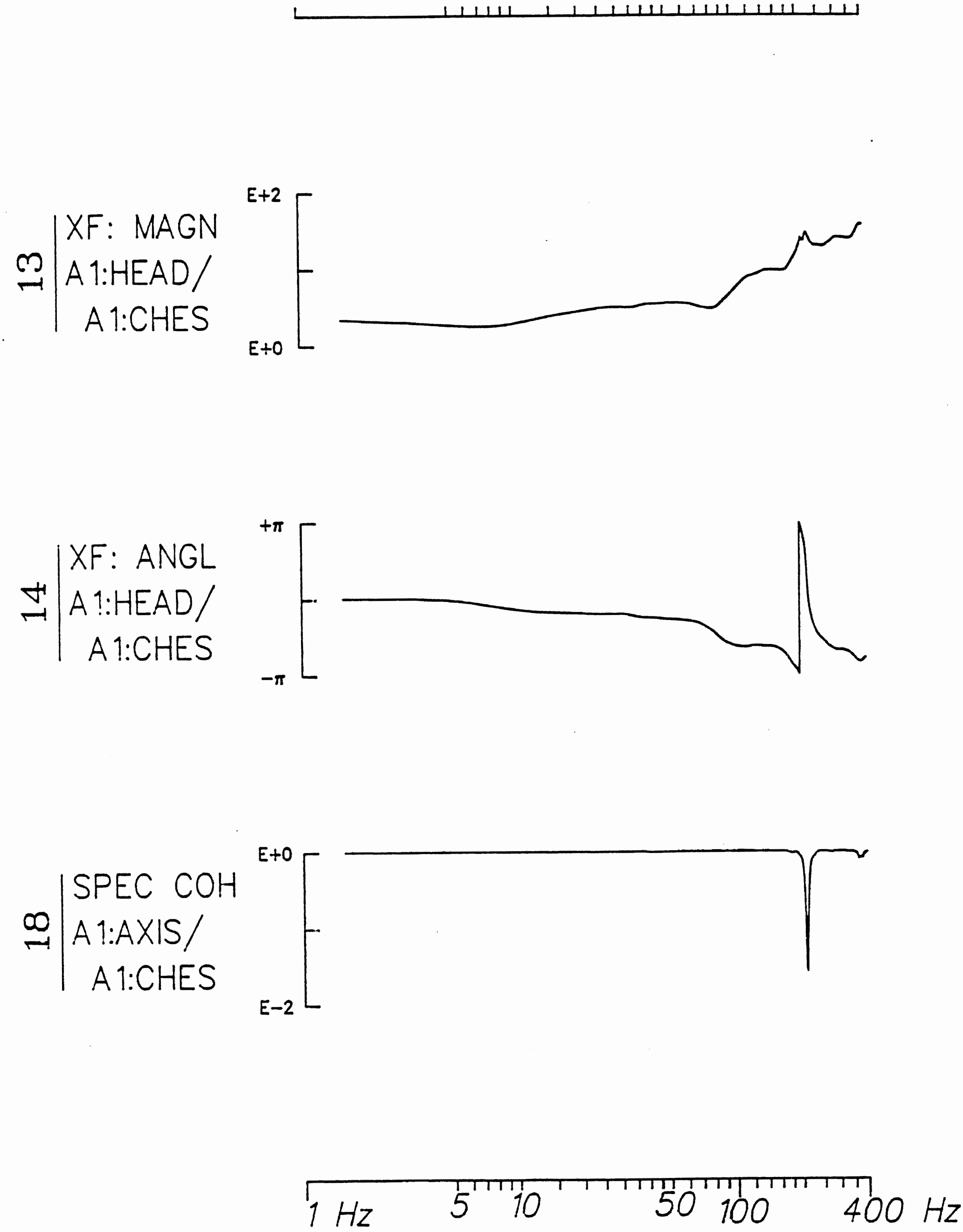

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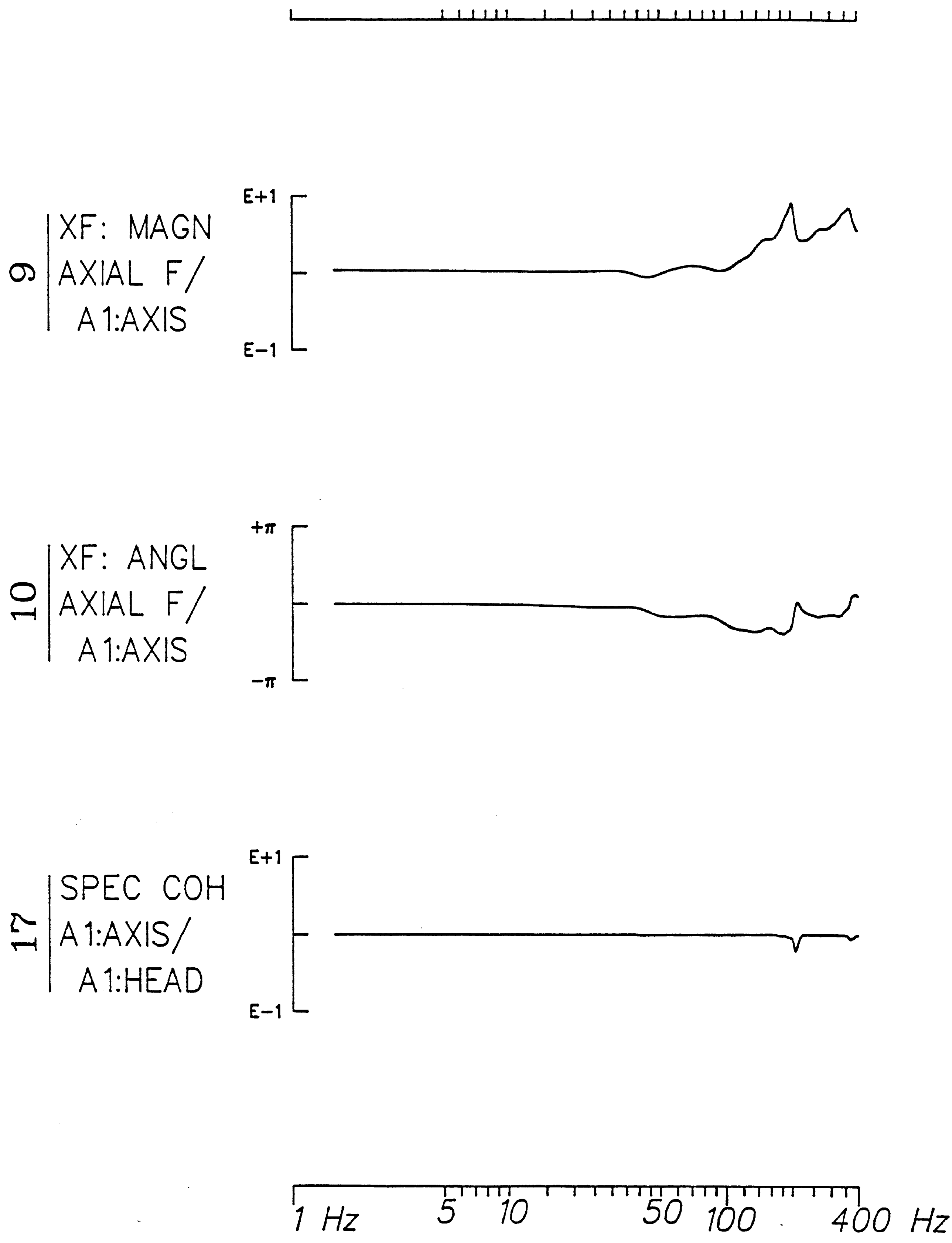

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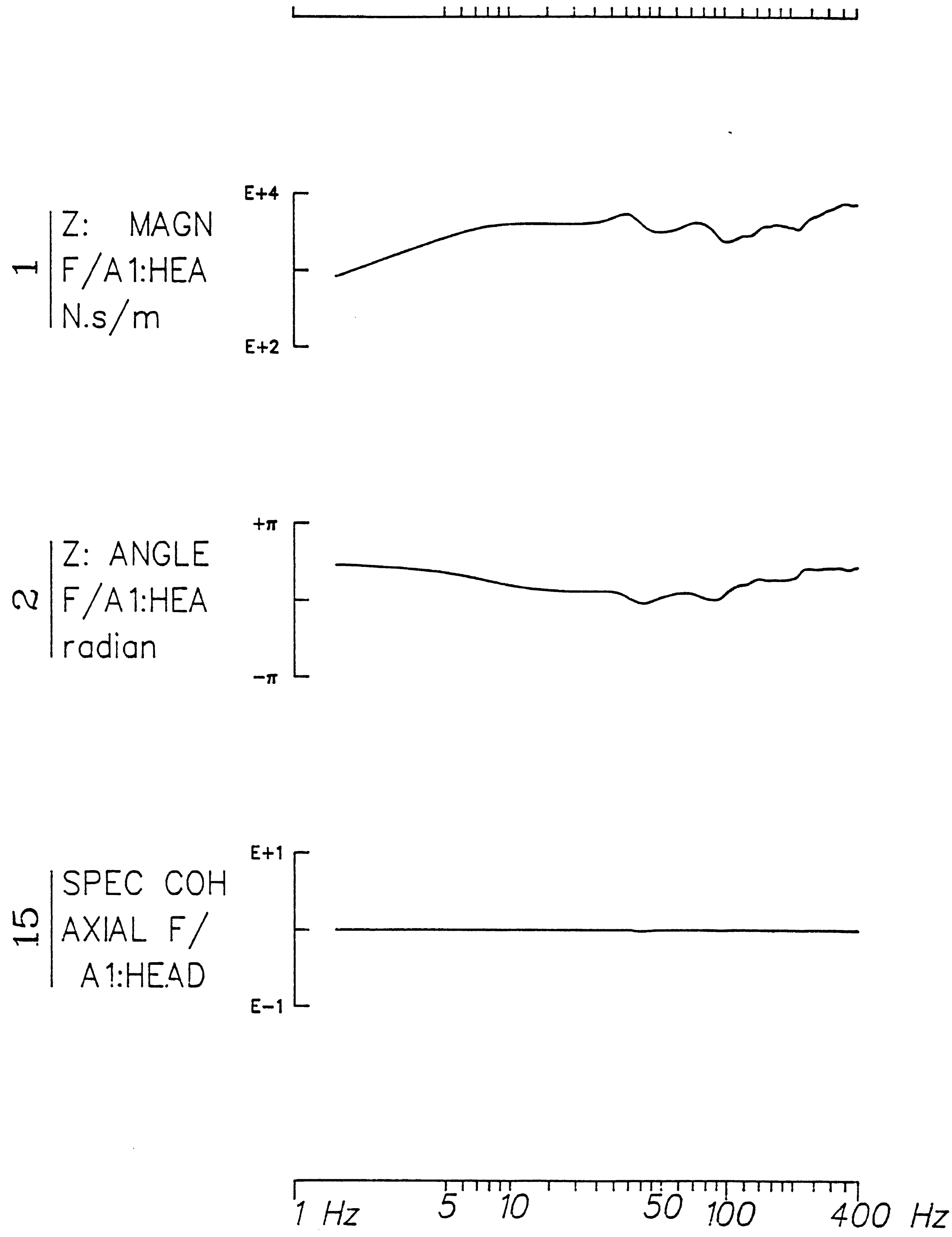

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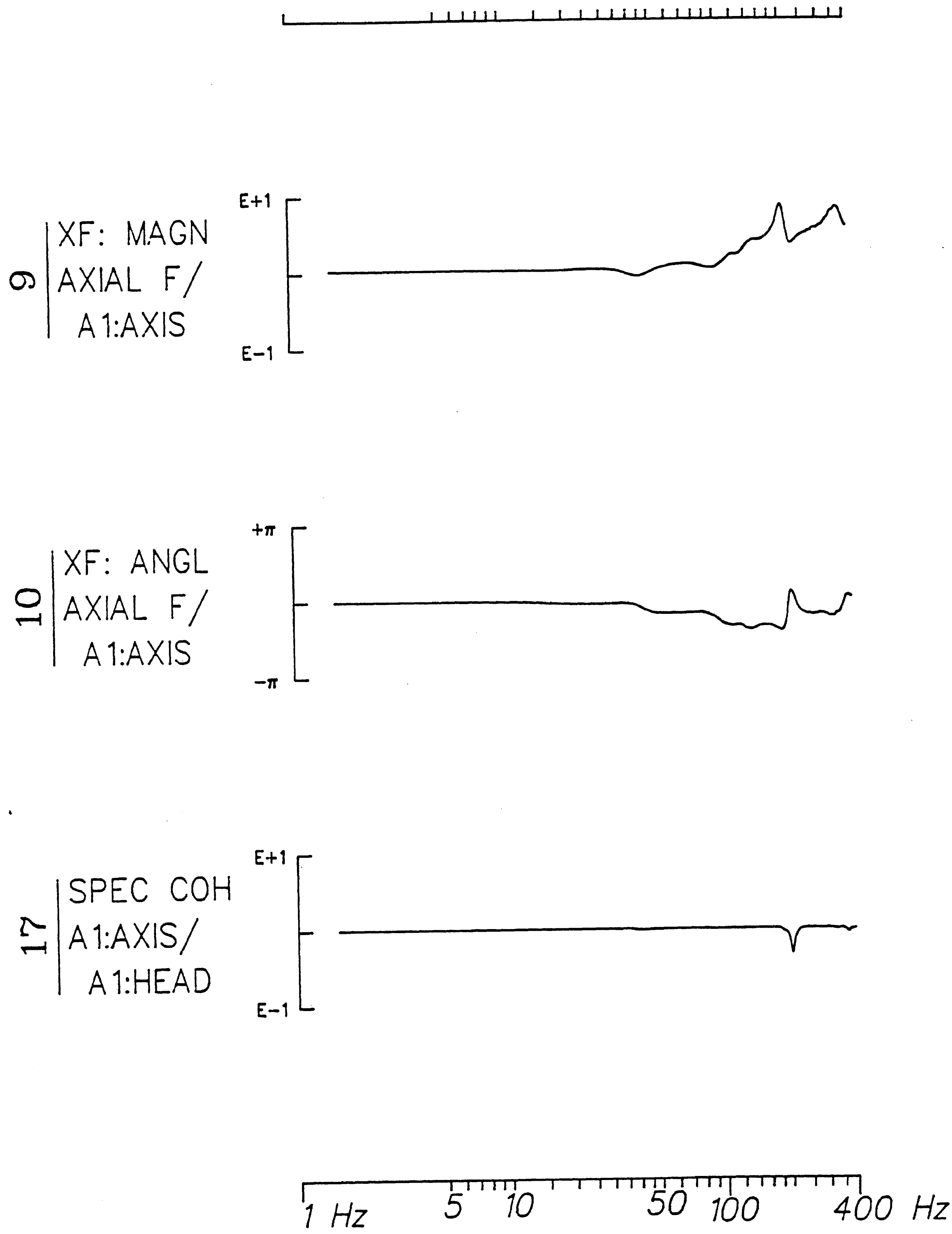

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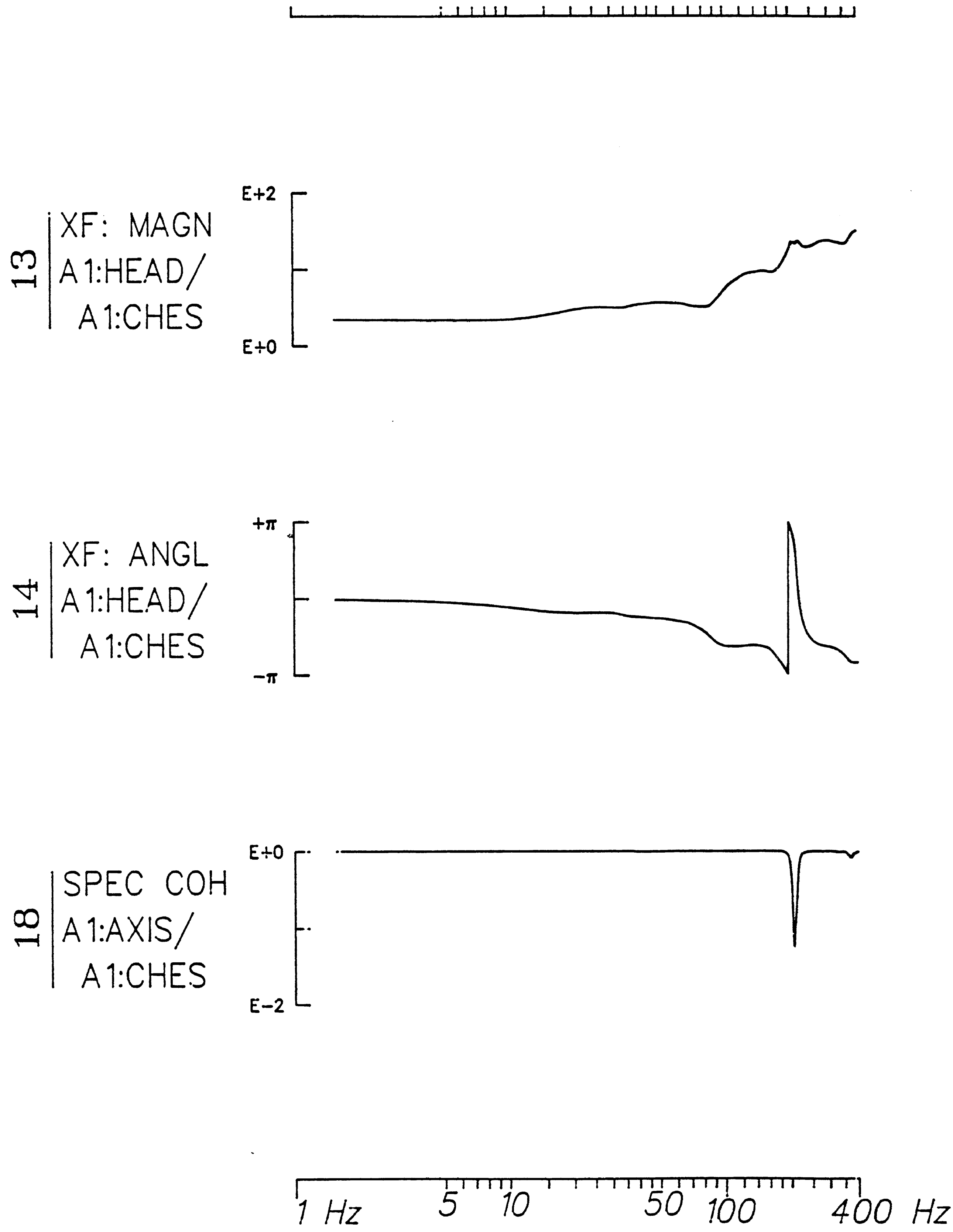

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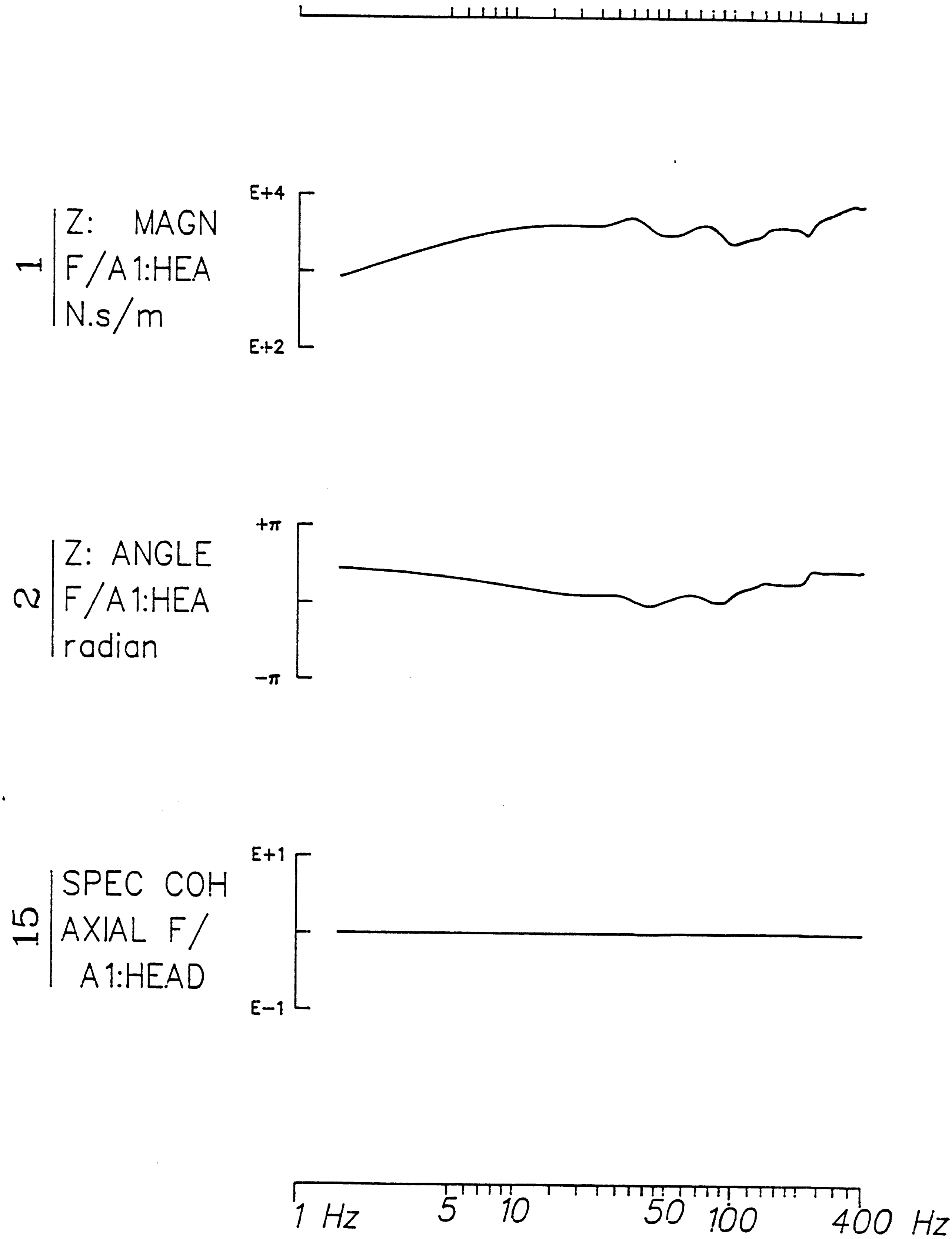

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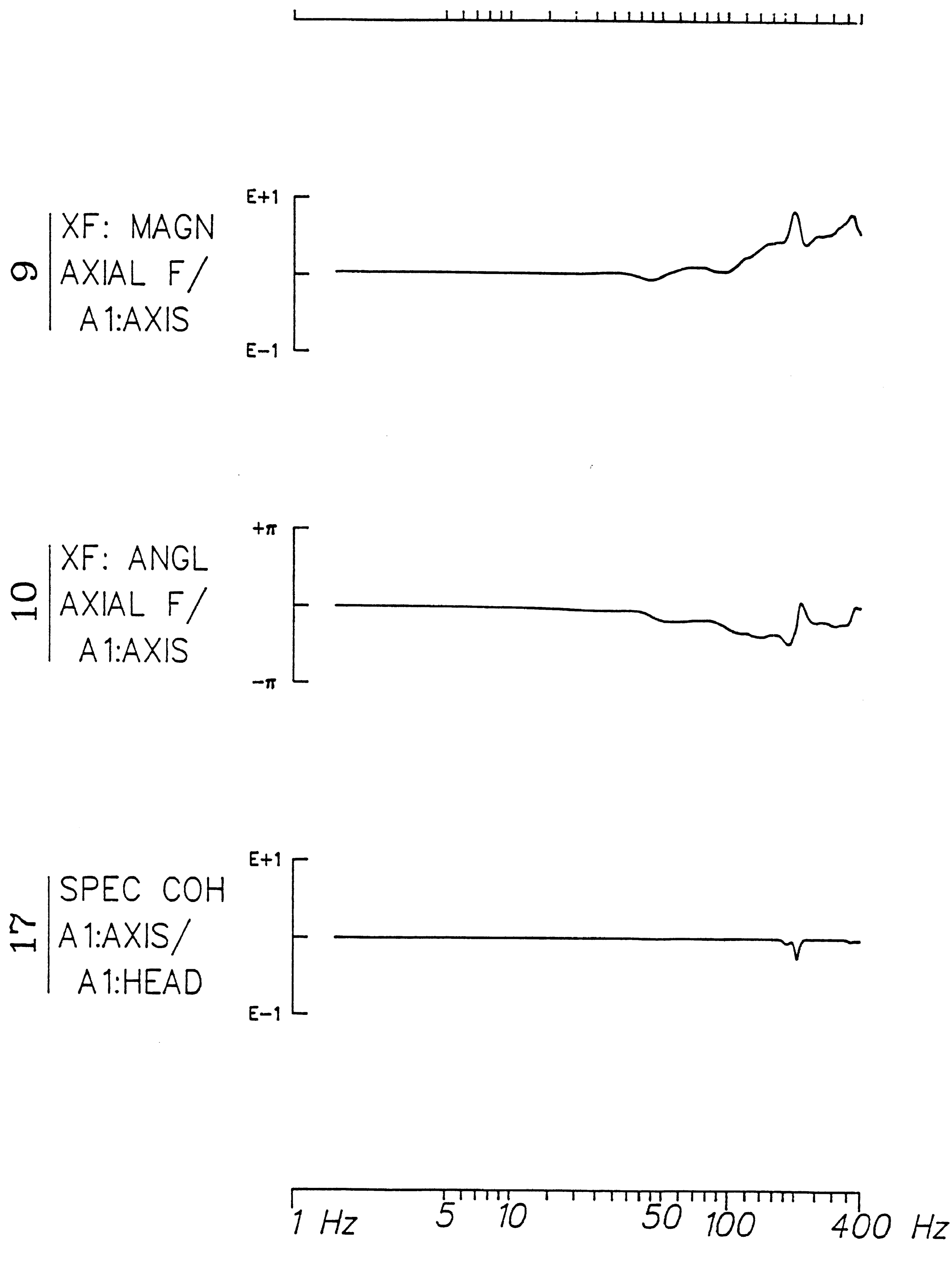

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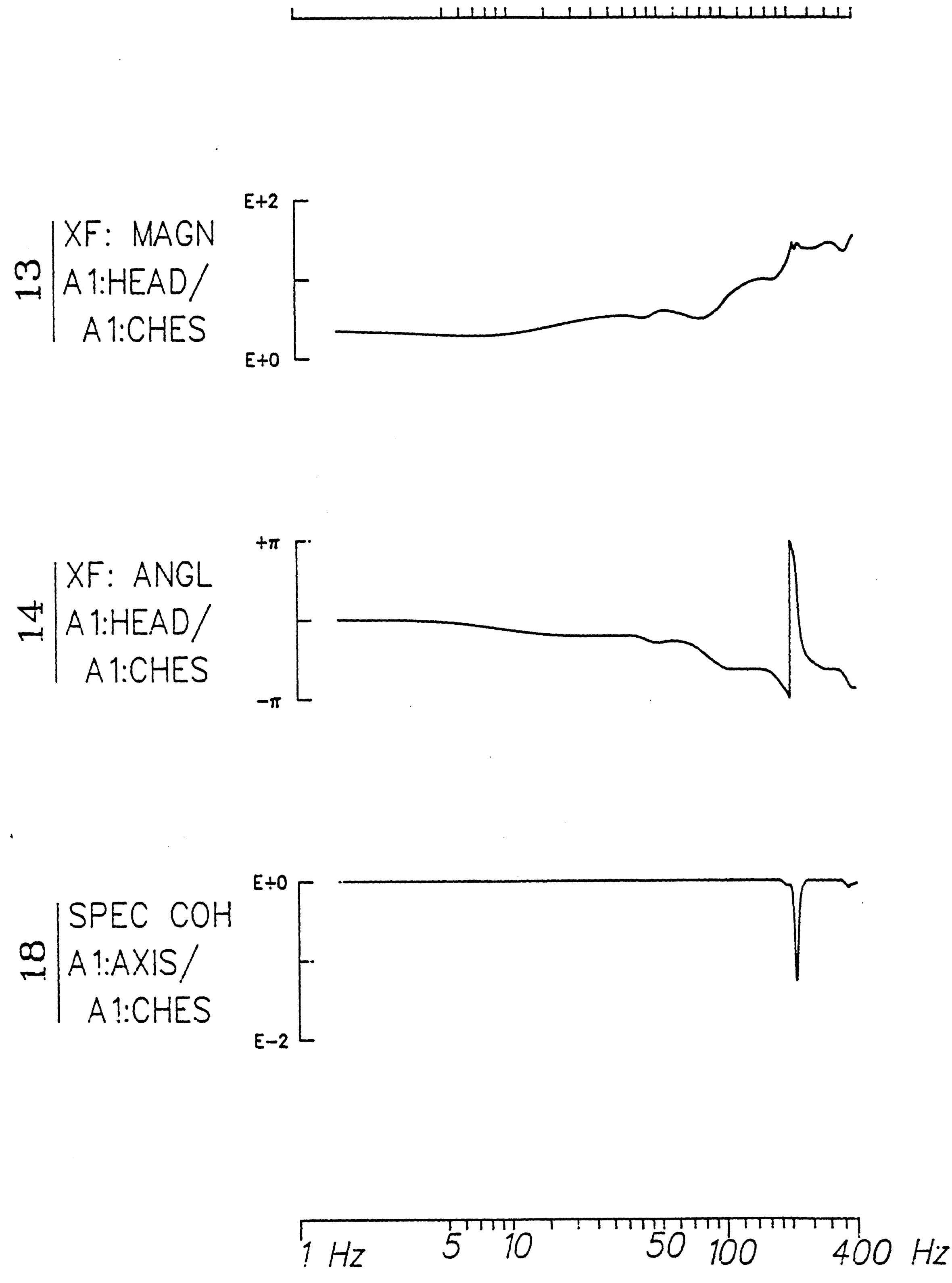

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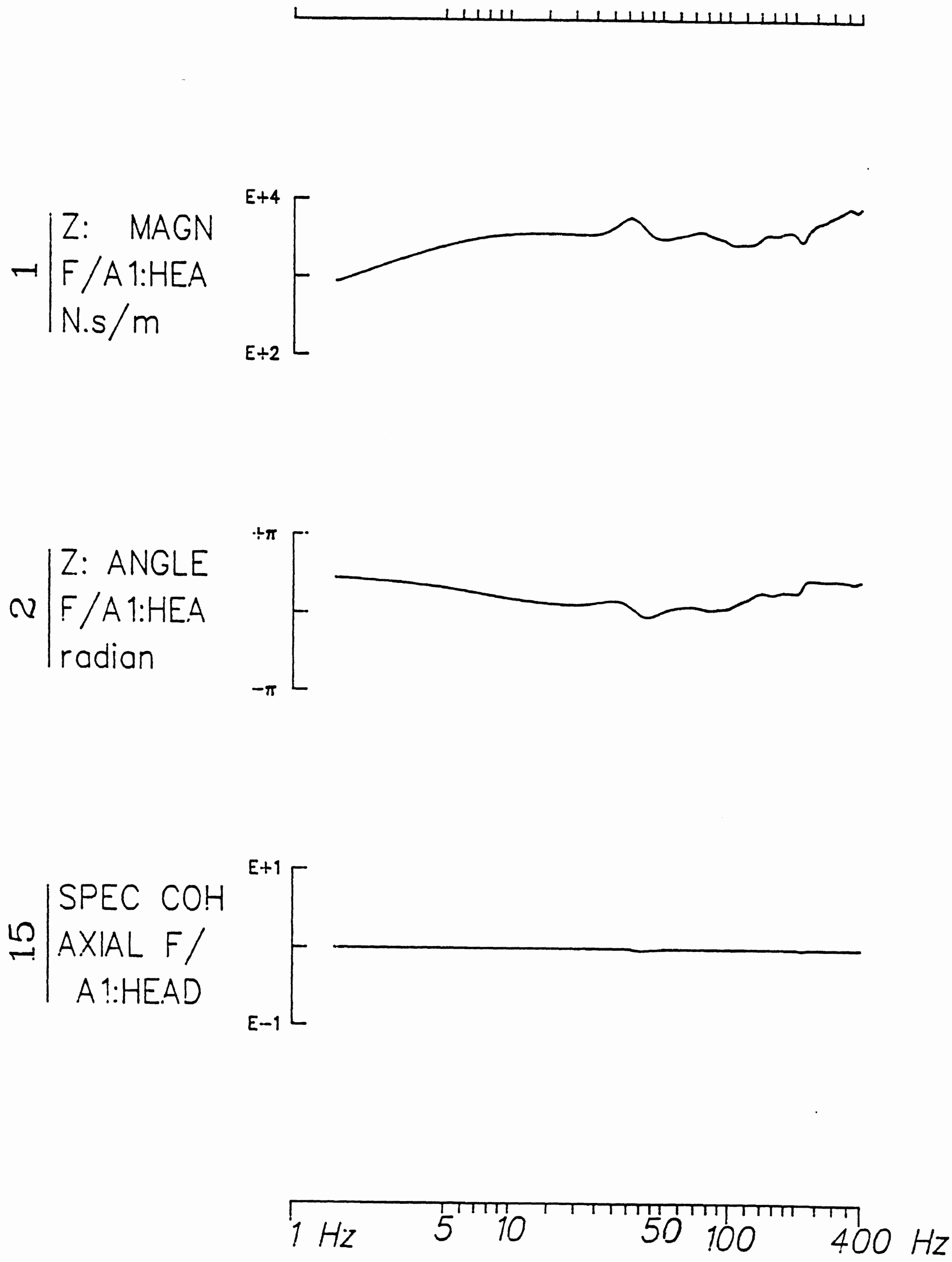

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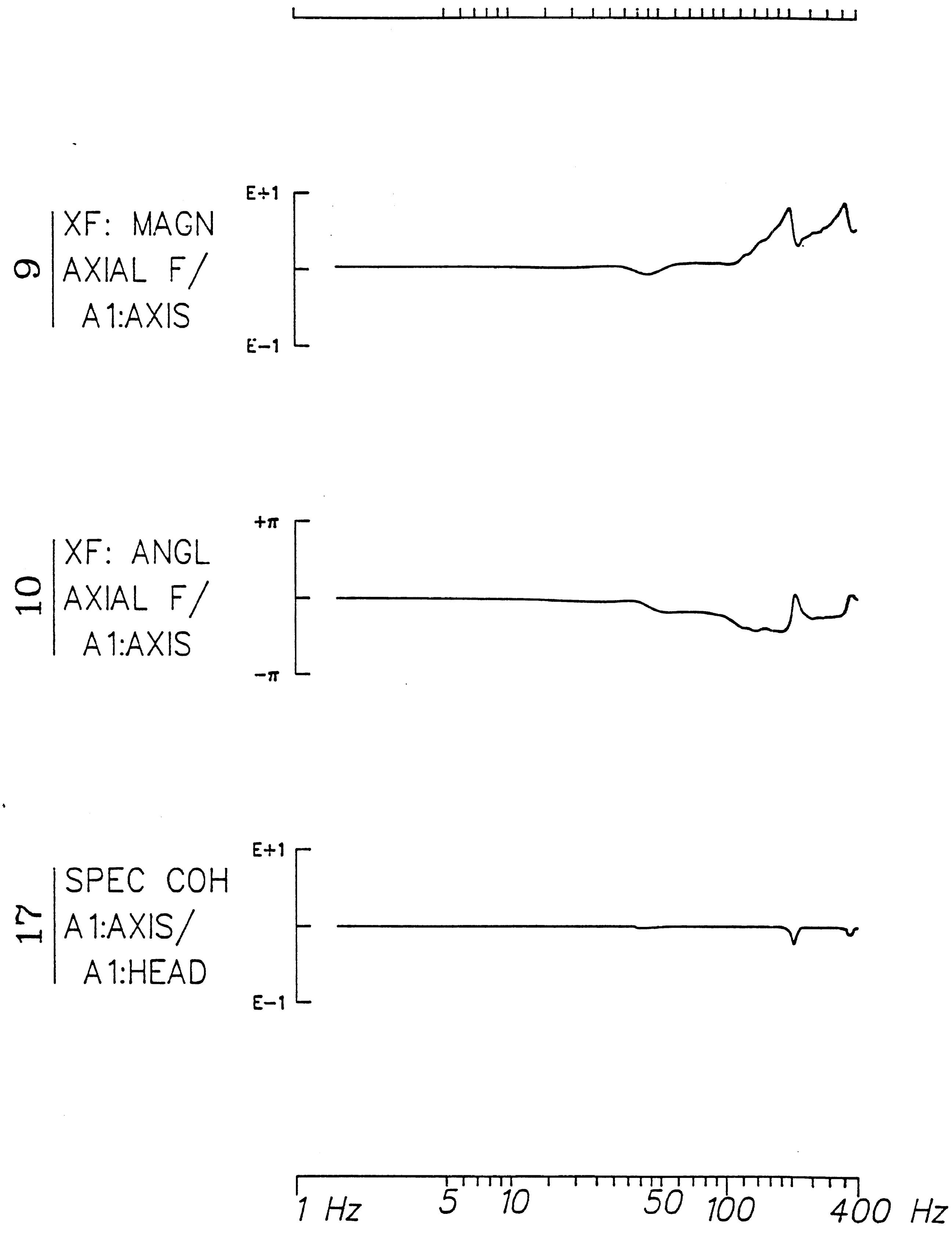

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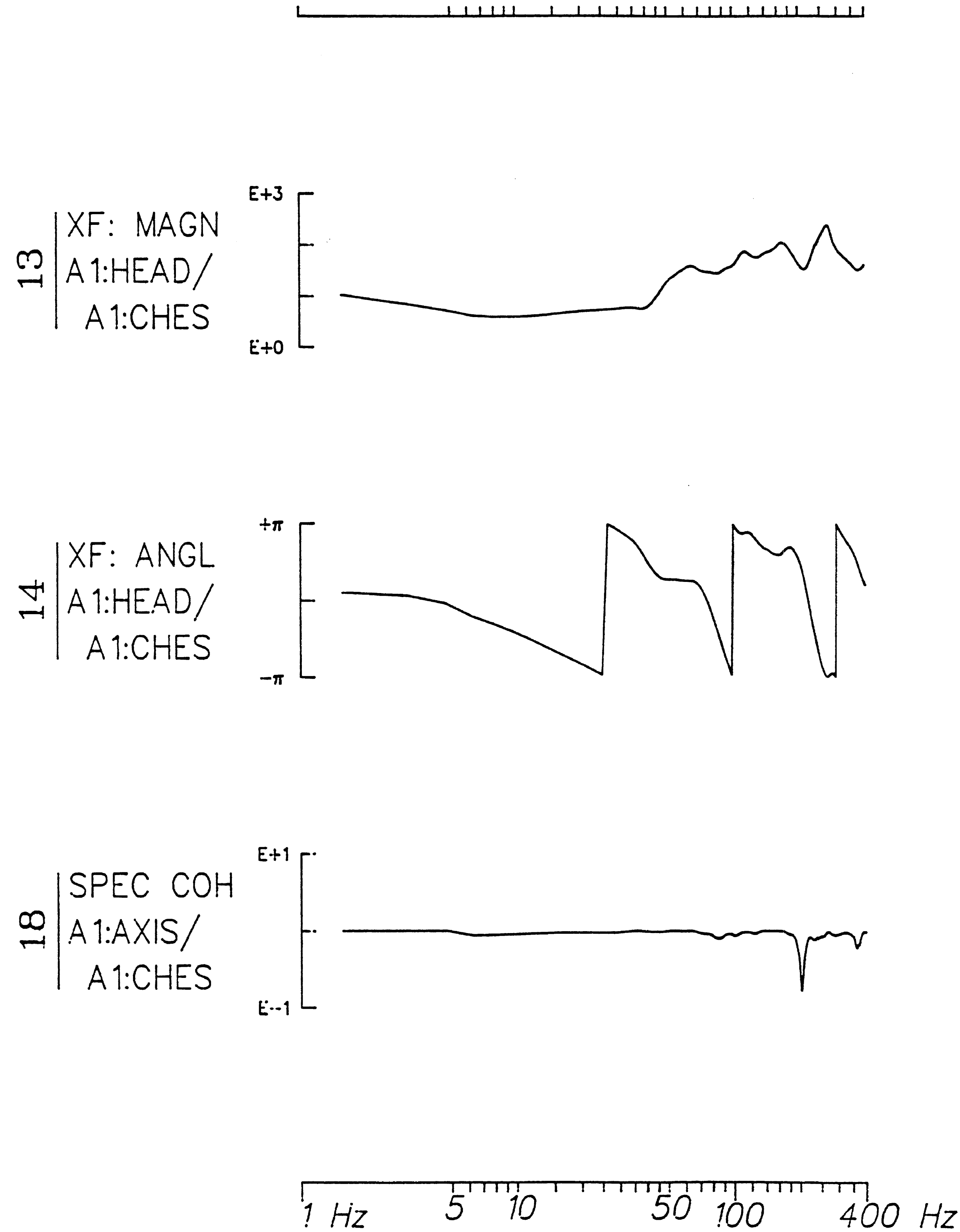

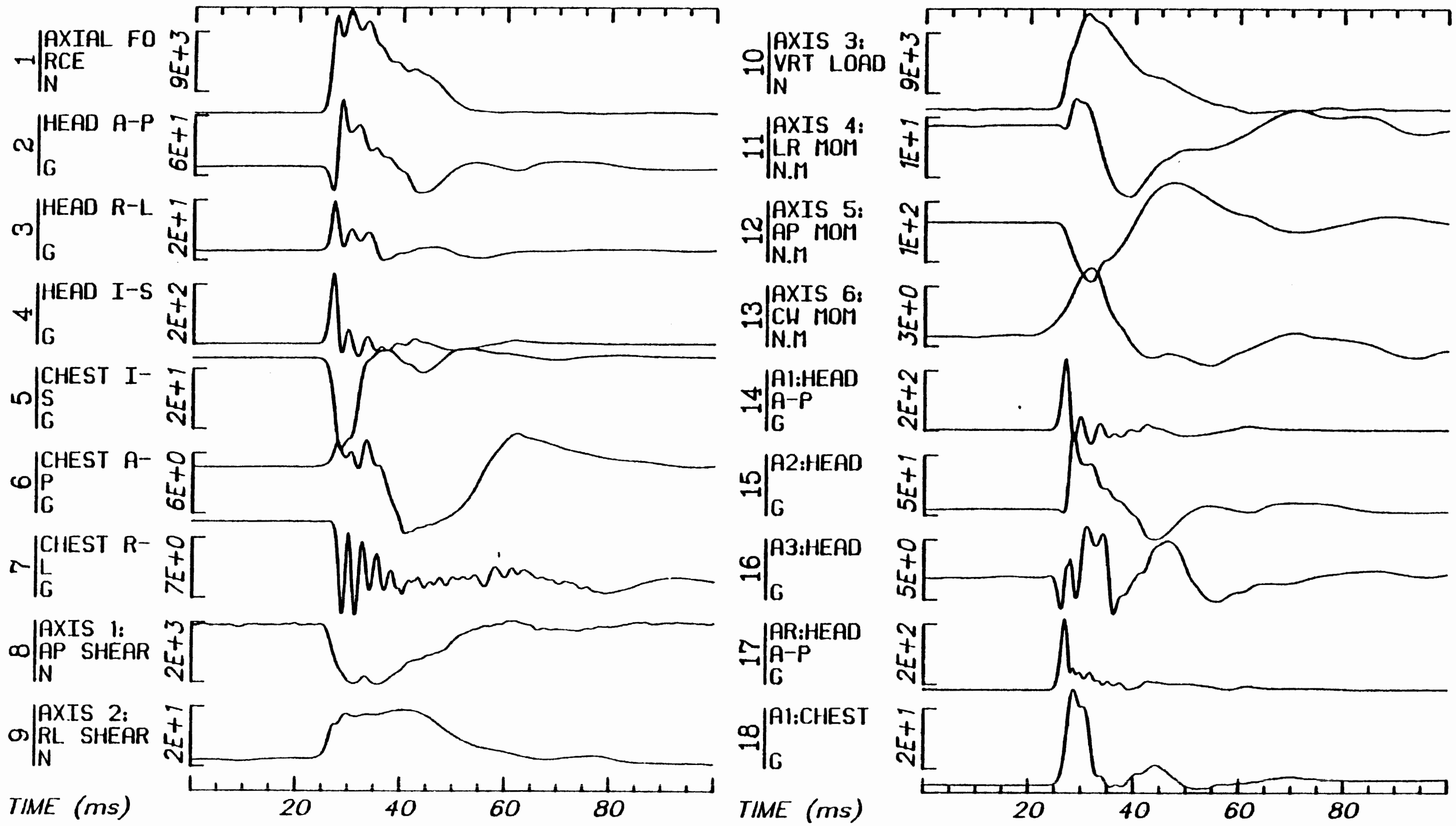

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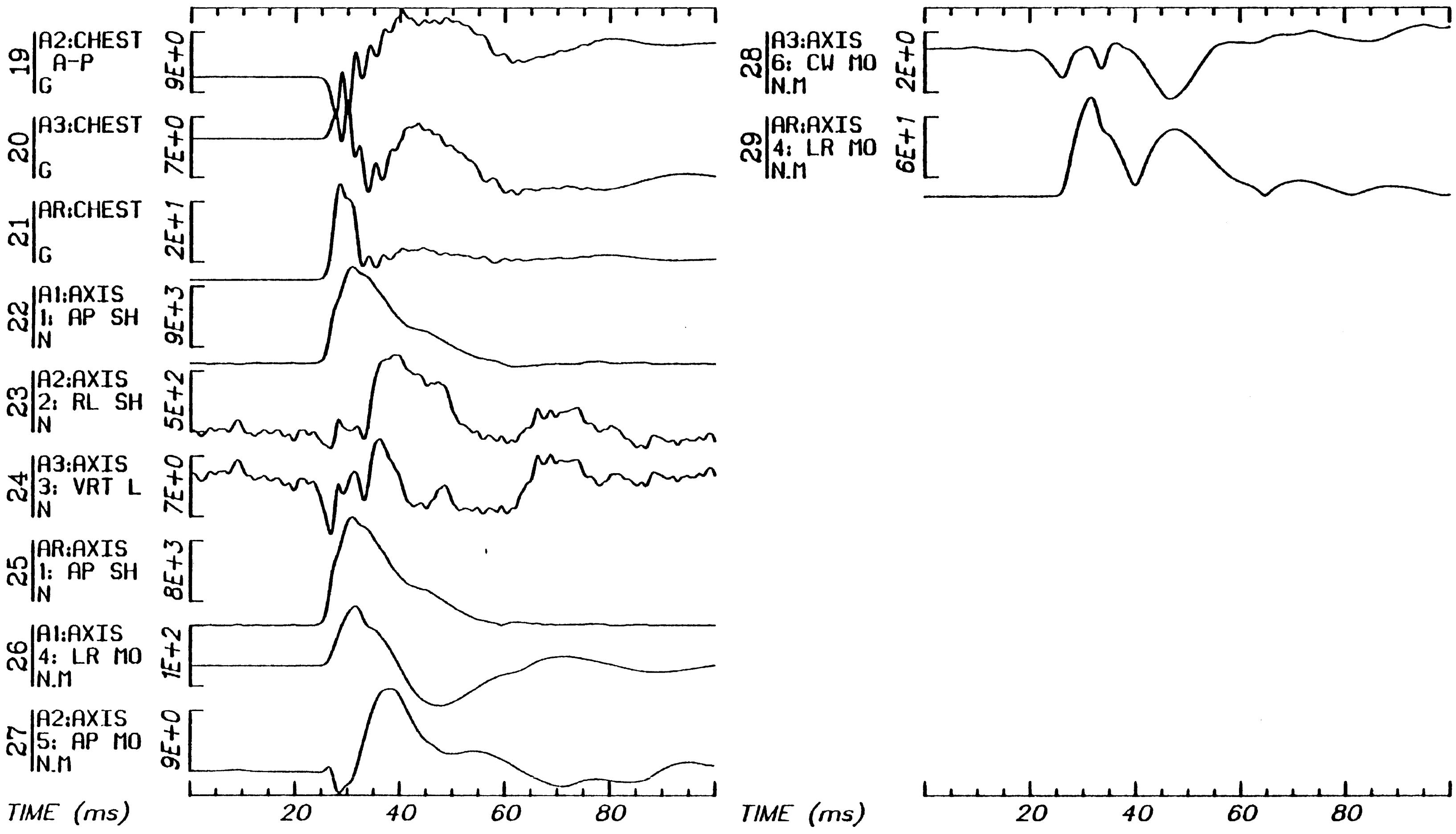

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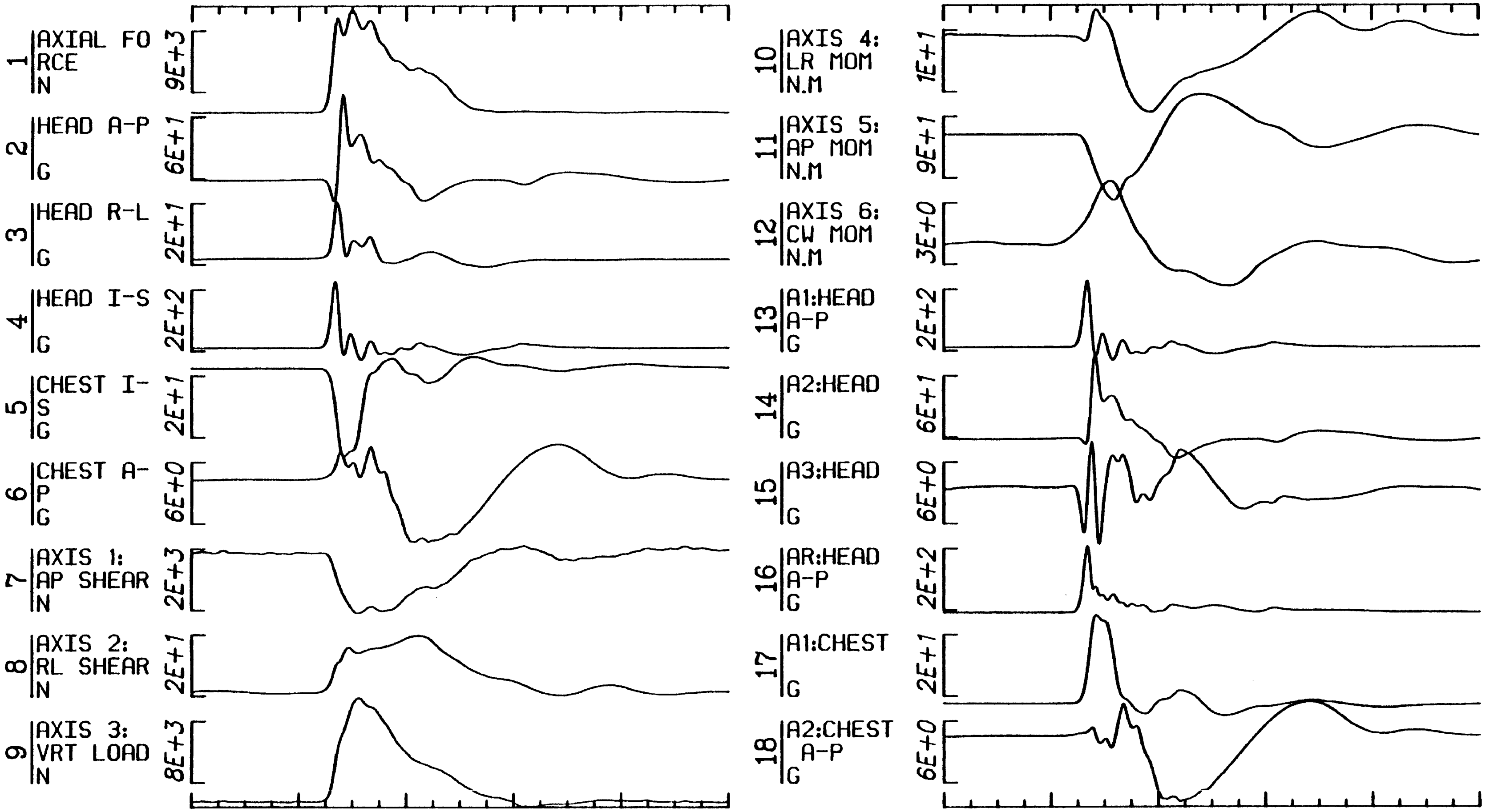

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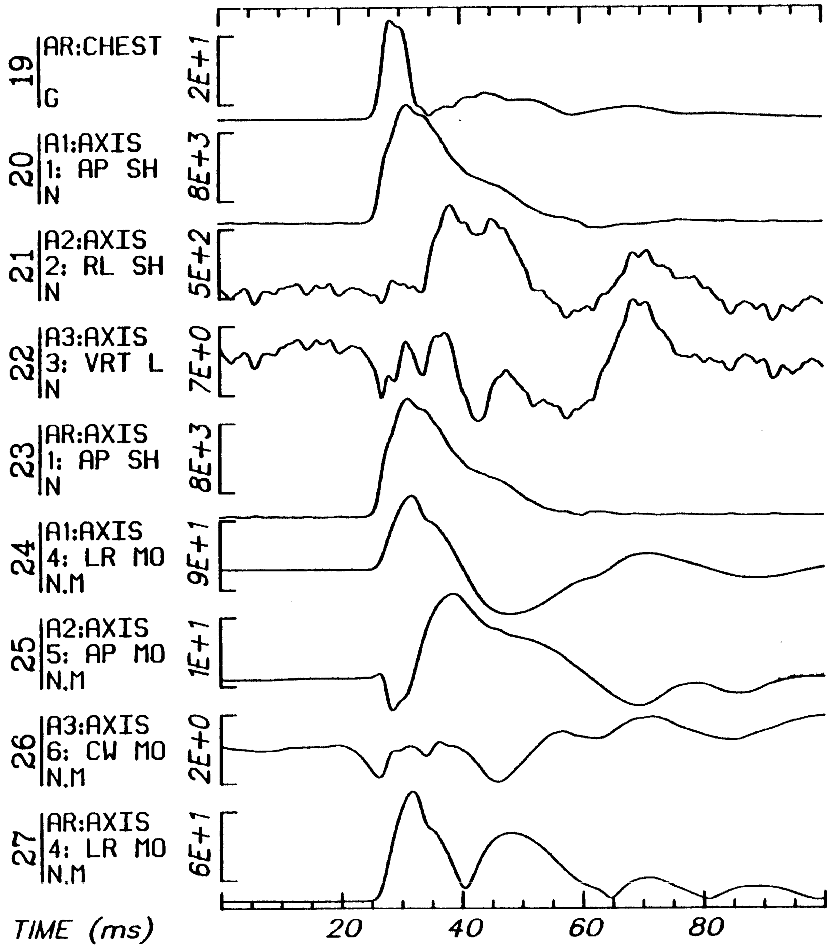

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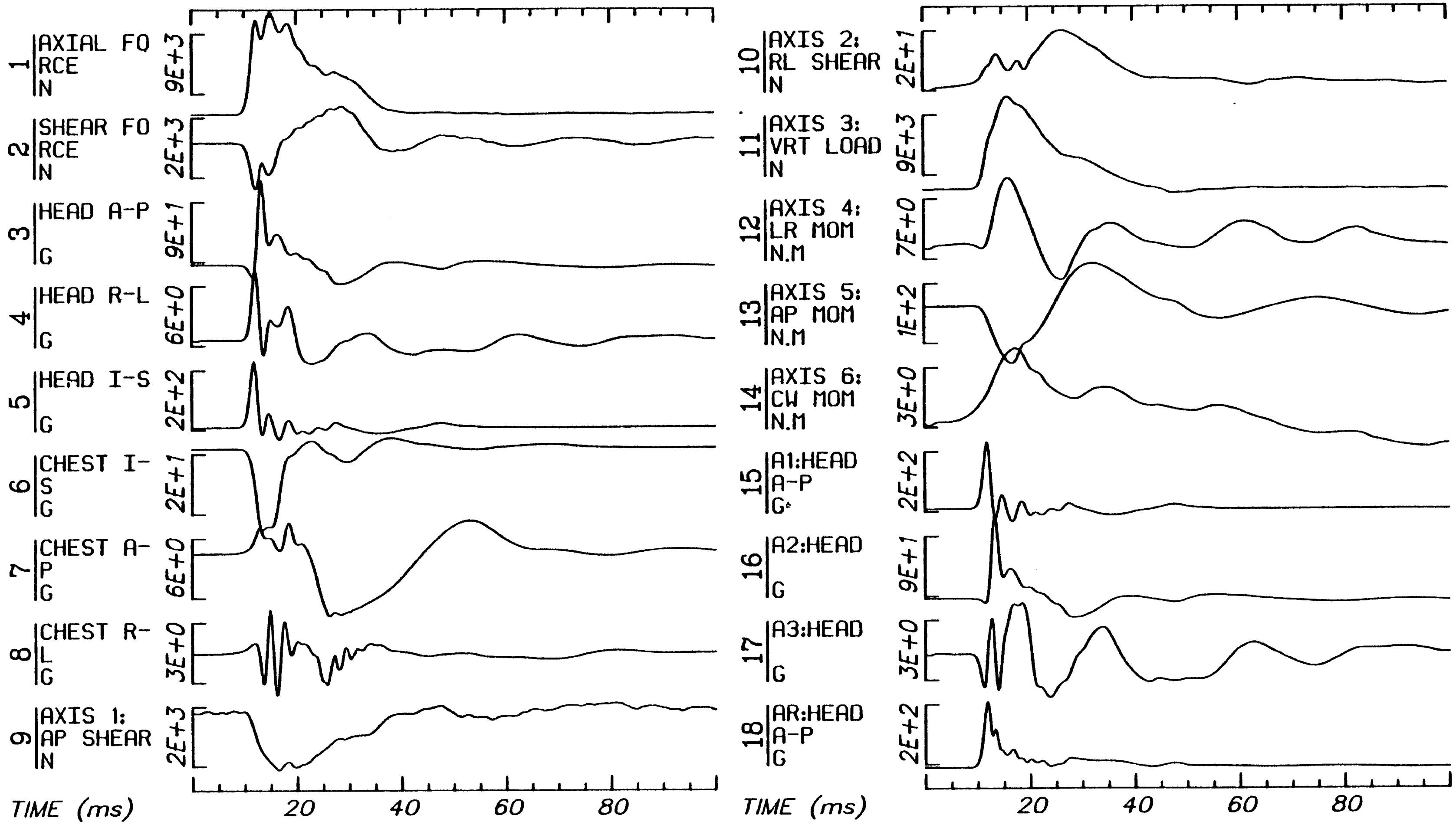

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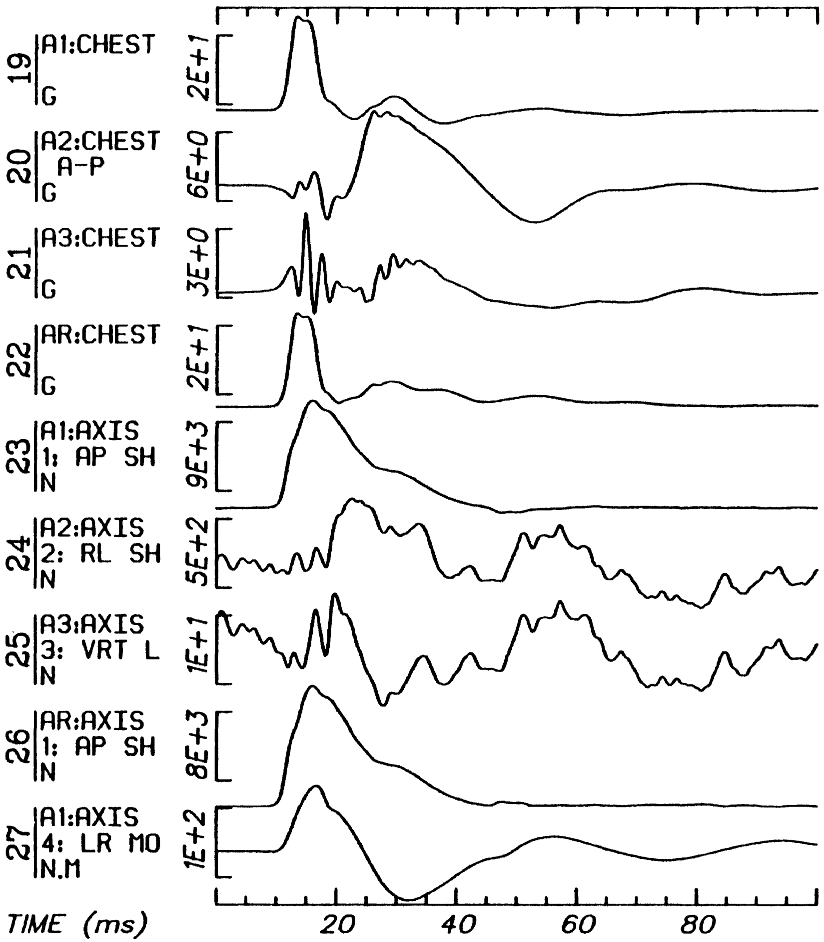

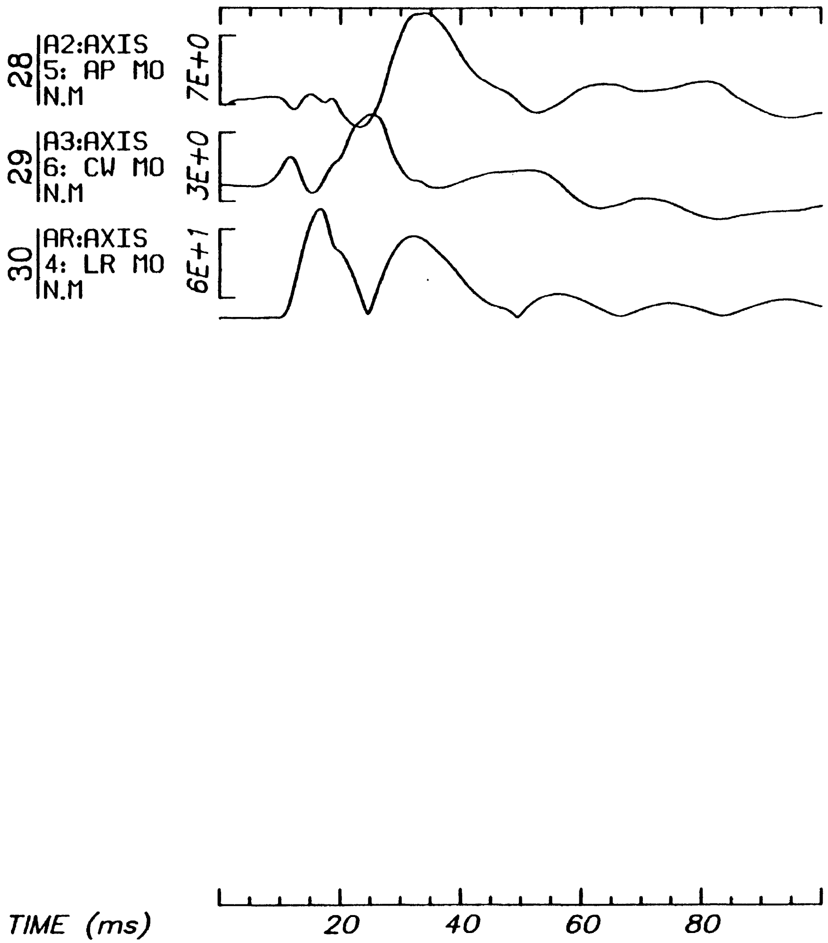

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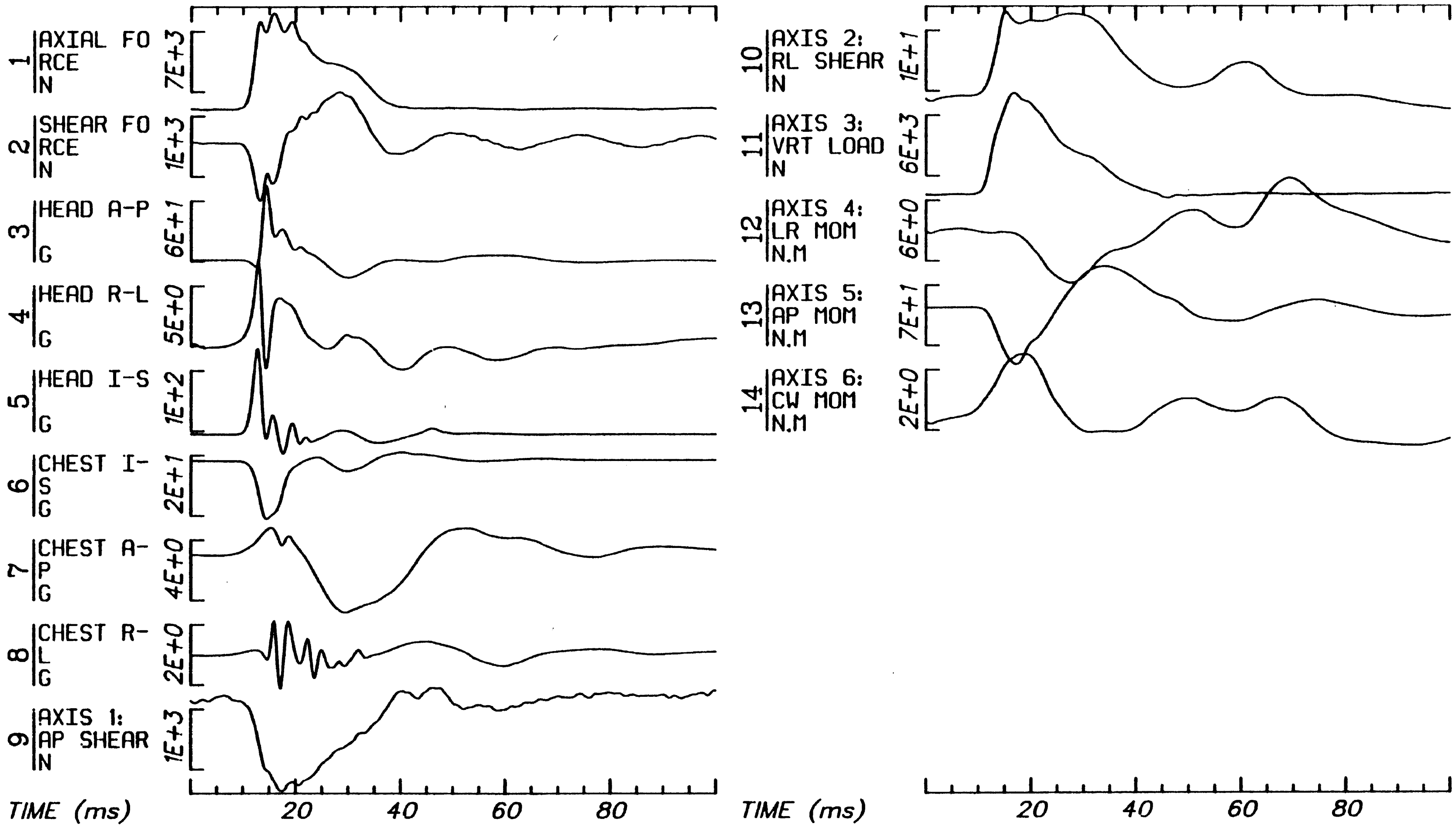

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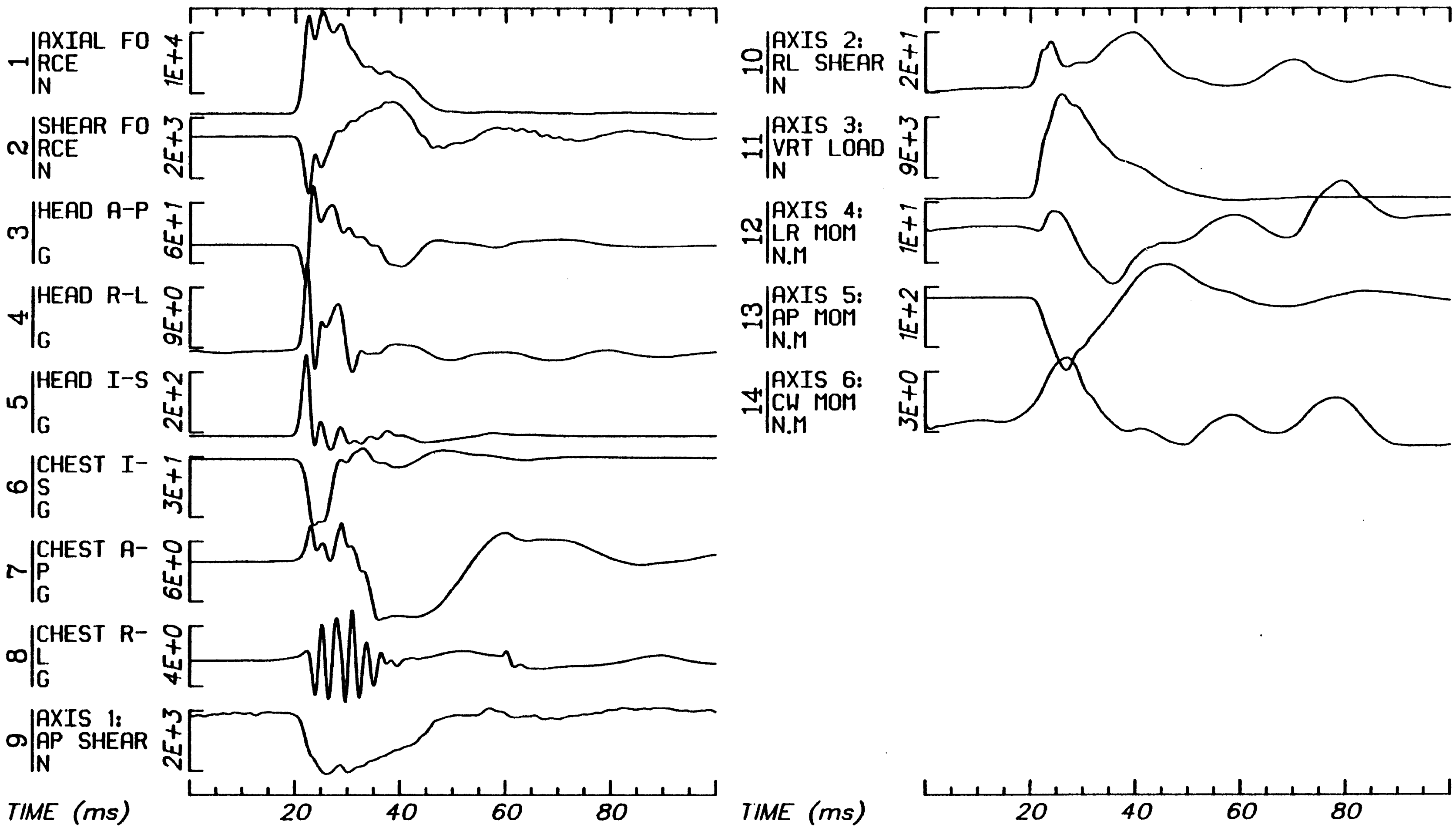

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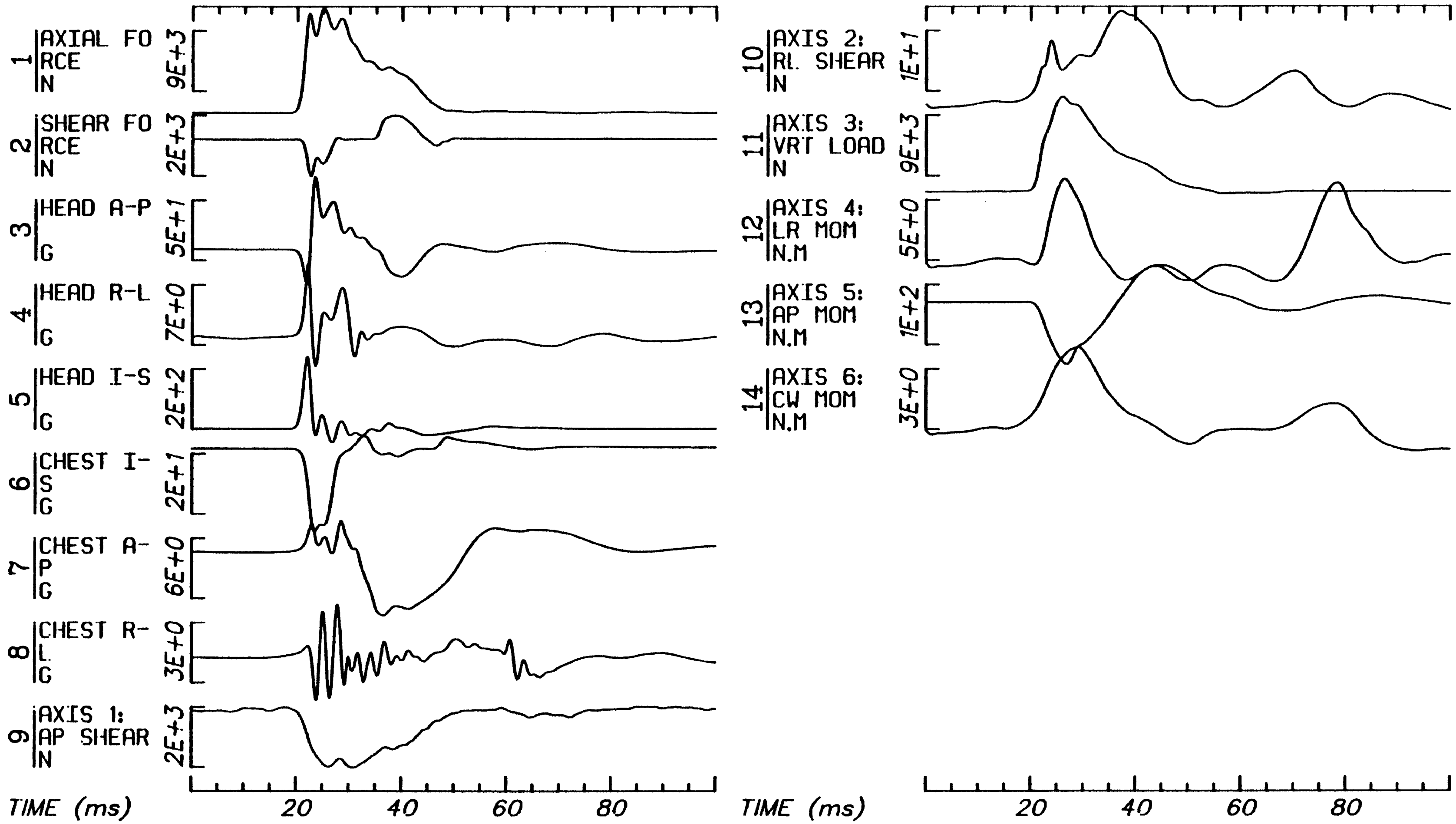

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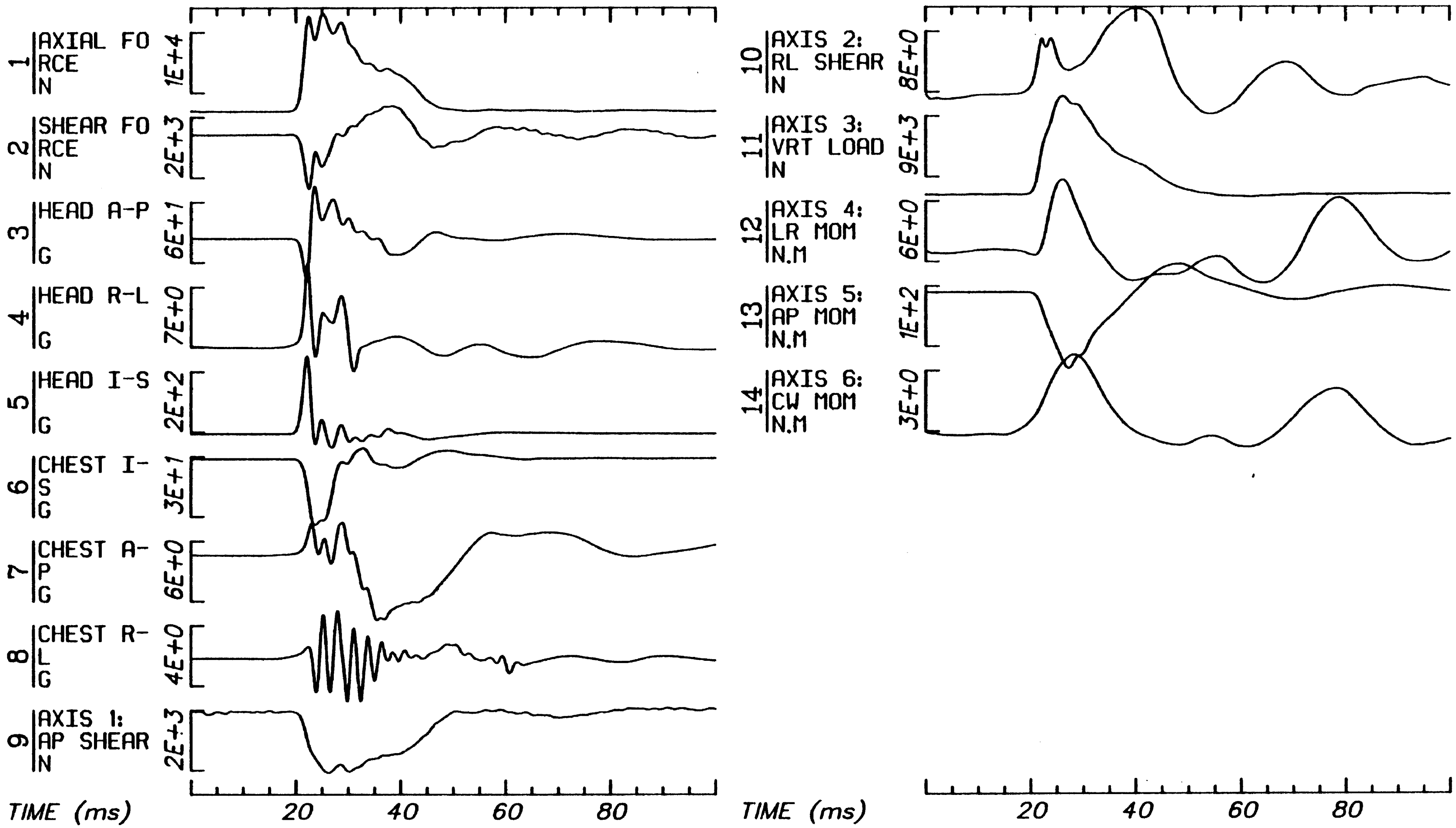

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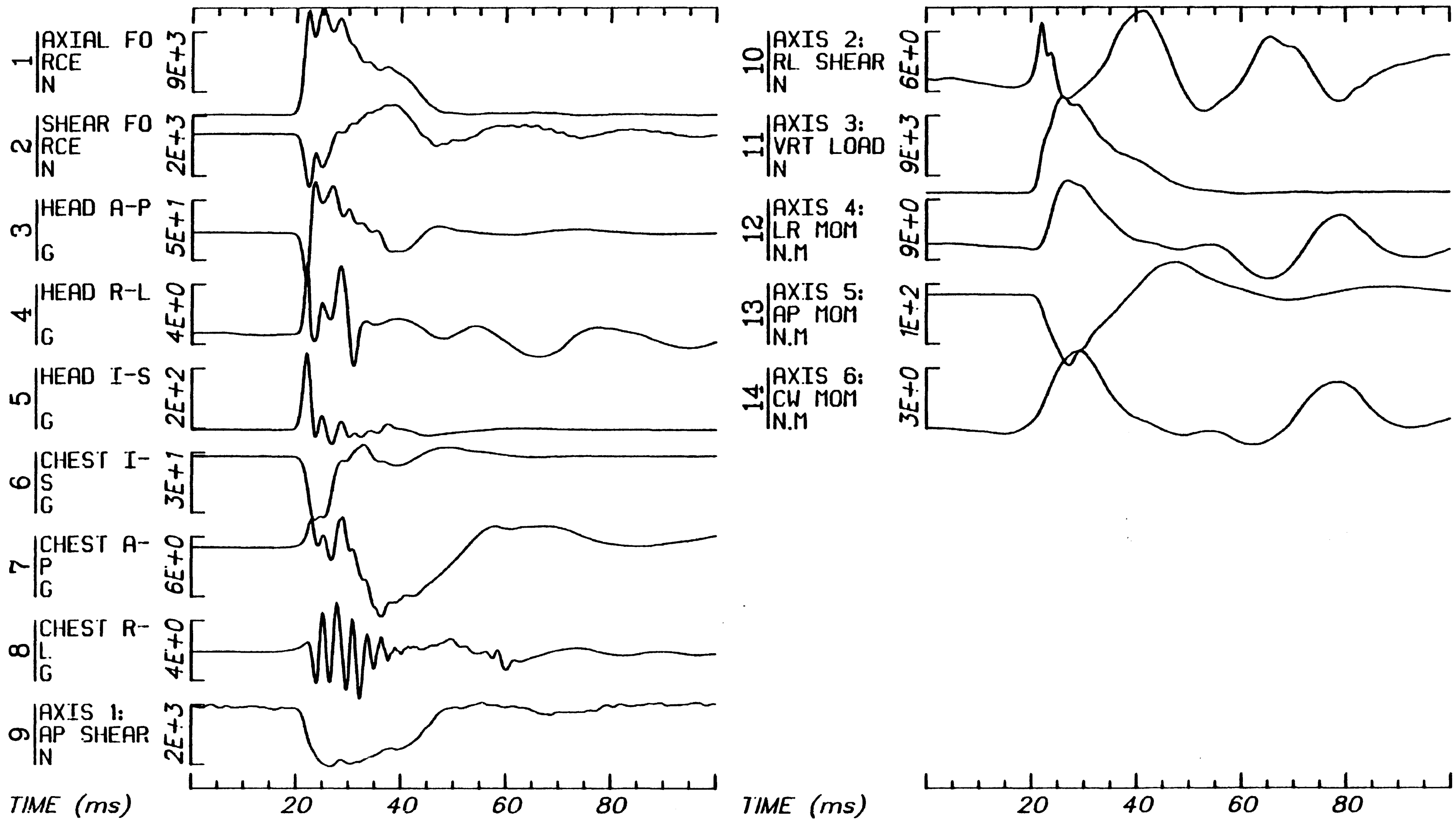

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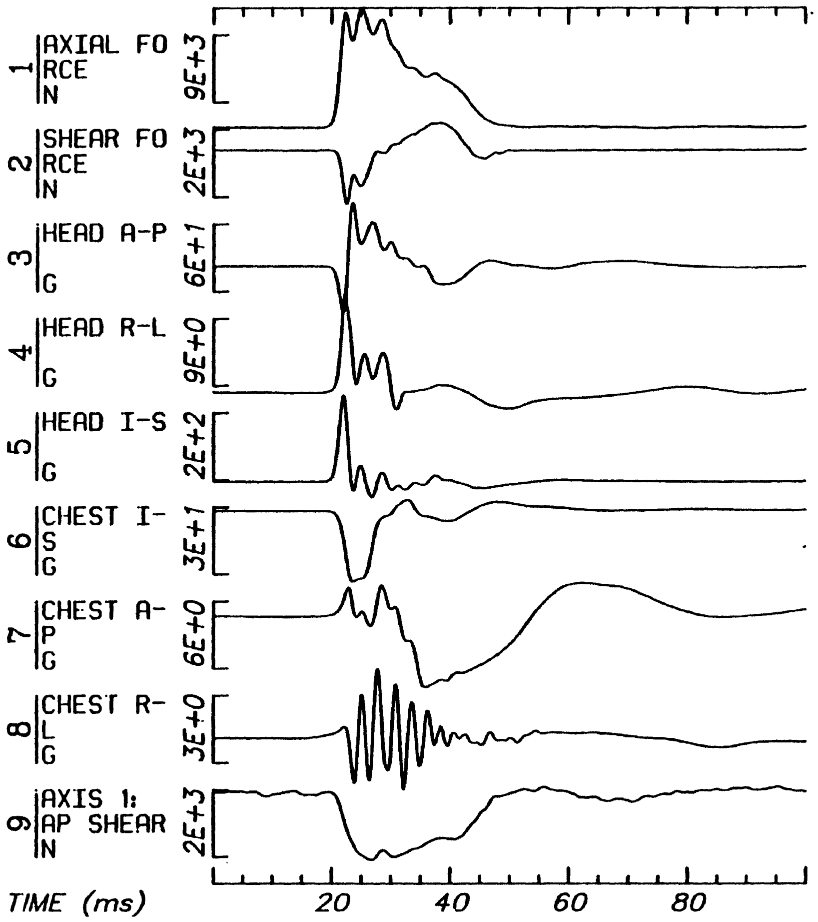

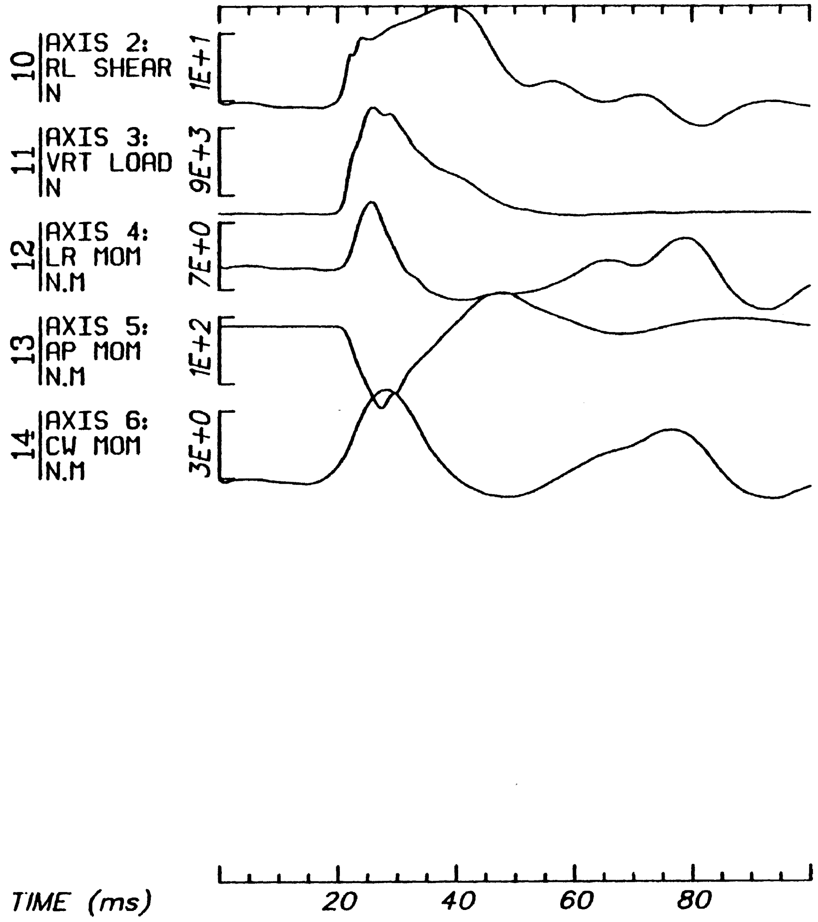

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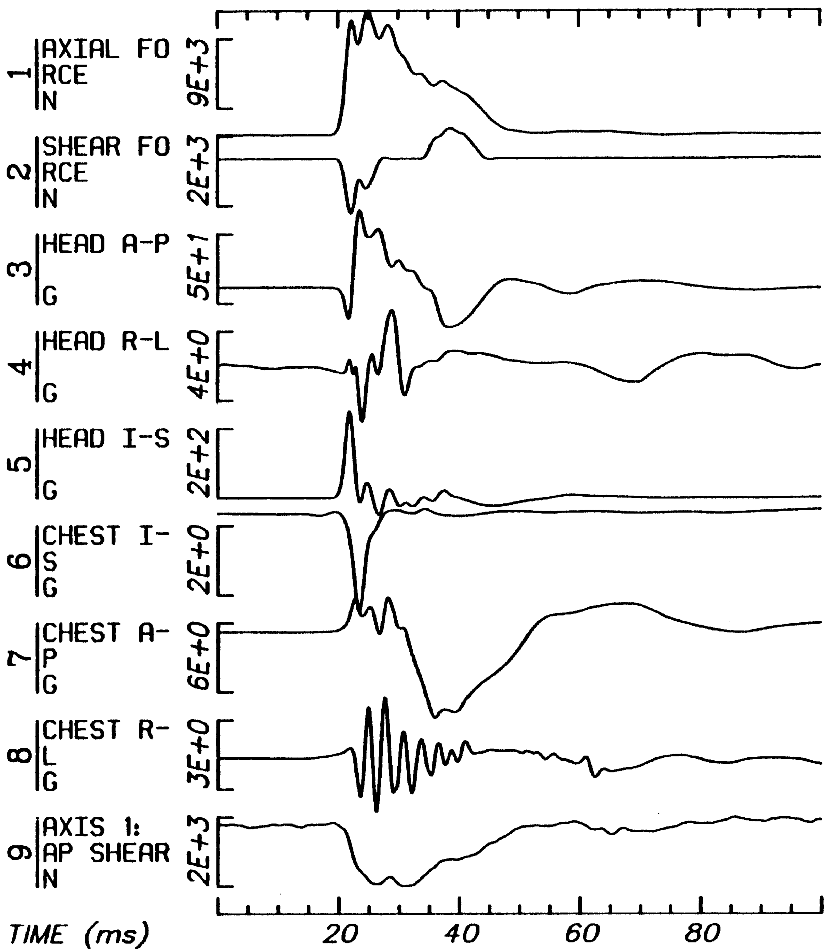

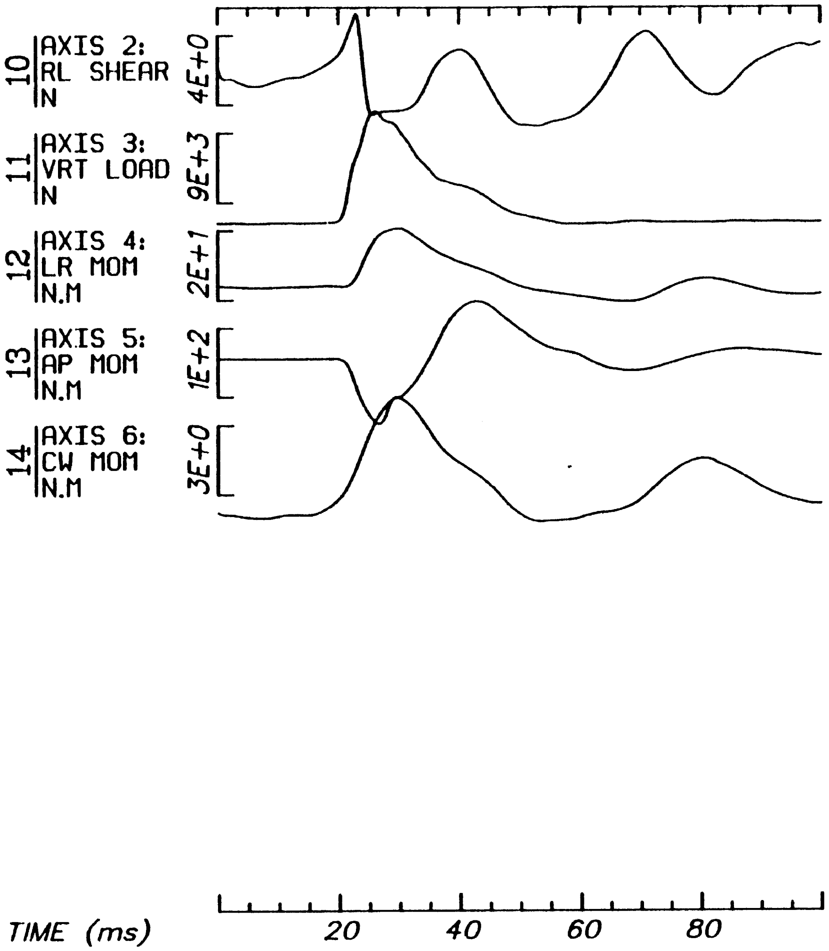

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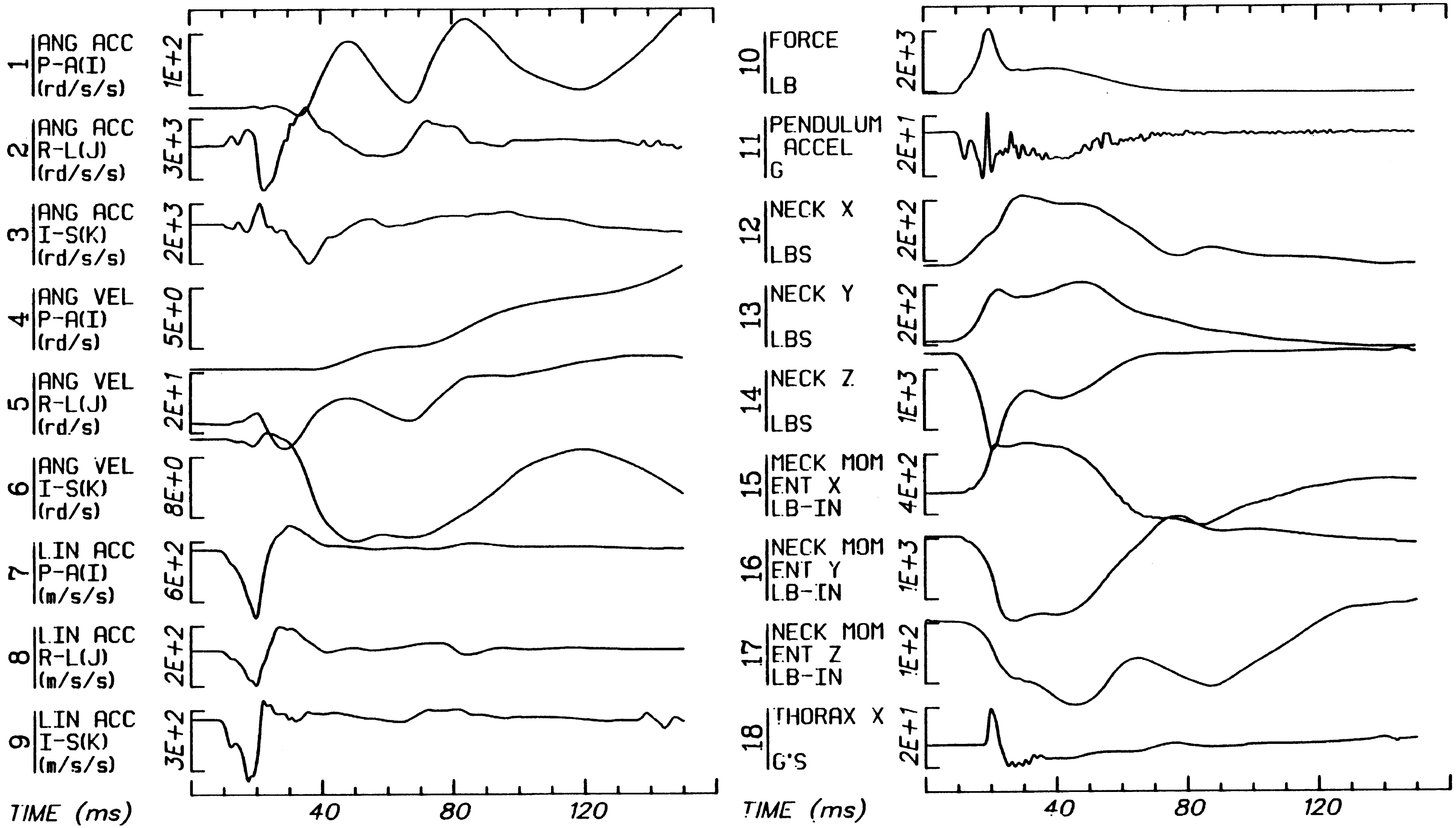
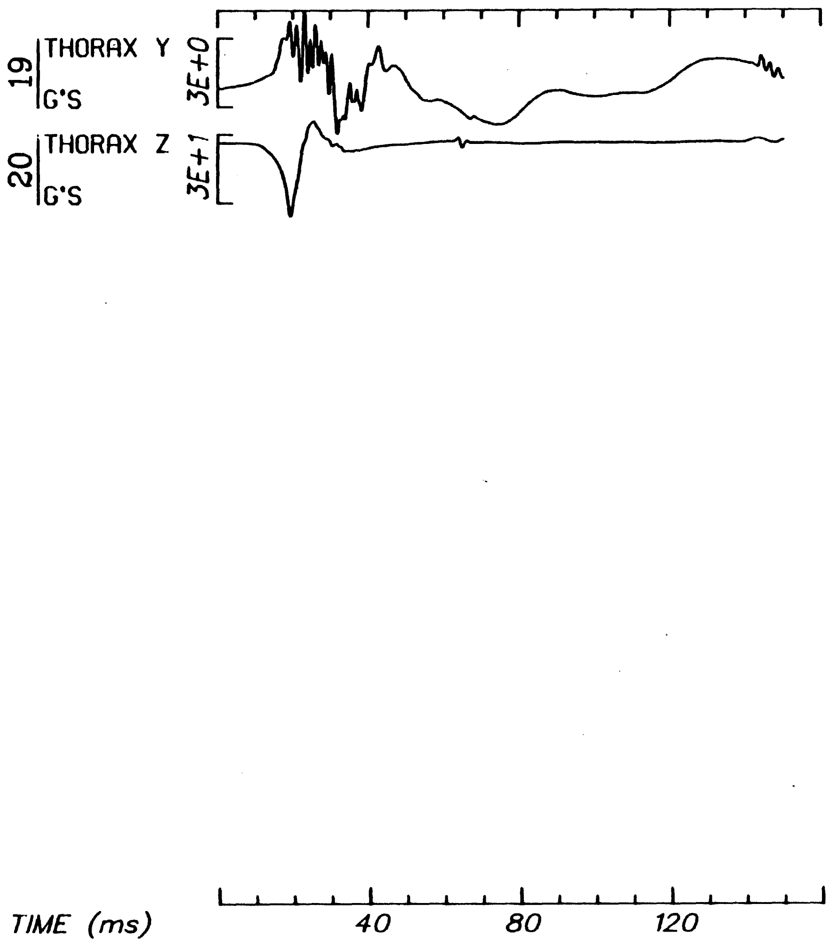


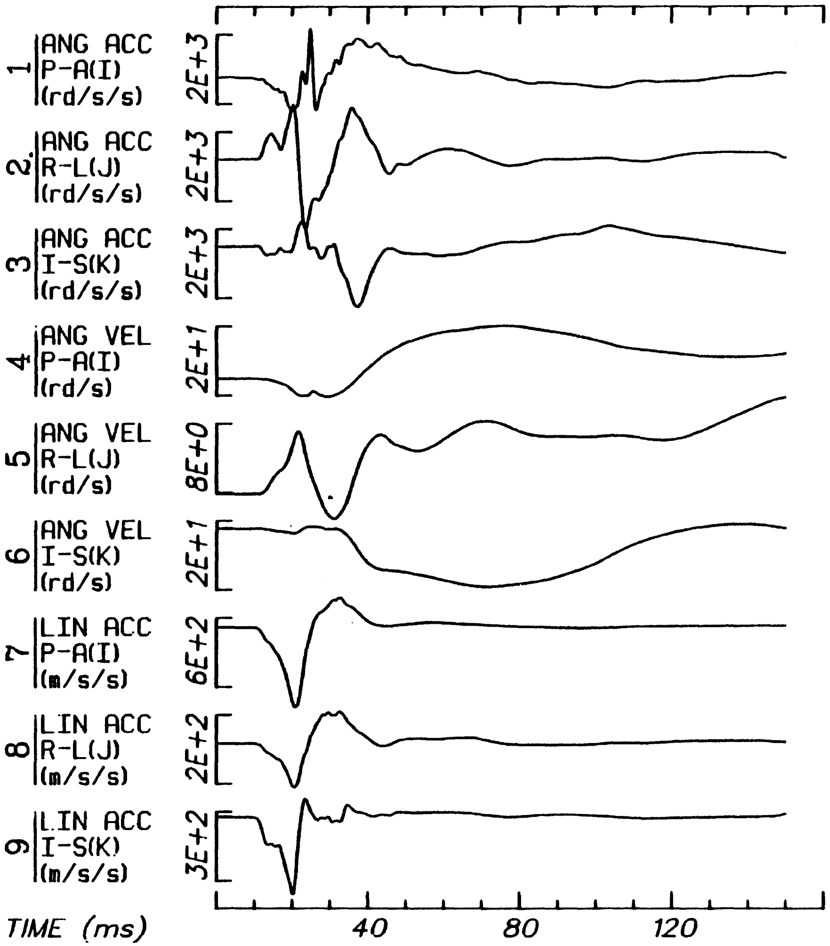
Run ID: 86L519 AH Disk: L519.GM File: 1 Date: AUG 13, 1986 Sheet: 1

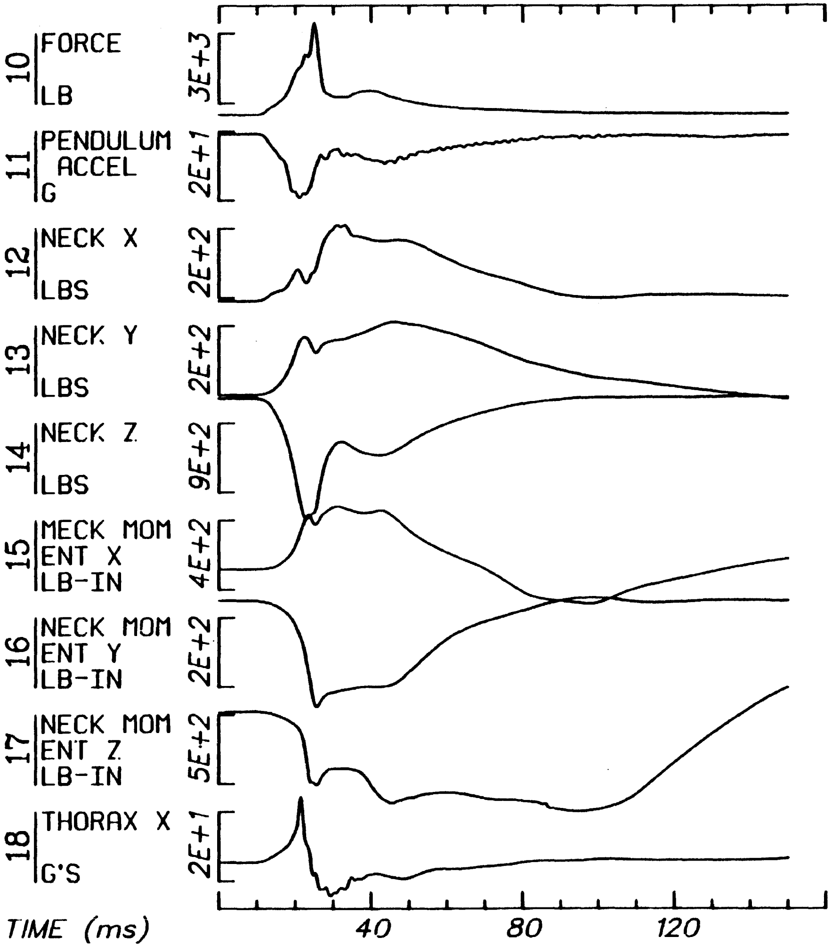
GM data for tape formatting



Run ID: 86L519 AH Disk: L519.GM File: 1 Date: AUG 13, 1986 Sheet: 2

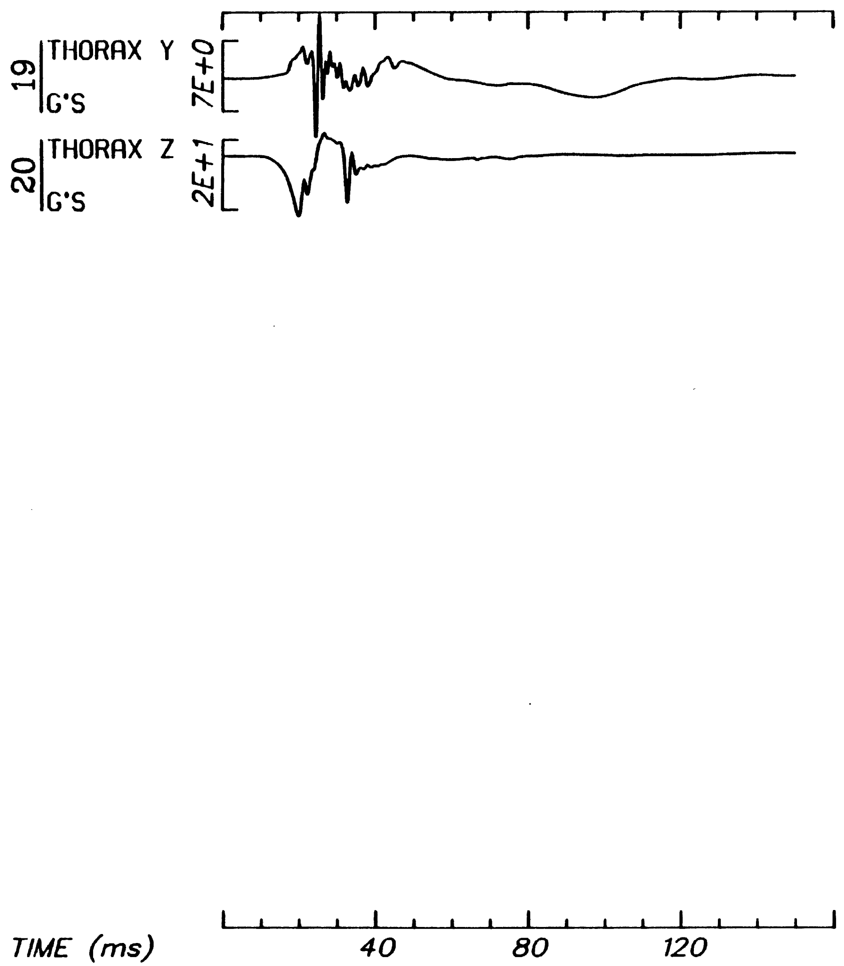
GM data for tape formatting





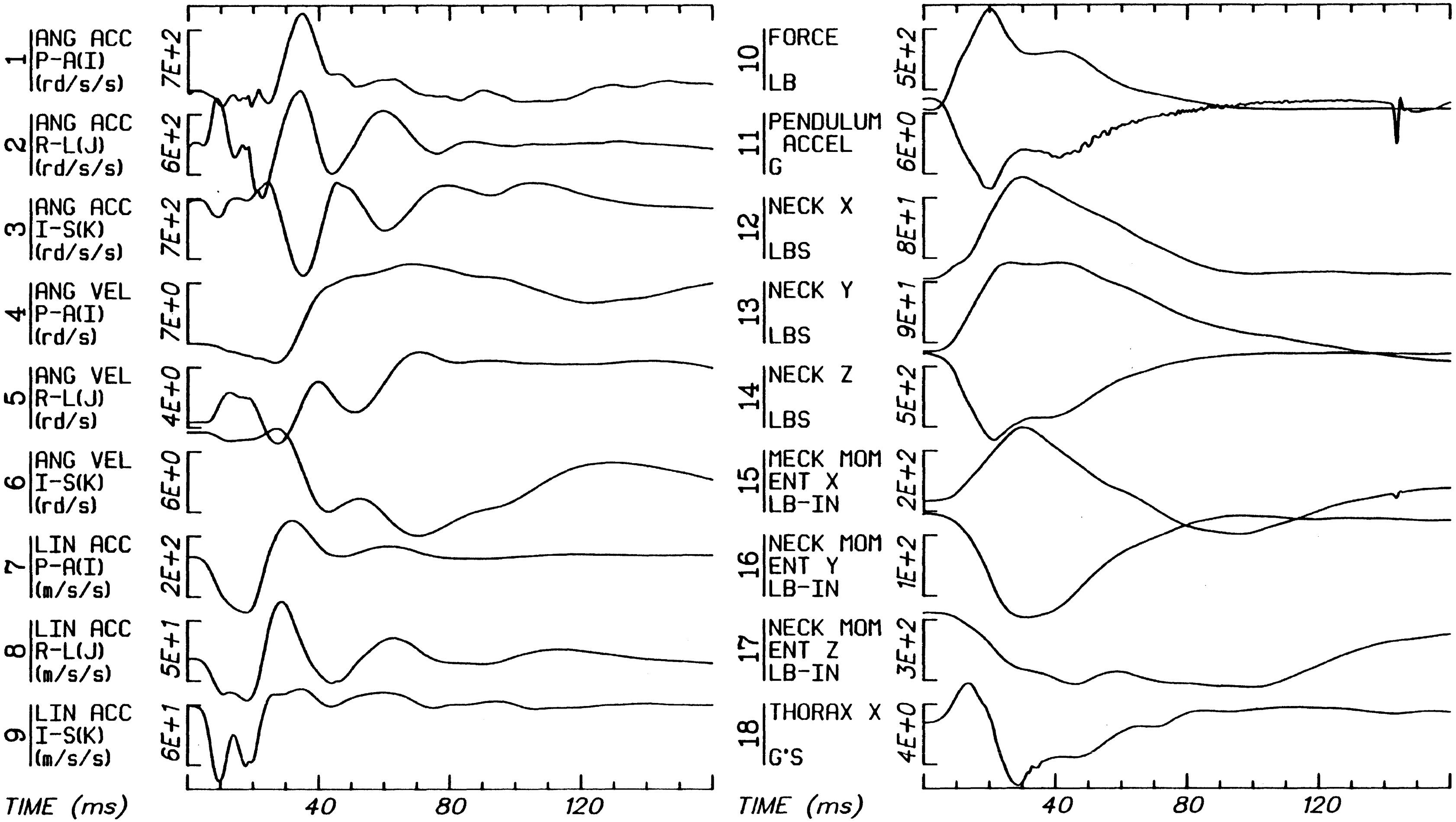
Run ID: 86L520 AH Disk: L520.GM File: 1 Date: AUG 13, 1986 Sheet: 1

GM data for tape formatting



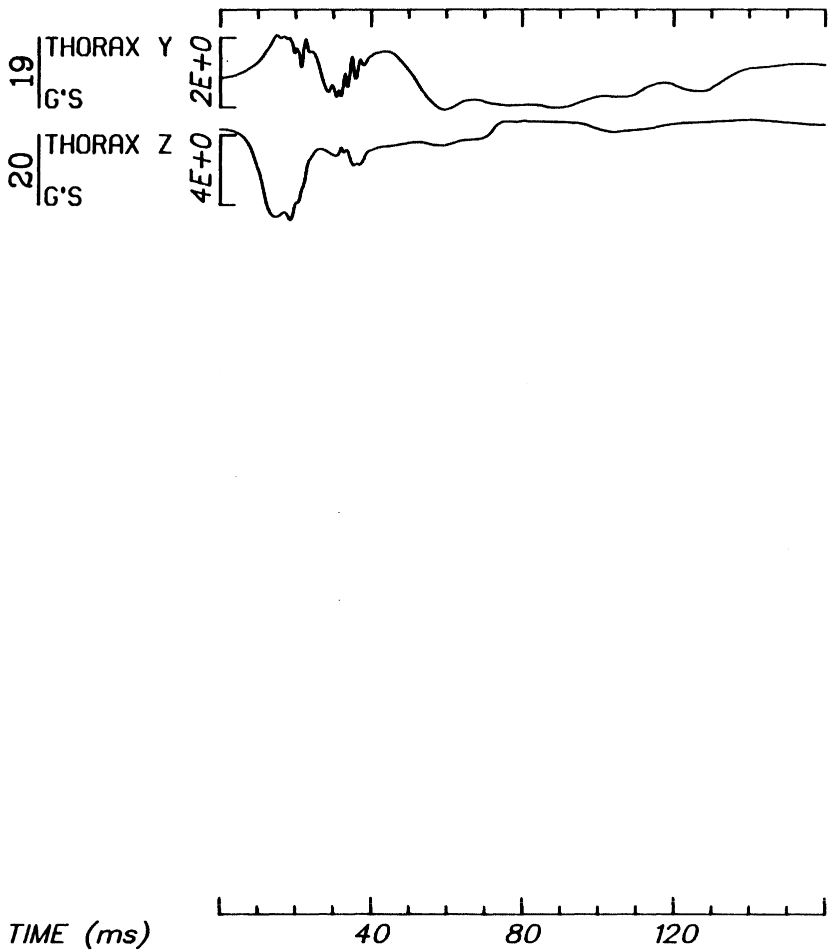
Run ID: 86L520 AH Disk: L520.GM File: 1 Date: AUG 13, 1986 Sheet: 2

GM data for tape formatting



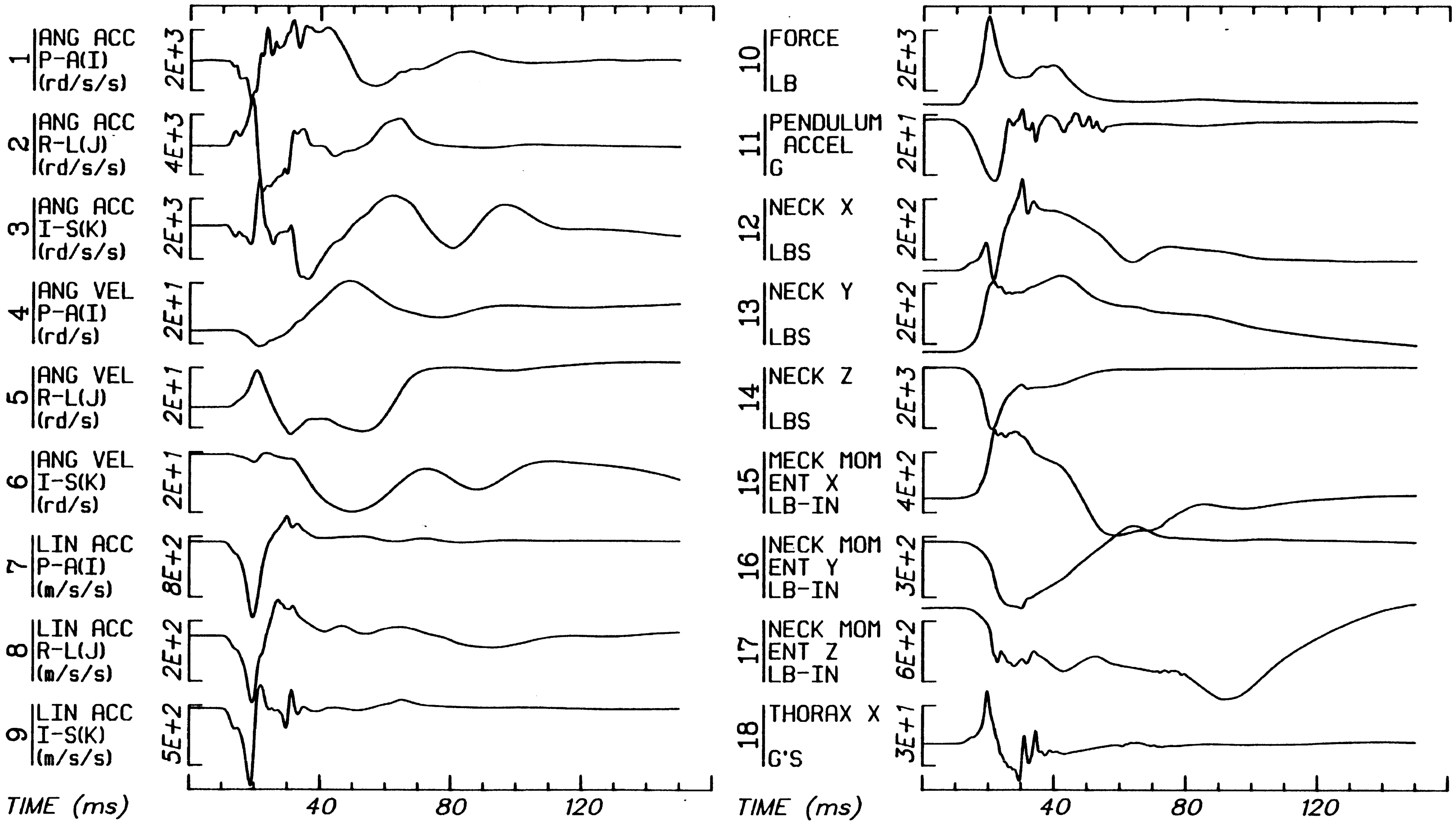
Run ID: 86L521 AH Disk: L521.GM File: 1 Date: AUG 13, 1986 Sheet: 1

GM data for tape formatting



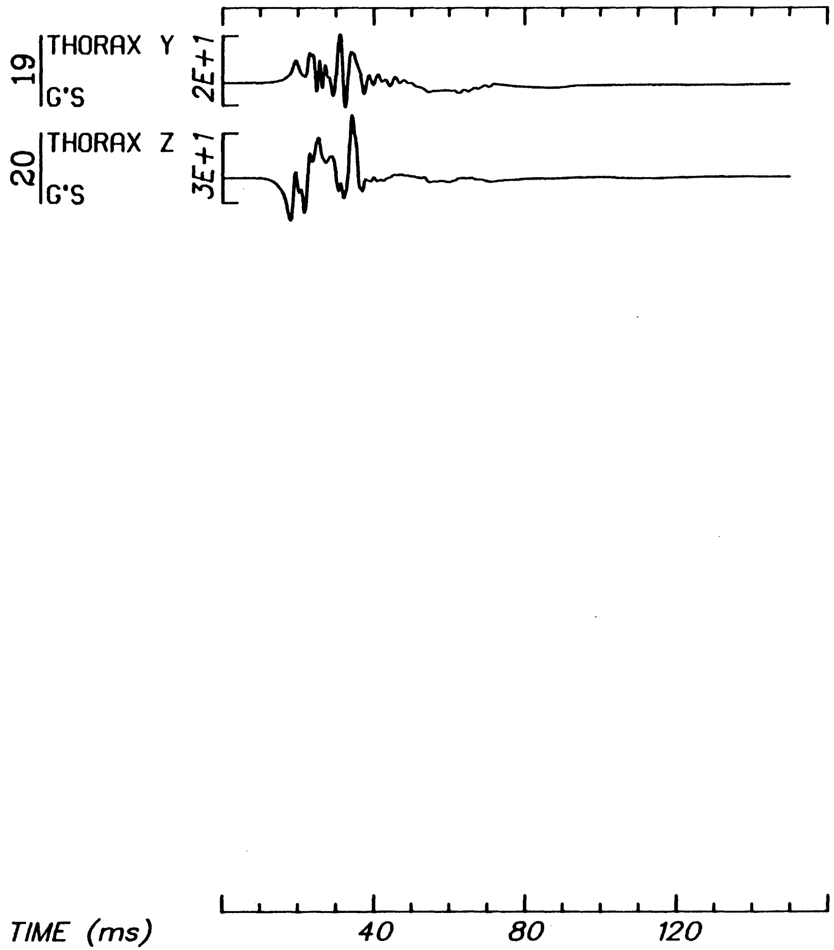
Run ID: 86L521 AH Disk: L521.GM File: 1 Date: AUG 13, 1986 Sheet: 2

GM data for tape formatting



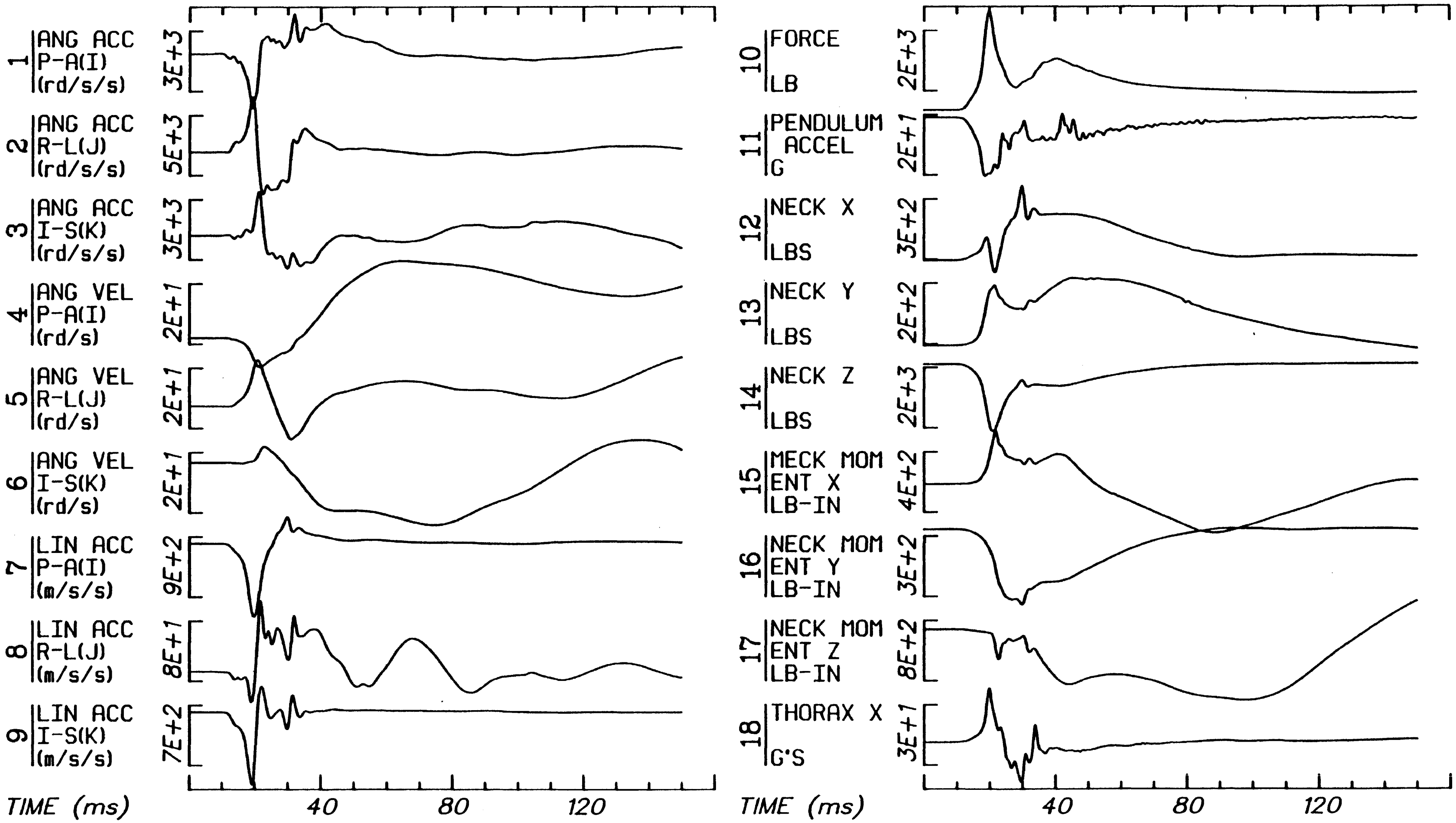
Run ID: 86L522 AH Disk: L522.GM File: 1 Date: AUG 13, 1986 Sheet: 1

GM data for tape formatting



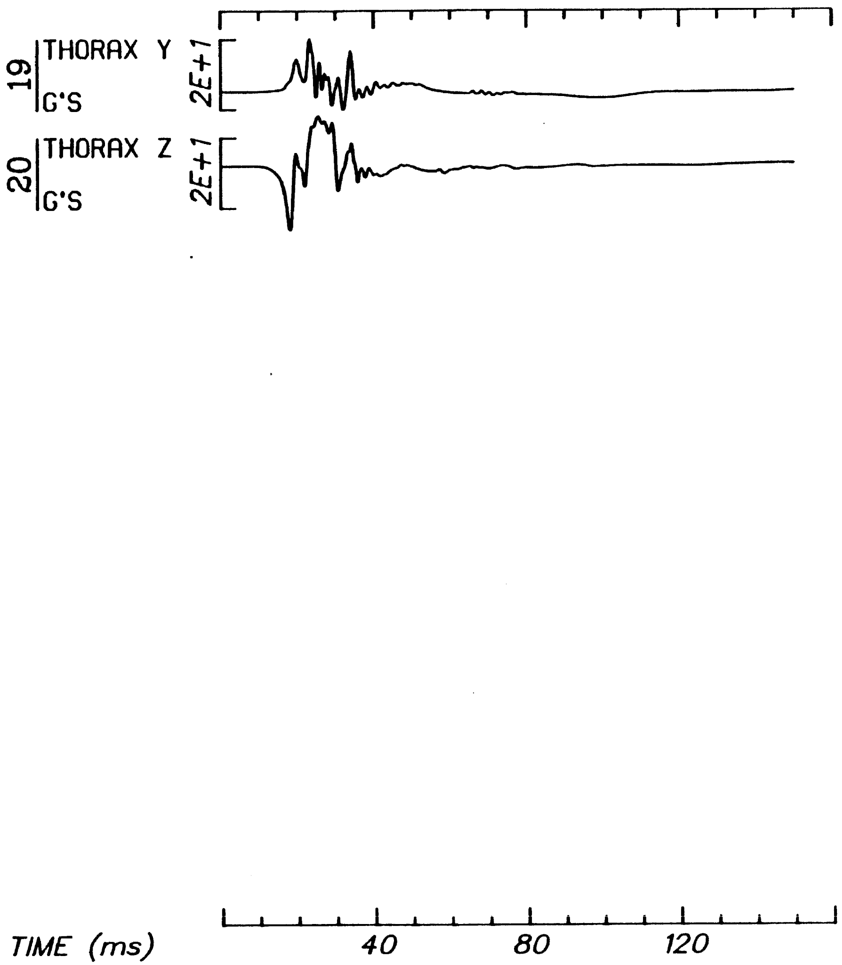
Run ID: 86L522 AH Disk: L522.GM File: 1 Date: AUG 13, 1986 Sheet: 2

GM data for tape formatting



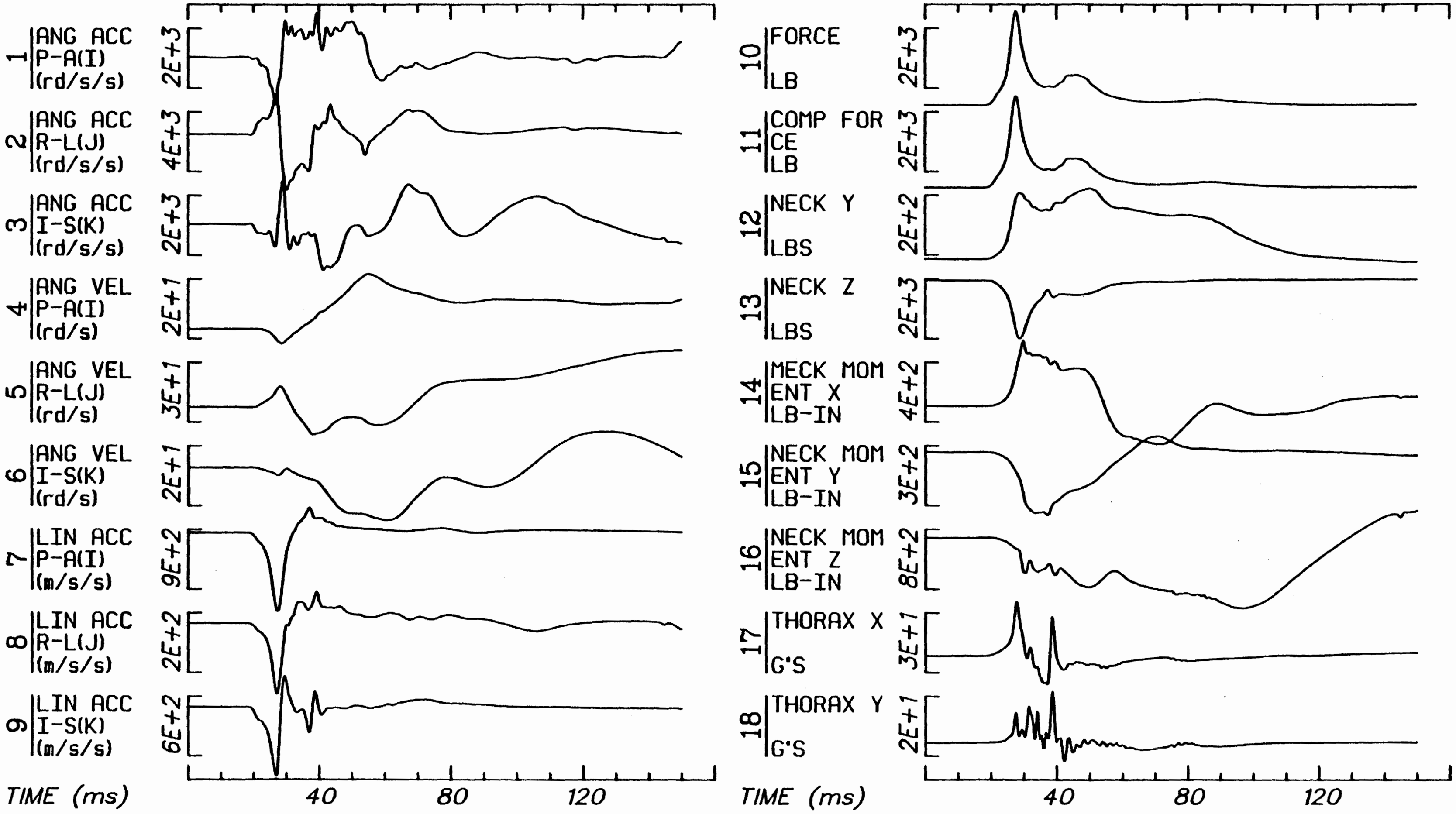
Run ID: 86L524 AH Disk: L524.GM File: 1 Date: AUG 13, 1986 Sheet: 1

GM data for tape formatting



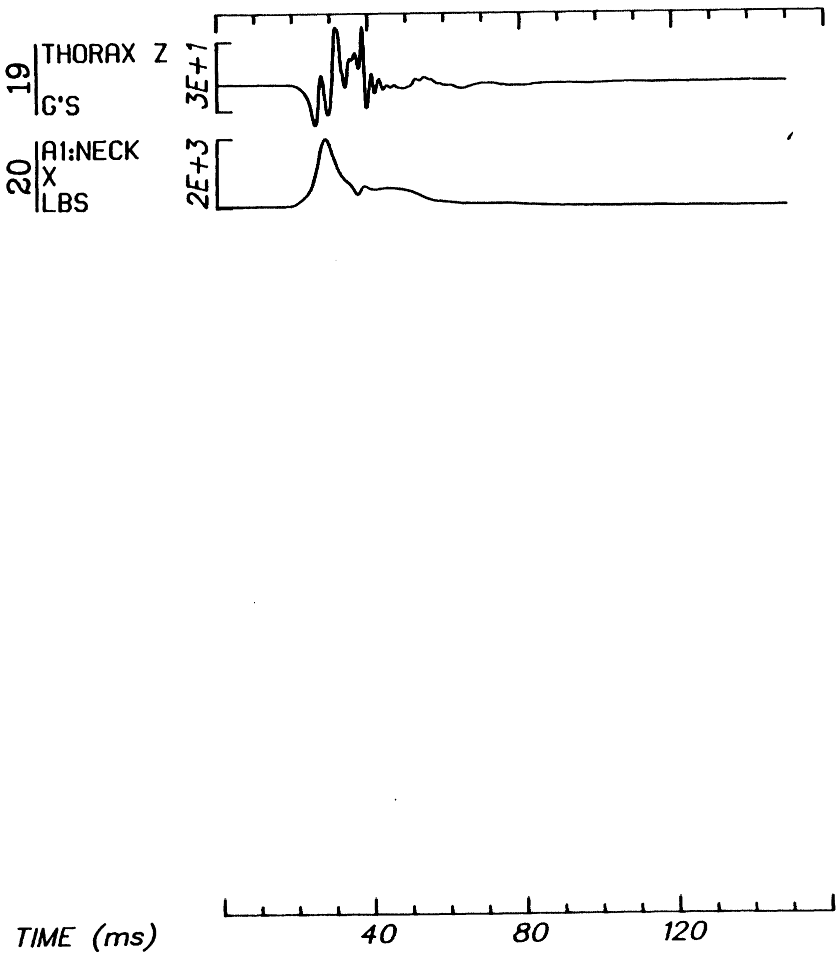
Run ID: 86L524 AH Disk: L524.GM File: 1 Date: AUG 13, 1986 Sheet: 2

GM data for tape formatting



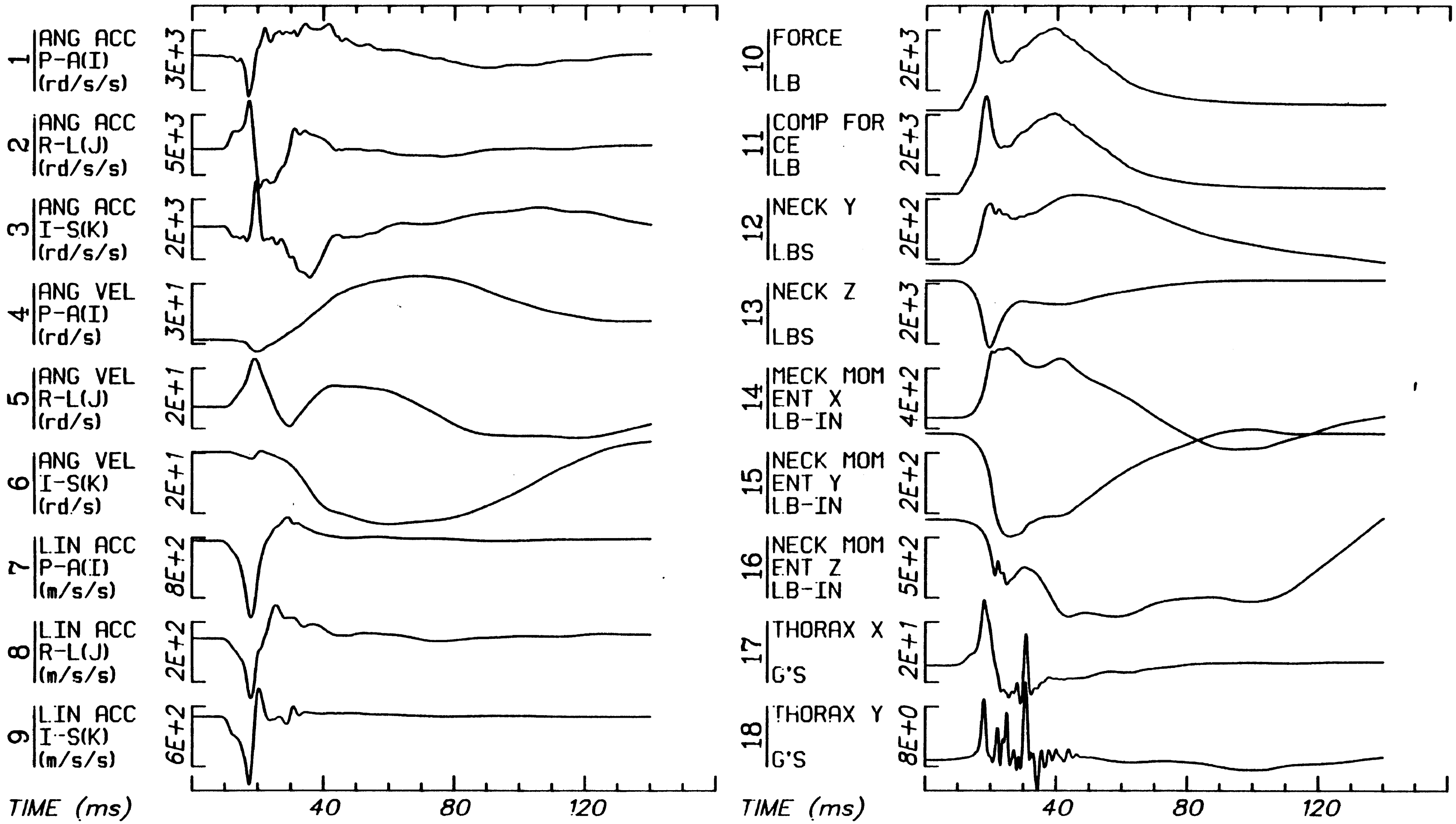
Run ID: 86L525 AH Disk: L525.GM File: 1 Date: AUG 13, 1986 Sheet: 1

GM data for tape formatting



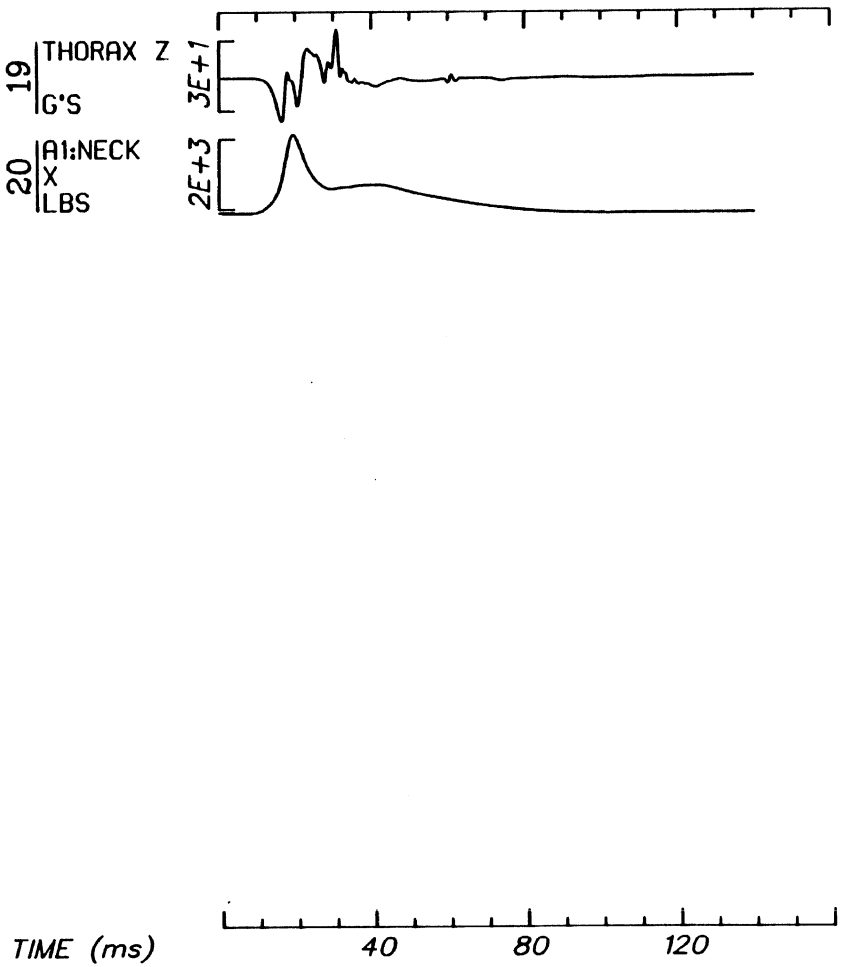
Run ID: 86L525 AH Disk: L525.GM File: 1 Date: AUG 13, 1986 Sheet: 2

GM data for tape formatting



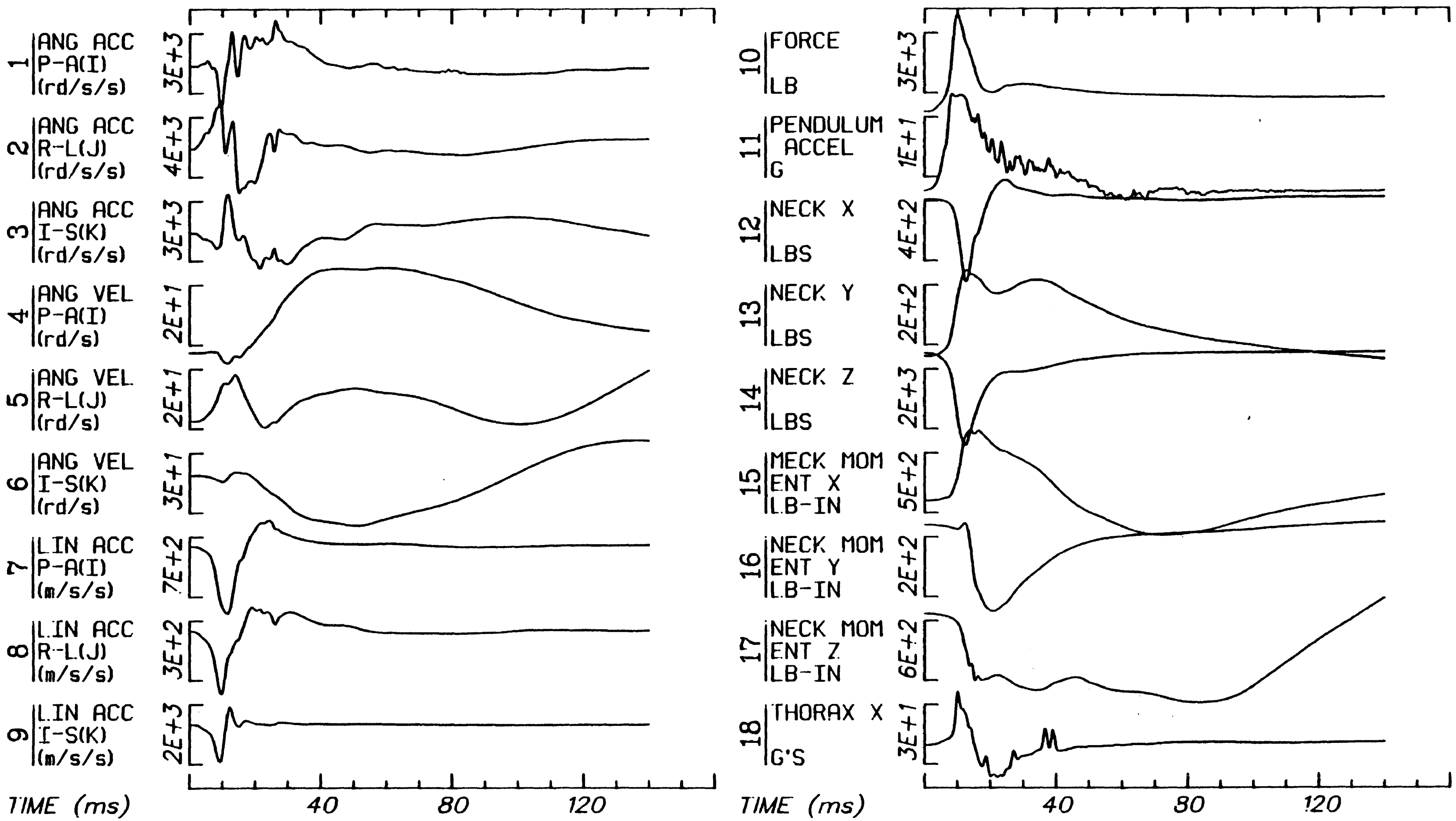
Run ID: 86L526 AH Disk: L526.GM File: 1 Date: AUG 13, 1986 Sheet: 1

GM data for tape formatting



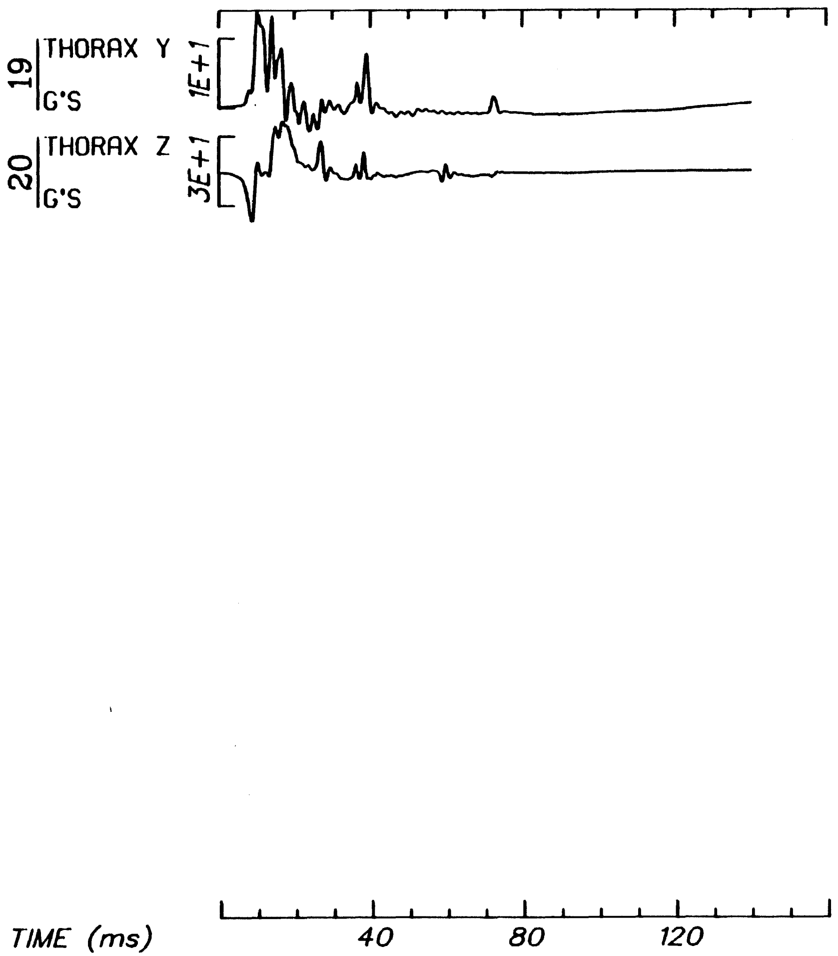
Run ID: 86L526 AH Disk: L526.GM File: 1 Date: AUG 13, 1986 Sheet: 2

GM data for tape formatting



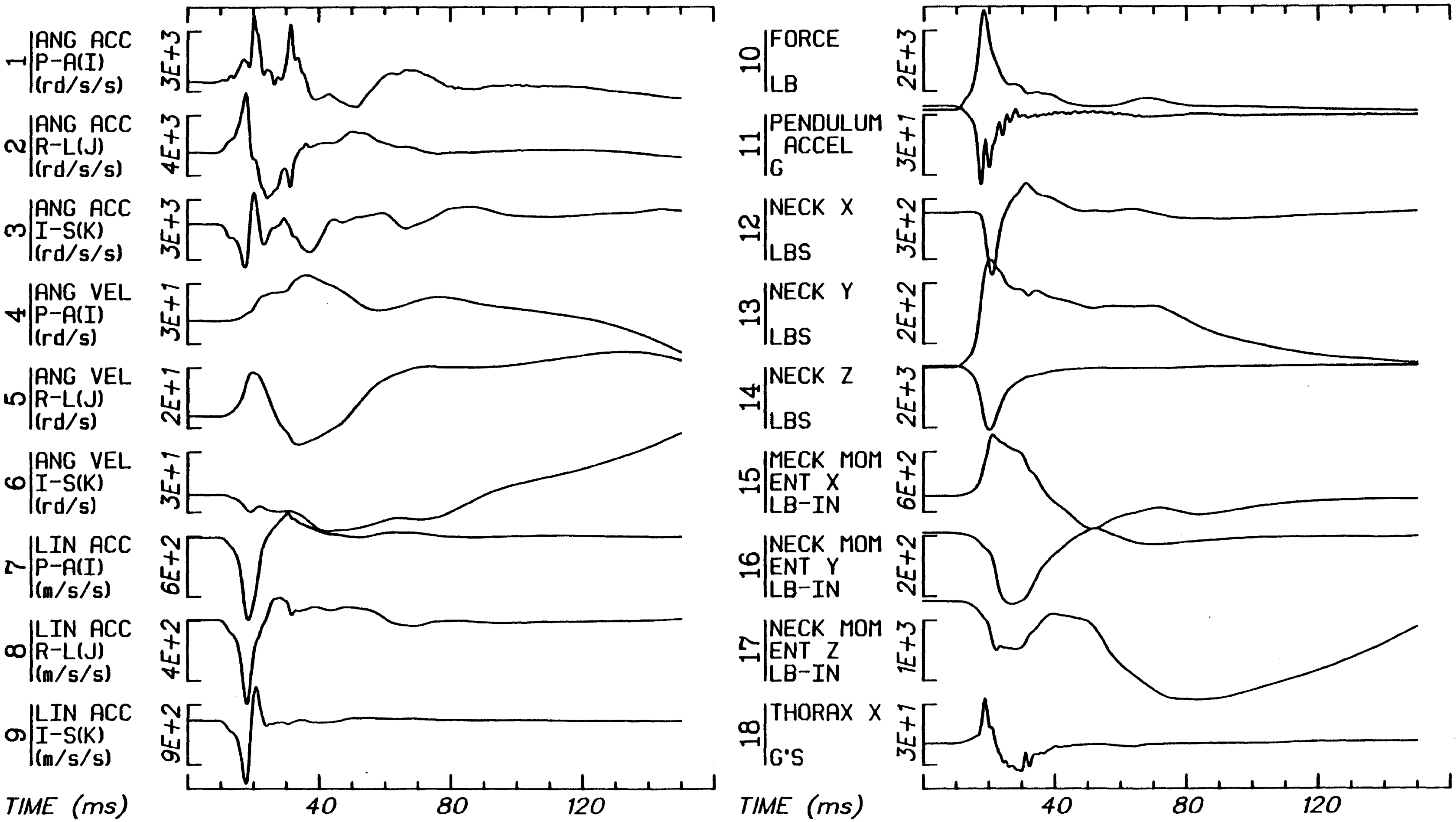
Run ID: 86L527 AH Disk: L527.GM File: 1 Date: AUG 13, 1986 Sheet: 1

GM data for tape formatting



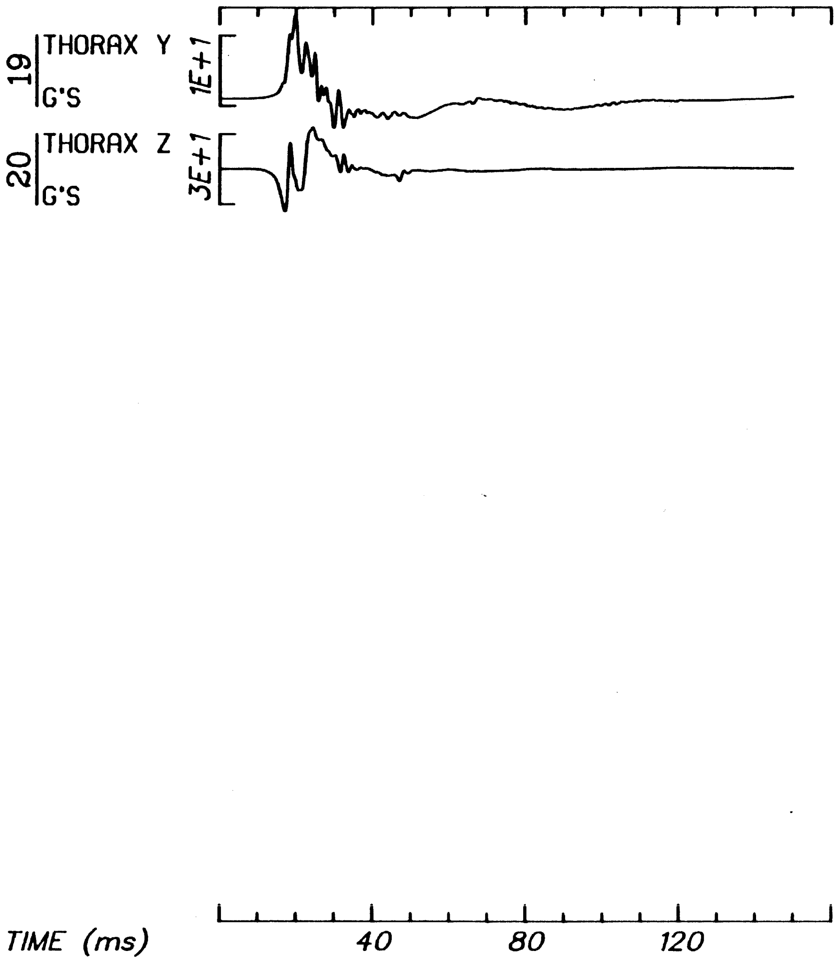
Run ID: 86L527 AH Disk: L527.GM File: 1 Date: AUG 13, 1986 Sheet: 2

GM data for tape formatting



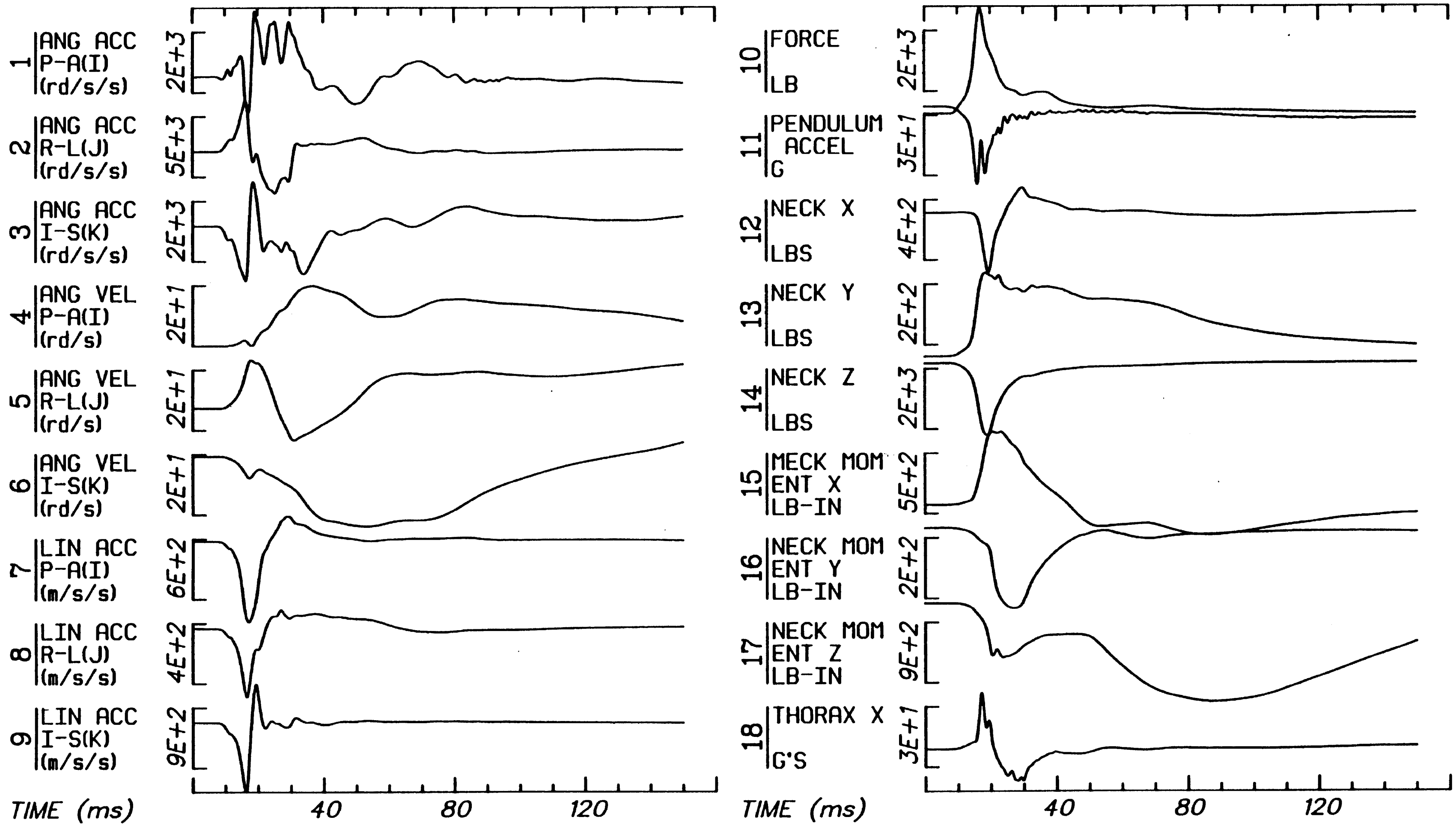
Run ID: 86L528 AH Disk: L528.GM File: 1 Date: AUG 13, 1986 Sheet: 1

GM data for tape formatting



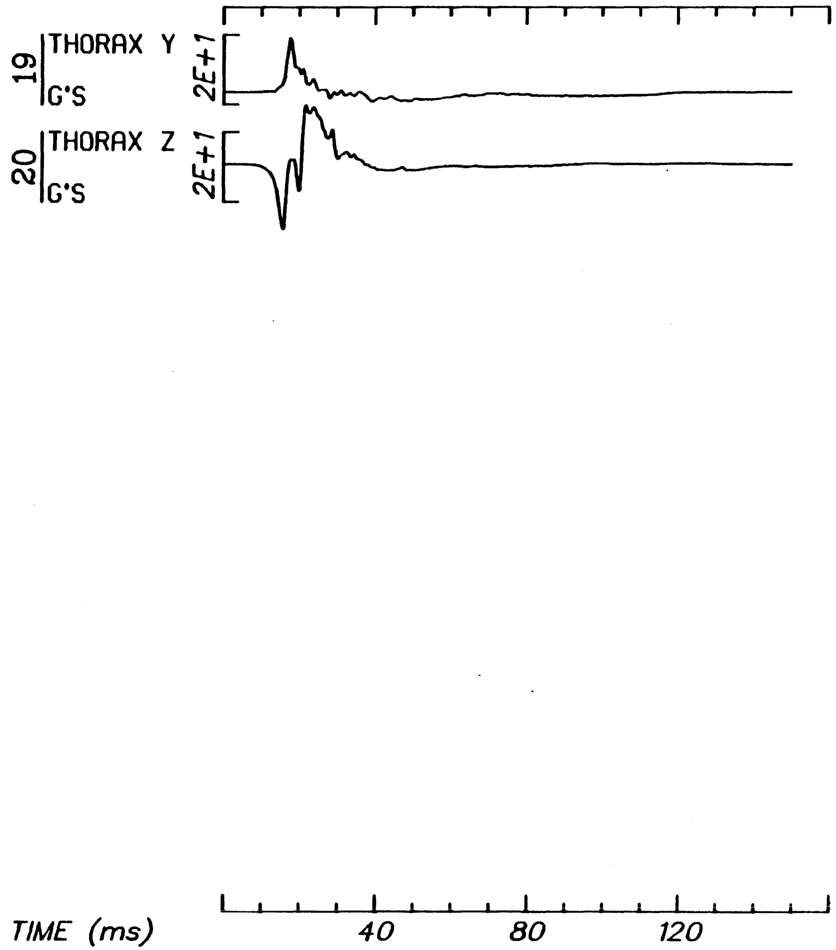
Run ID: 86L528 AH Disk: L528.GM File: 1 Date: AUG 13, 1986 Sheet: 2

GM data for tape formatting



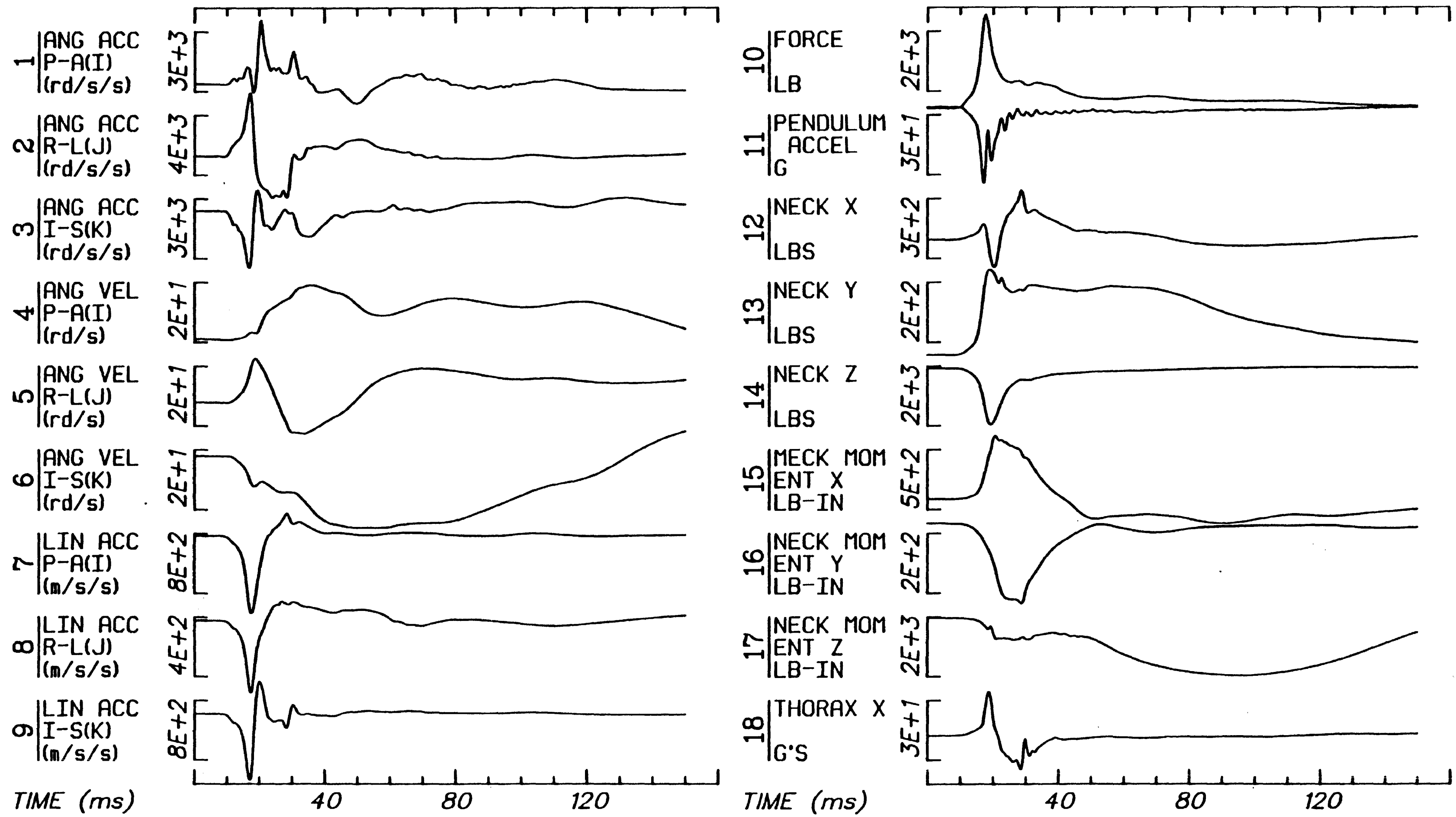
Run ID: 86L529 AH Disk: L529.GM File: 1 Date: AUG 13, 1986 Sheet: 1

GM data for tape formatting



Run ID: 86L529 AH Disk: L529.GM File: 1 Date: AUG 13, 1986 Sheet: 2

GM data for tape formatting



Run ID: 86L530 AH Disk: L530.GM File: 1 Date: AUG 13, 1986 Sheet: 1

GM data for tape formatting

KEY

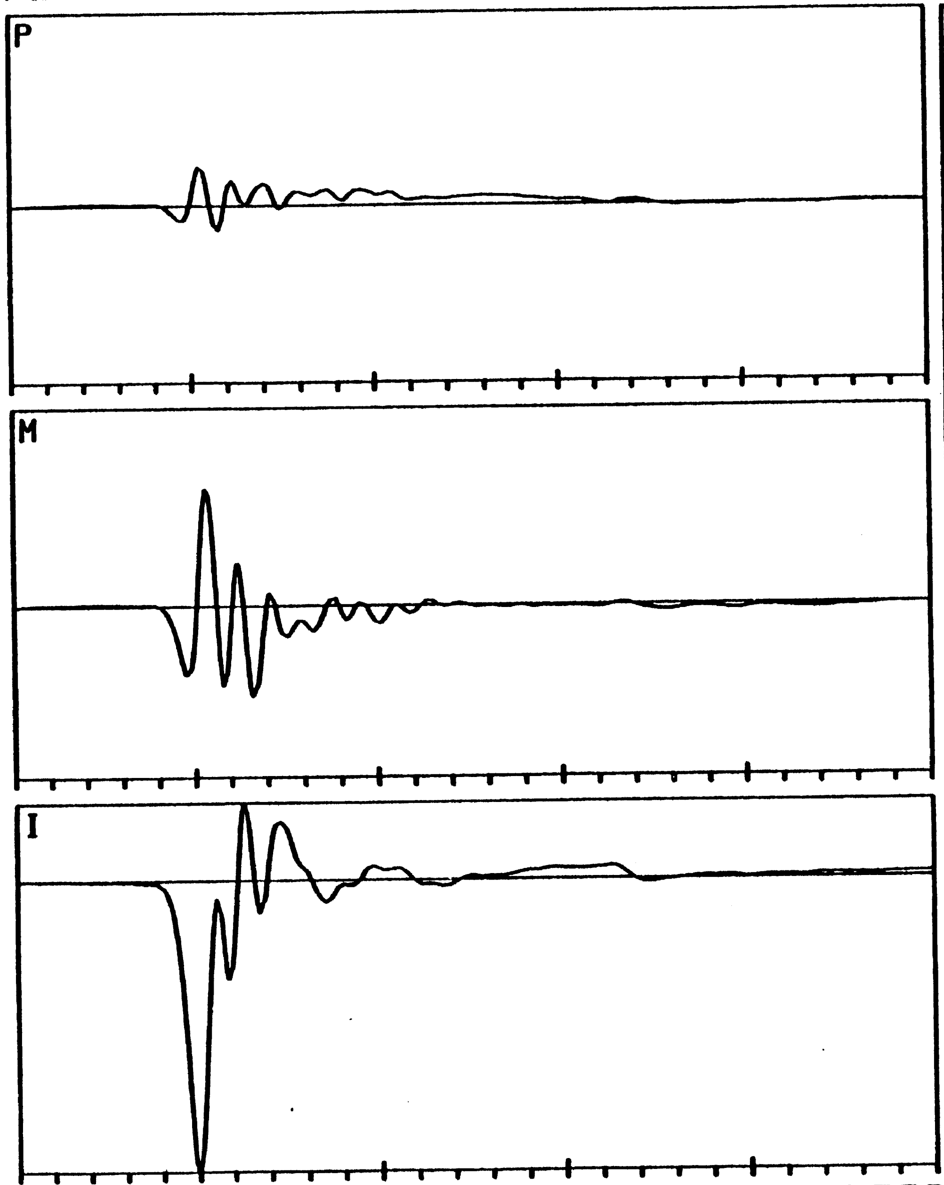
AV = Angular velocity of the head
AC = Linear acceleration of the head
AA = Angular acceleration of the head

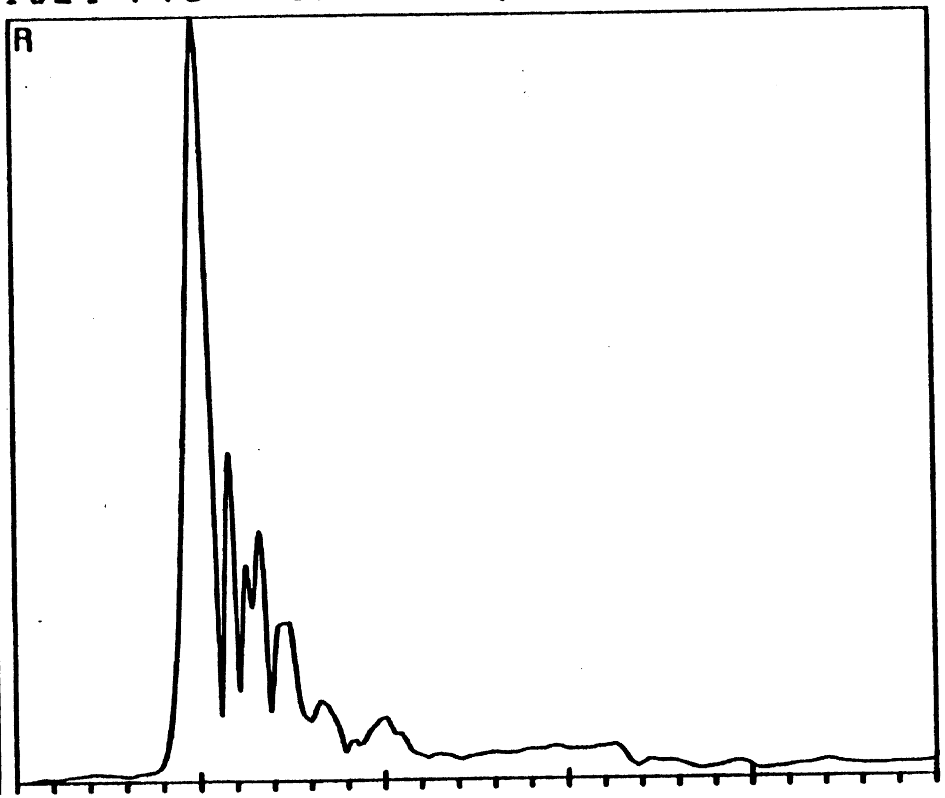
* = y range for all graphs

P = posterior-to-anterior
M = right-to-left
I = inferior-to-superior
R = resultant angular velocity

rps = rads per second
rp2 = rads per second^2
G's = G's

PLOT 02-10-86 DATA 102.300 MS = 1024 PTS @ 10000 HZ. 1000-HZ FILTER





4.100- 54.100 MS. 400-HZ FILTER

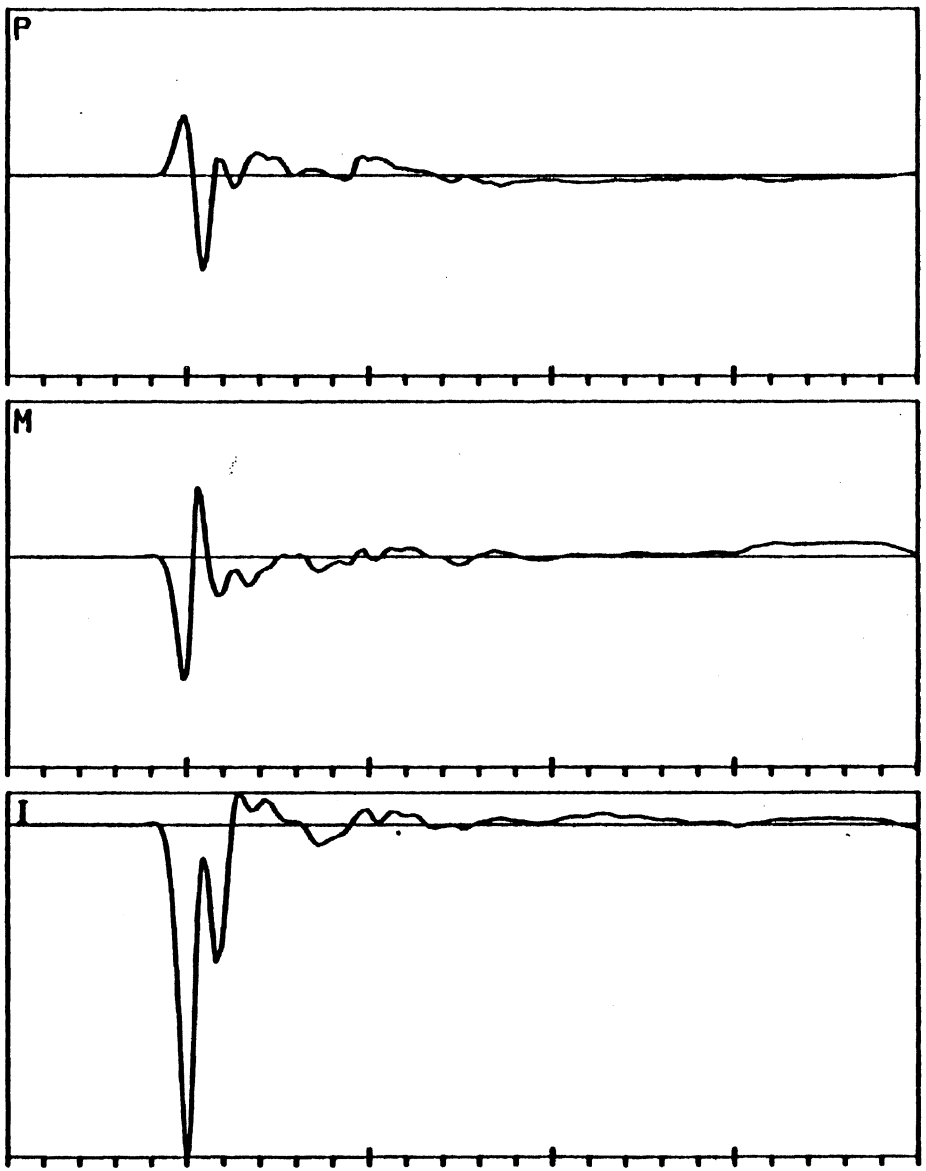
	P =	41.0	-24.3	G'S
	M =	119.	-93.1	G'S
*	I =	78.2	-293.	G'S
	R =	295.		

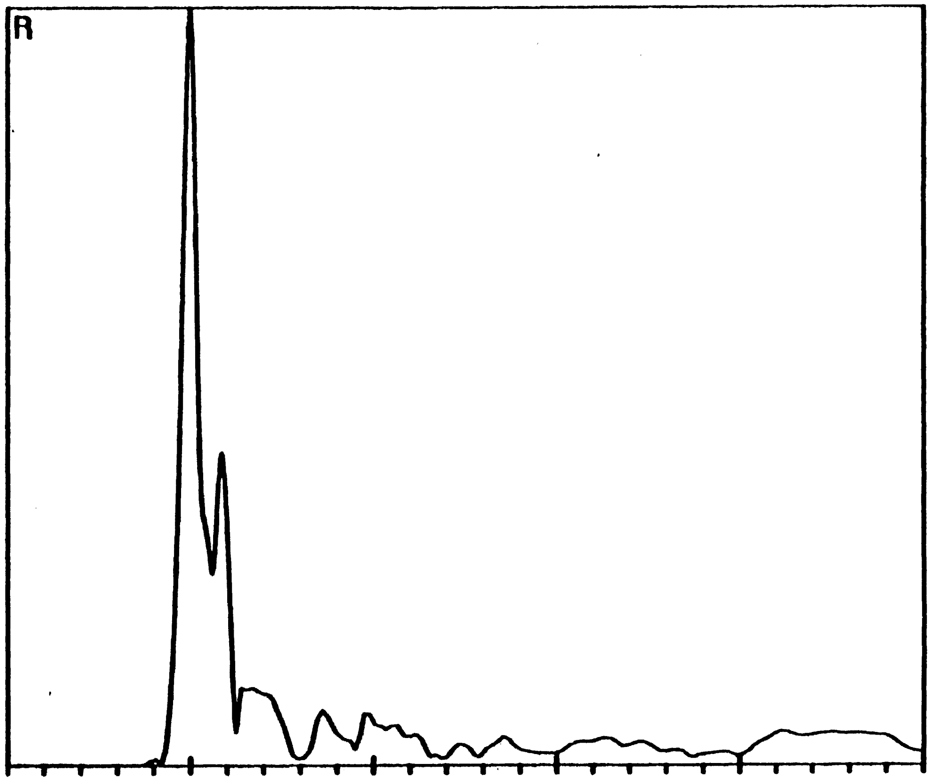
AC HED 85L514

03/18/85

x range=50 milliseconds
y range=3/1.2 G's

PLOT 02-10-86 DATA 102.300 MS = 1024 PTS @ 10000 HZ. 1000-HZ FILTER



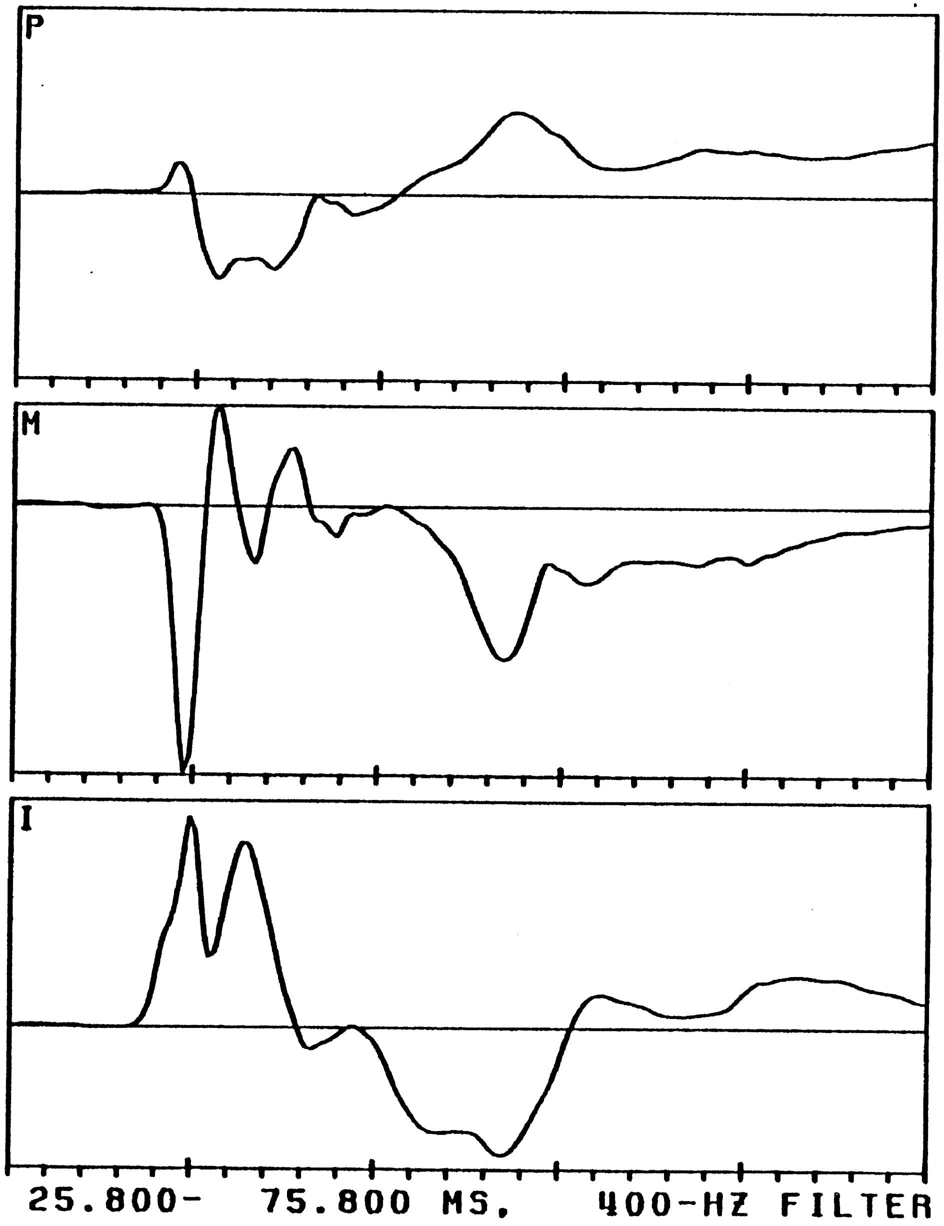


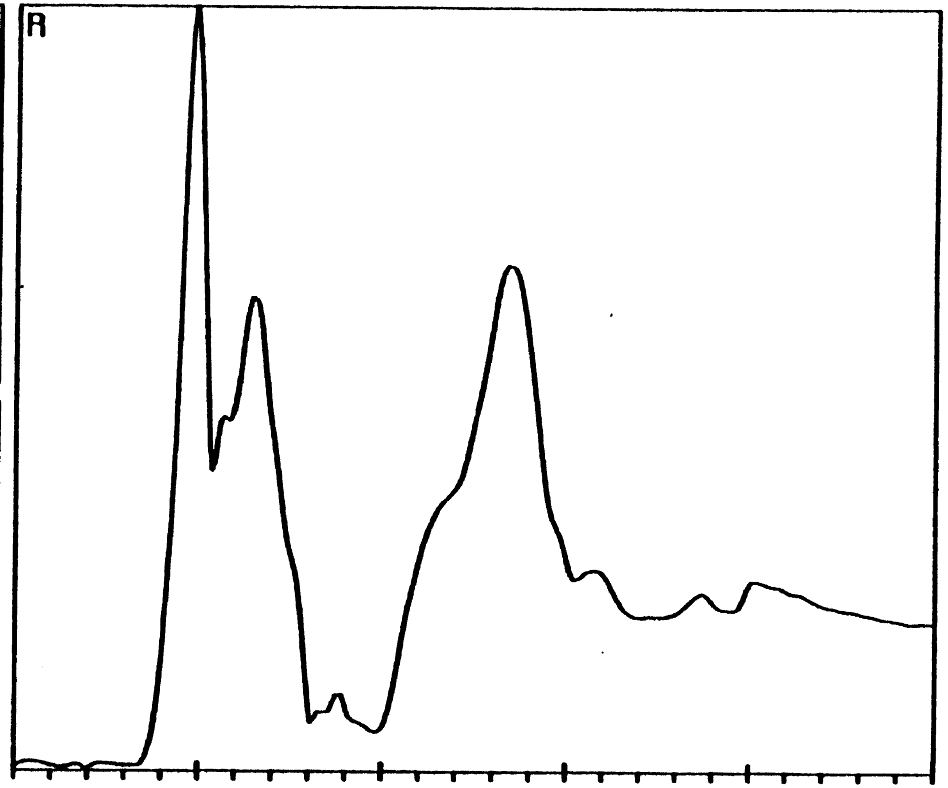
P =	53.1	-83.3	G'S
M =	63.2	-112.	G'S
* I =	28.6	-297.	G'S
R =	319.		

AC HED 85L515

04/12/85

PLOT 02-10-86 DATA 102.300 MS = 1024 PTS @ 10000 HZ. 1000-HZ FILTER



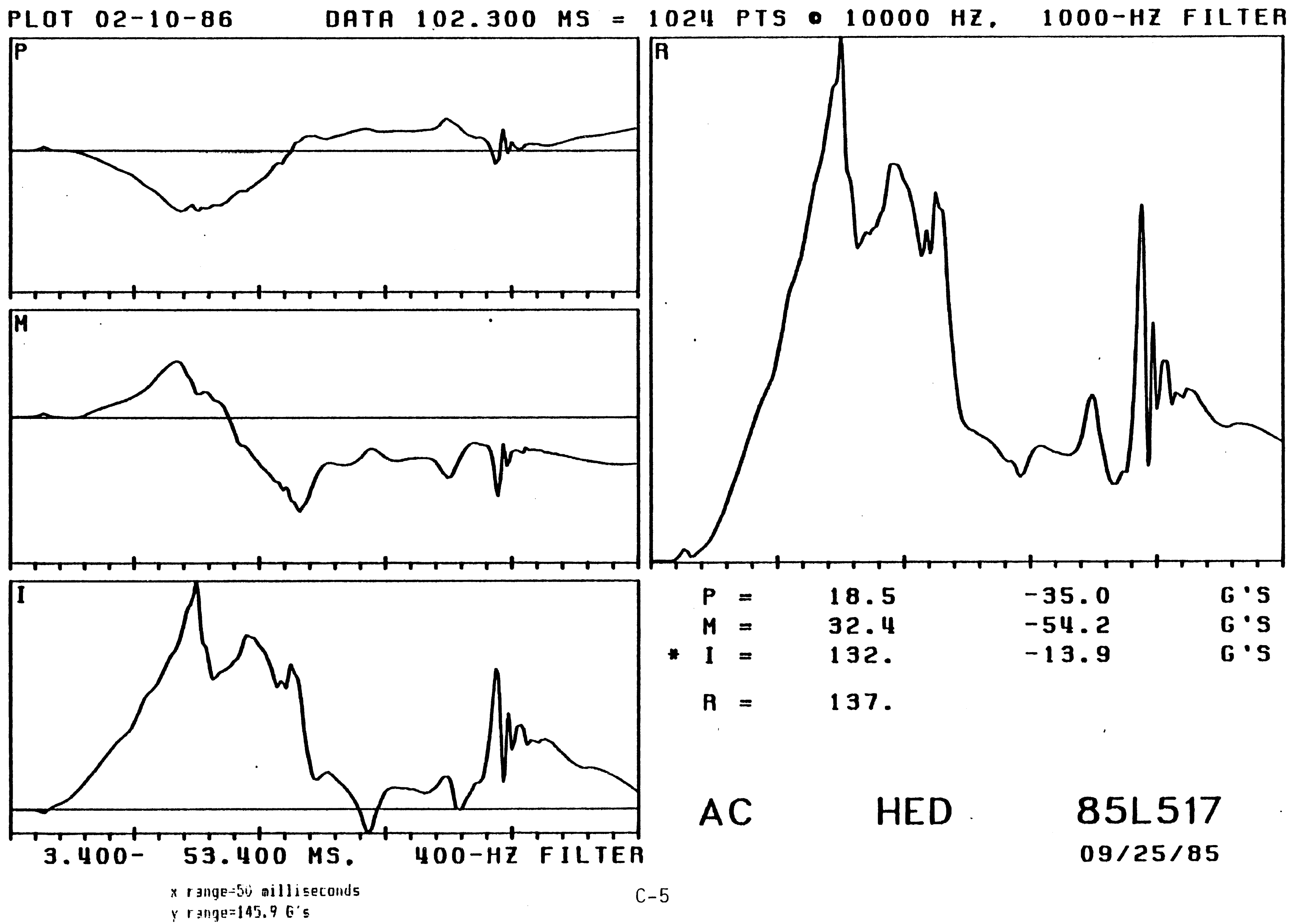


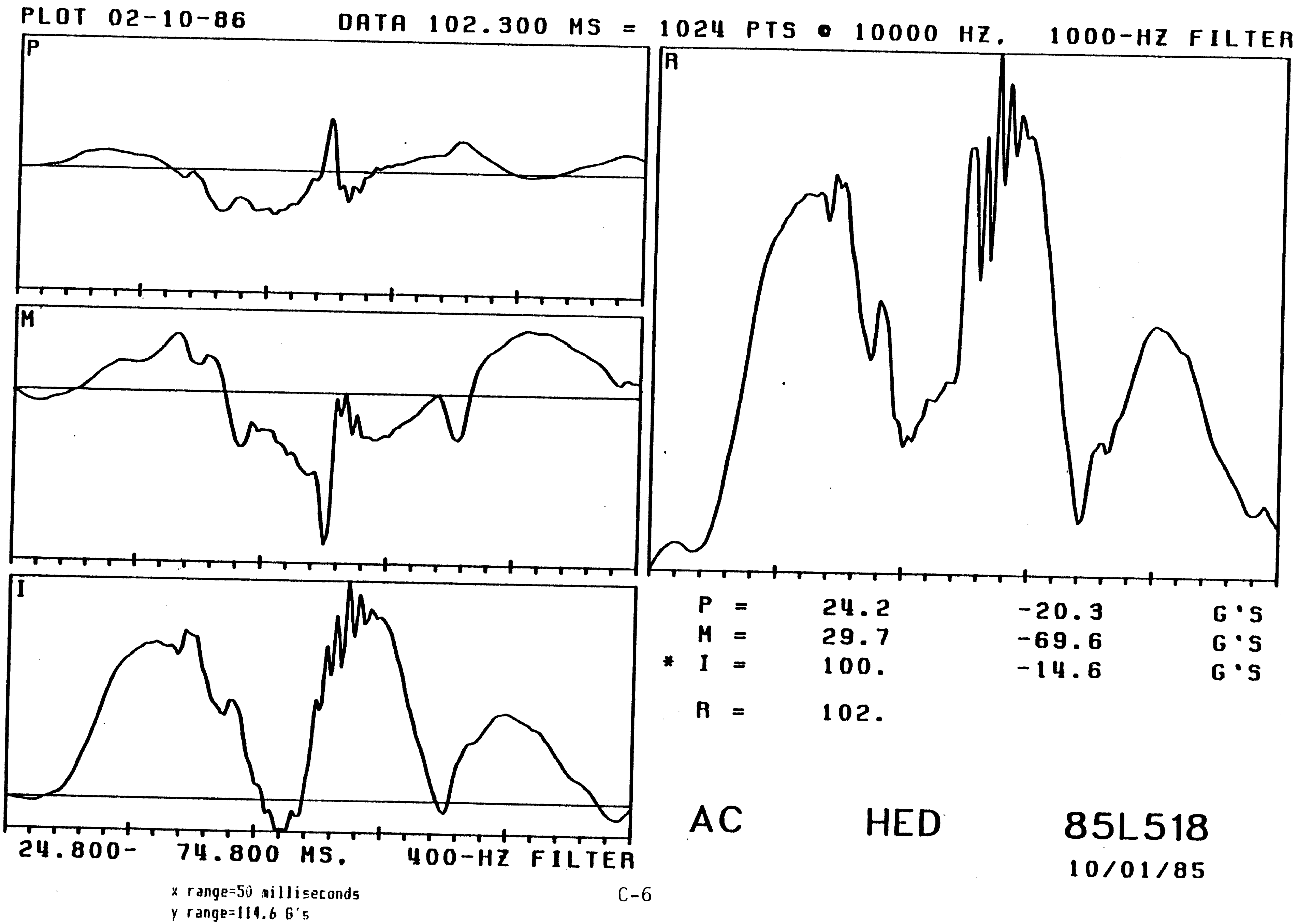
x range=50 milliseconds
y range=246.2 G's

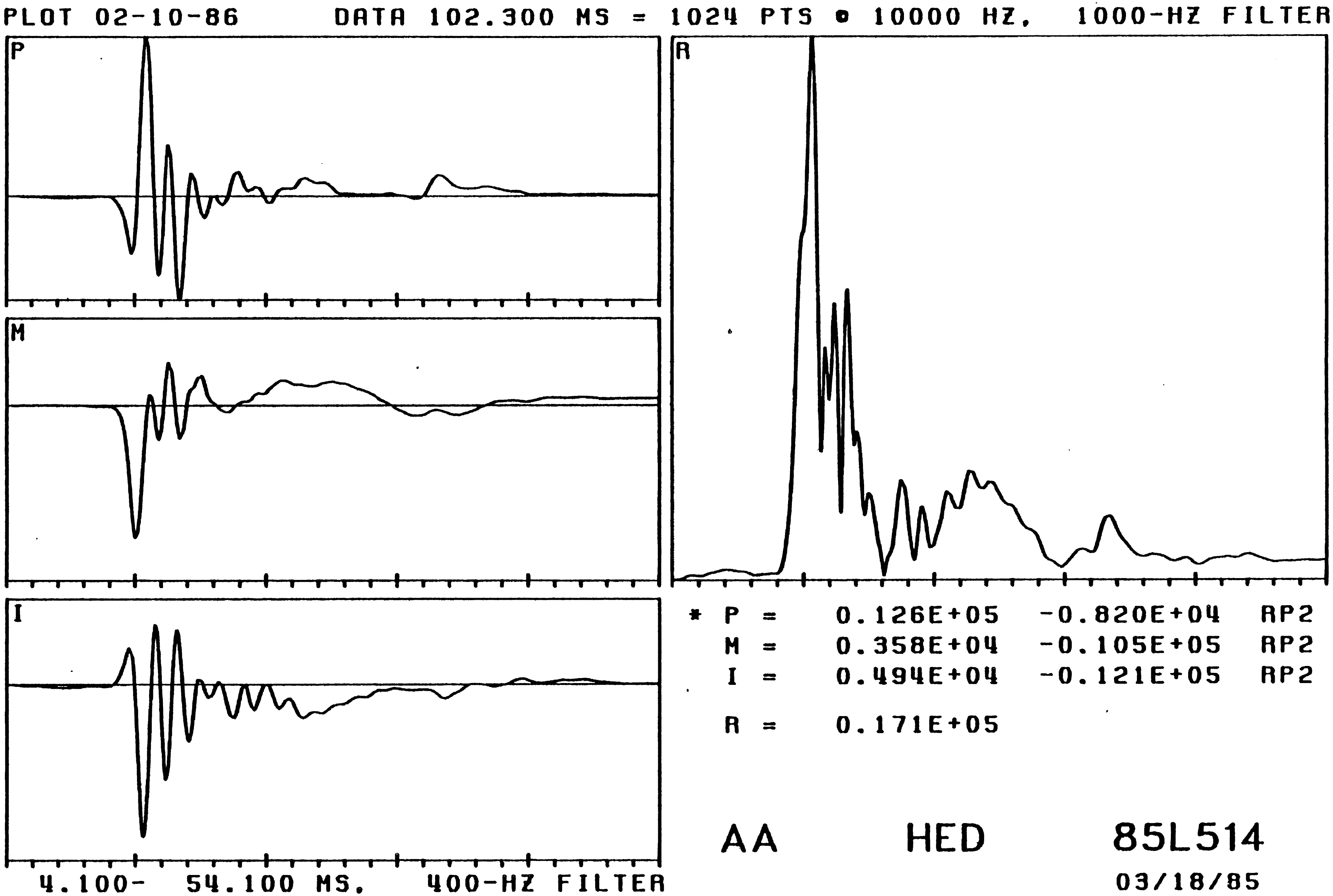
	P =	60.0	-61.0	G'S
*	M =	72.3	-194.	G'S
	I =	154.	-92.2	G'S
	R =	234.		

AC HED 85L516

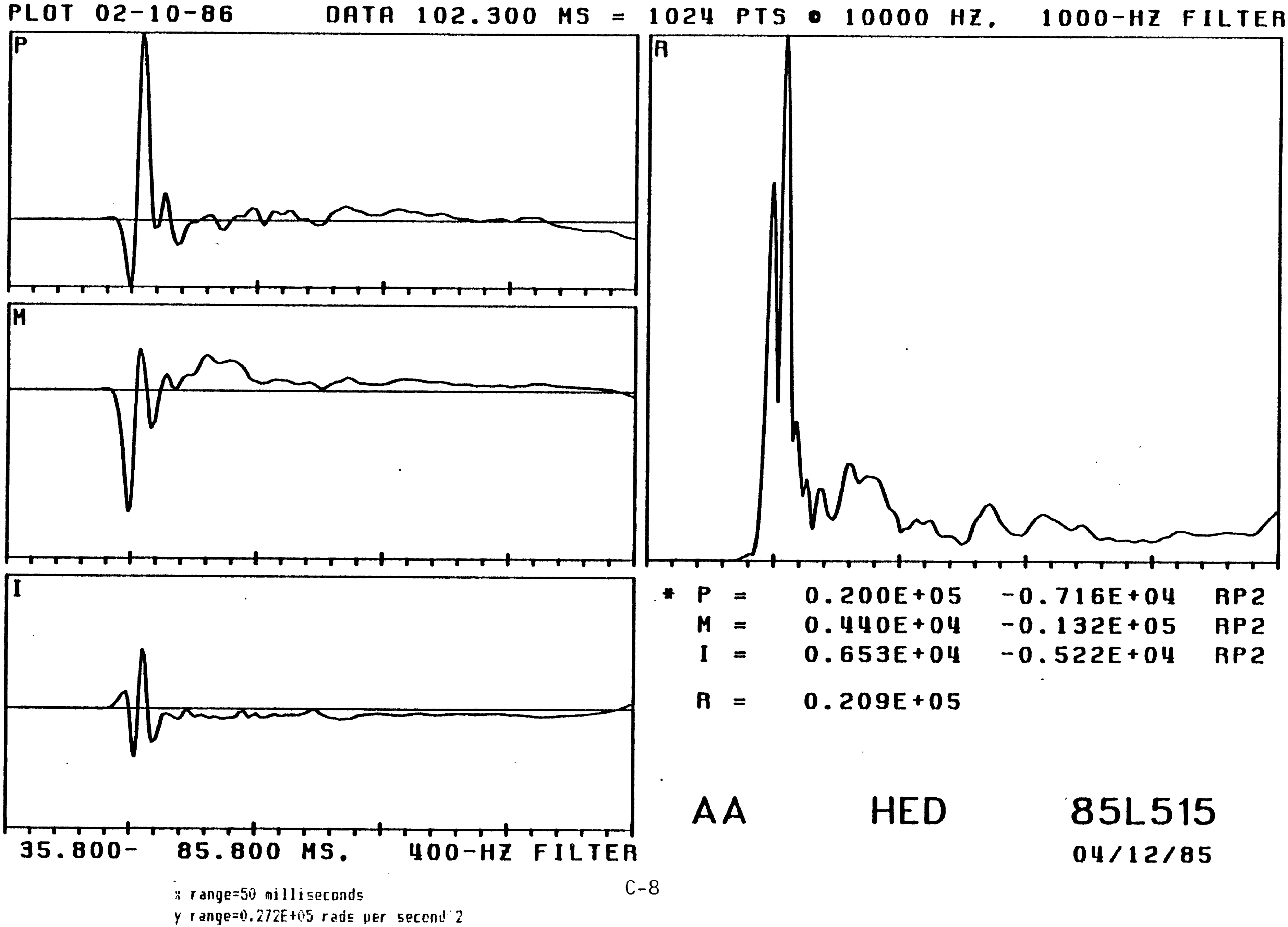
09/23/85


PLOT 02-10-86 DATA 102.300 MS = 1024 PTS @ 10000 HZ, 1000-HZ FILTER
P
M
I
R
P = 18.5 -35.0 G'S
M = 32.4 -54.2 G'S
* I = 132. -13.9 G'S
R = 137.
AC HED 85L517
09/25/85
3.400- 53.400 MS. 400-HZ FILTER
x range=50 milliseconds
y range=145.9 G's

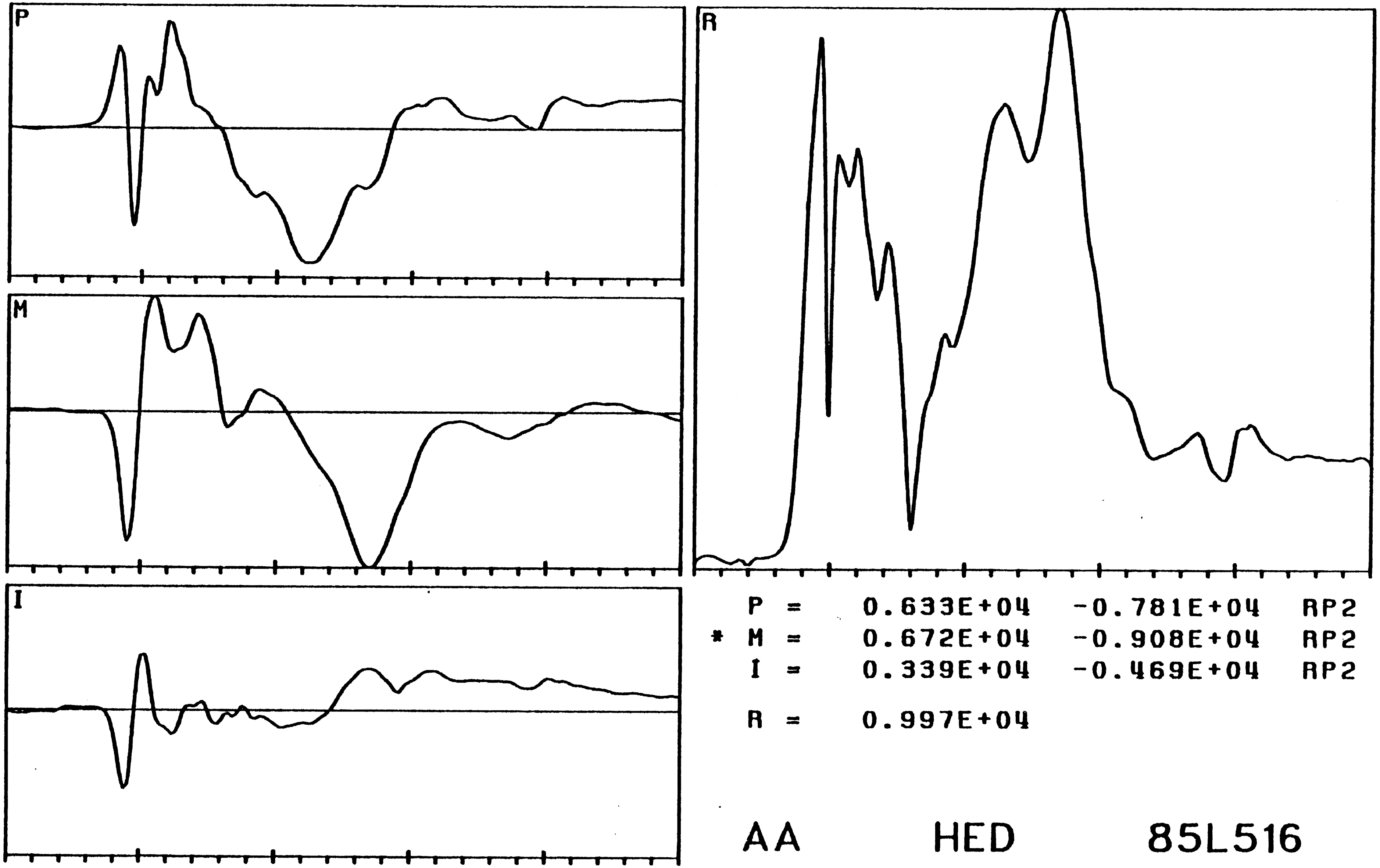

PLOT 02-10-86
DATA 102.300 MS = 1024 PTS @ 10000 HZ. 1000-HZ FILTER
P
M
I
R
24.800- 74.800 MS. 400-HZ FILTER
x range=50 milliseconds
y range=114.6 G's
P = 24.2 -20.3 G'S
M = 29.7 -69.6 G'S
* I = 100. -14.6 G'S
R = 102.
AC
HED
85L518
10/01/85



x range=50 milliseconds
y range=0.208E+05 rads per second^2


PLOT 02-10-86 DATA 102.300 MS = 1024 PTS @ 10000 HZ, 1000-HZ FILTER
P
M
I
R
* P = 0.200E+05 -0.716E+04 RP2
M = 0.440E+04 -0.132E+05 RP2
I = 0.653E+04 -0.522E+04 RP2
R = 0.209E+05
AA
HED
85L515
04/12/85
35.800- 85.800 MS. 400-HZ FILTER
x range=50 milliseconds
y range=0.272E+05 rads per second^2

PLOT 02-10-86 DATA 102.300 MS = 1024 PTS @ 10000 HZ. 1000-HZ FILTER



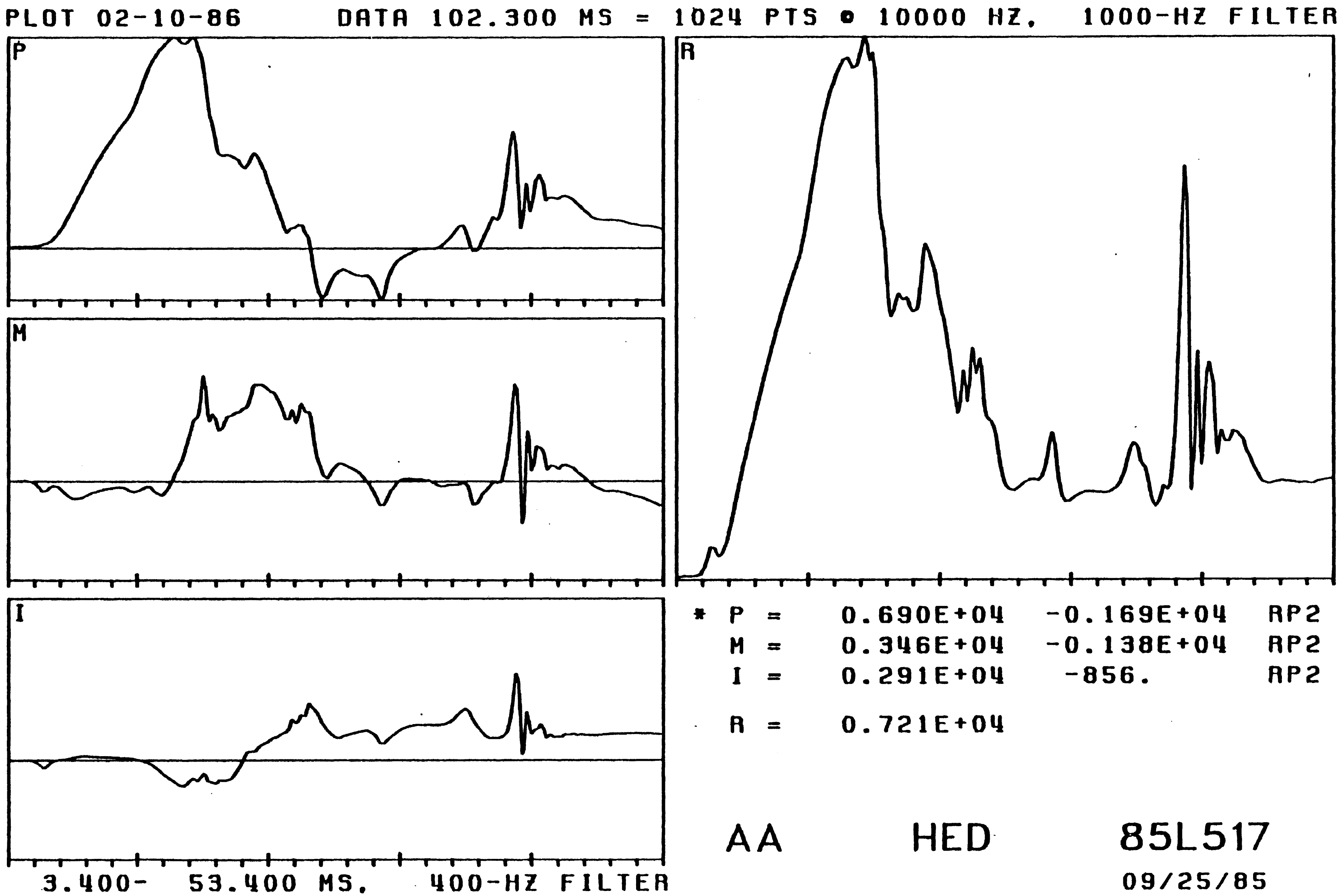
25.800- 75.800 MS. 400-HZ FILTER

x range=50 milliseconds
y range=0.158E+05 rads per second^2

	P =	0.633E+04	-0.781E+04	RP2
*	M =	0.672E+04	-0.908E+04	RP2
	I =	0.339E+04	-0.469E+04	RP2
	R =	0.997E+04		

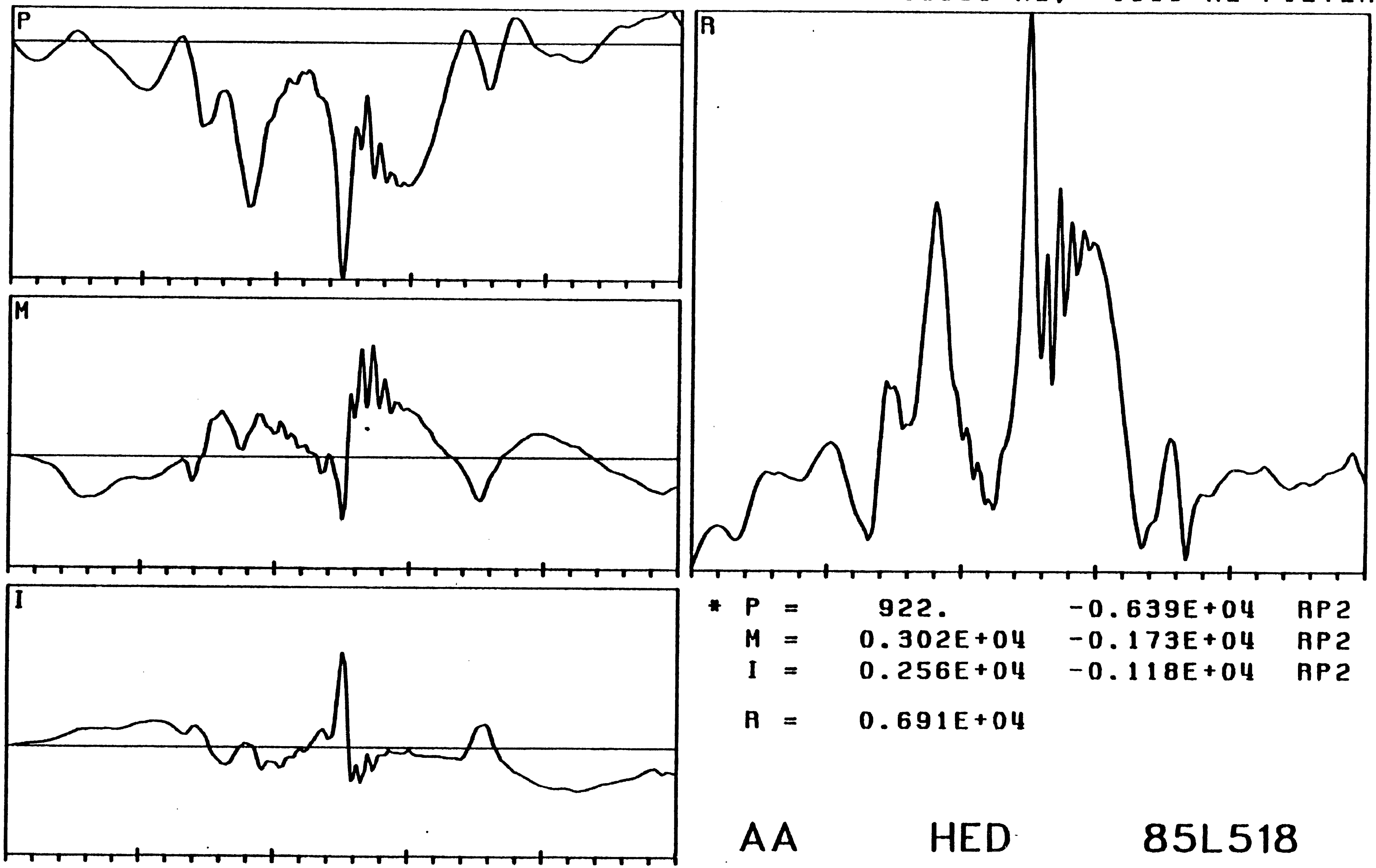
AA HED 85L516

09/23/85



x range=50 milliseconds
y range=0.759E+04 rads per second^2

PLOT 02-10-86 DATA 102.300 MS = 1024 PTS @ 10000 HZ. 1000-HZ FILTER



24.800- 74.800 MS. 400-HZ FILTER

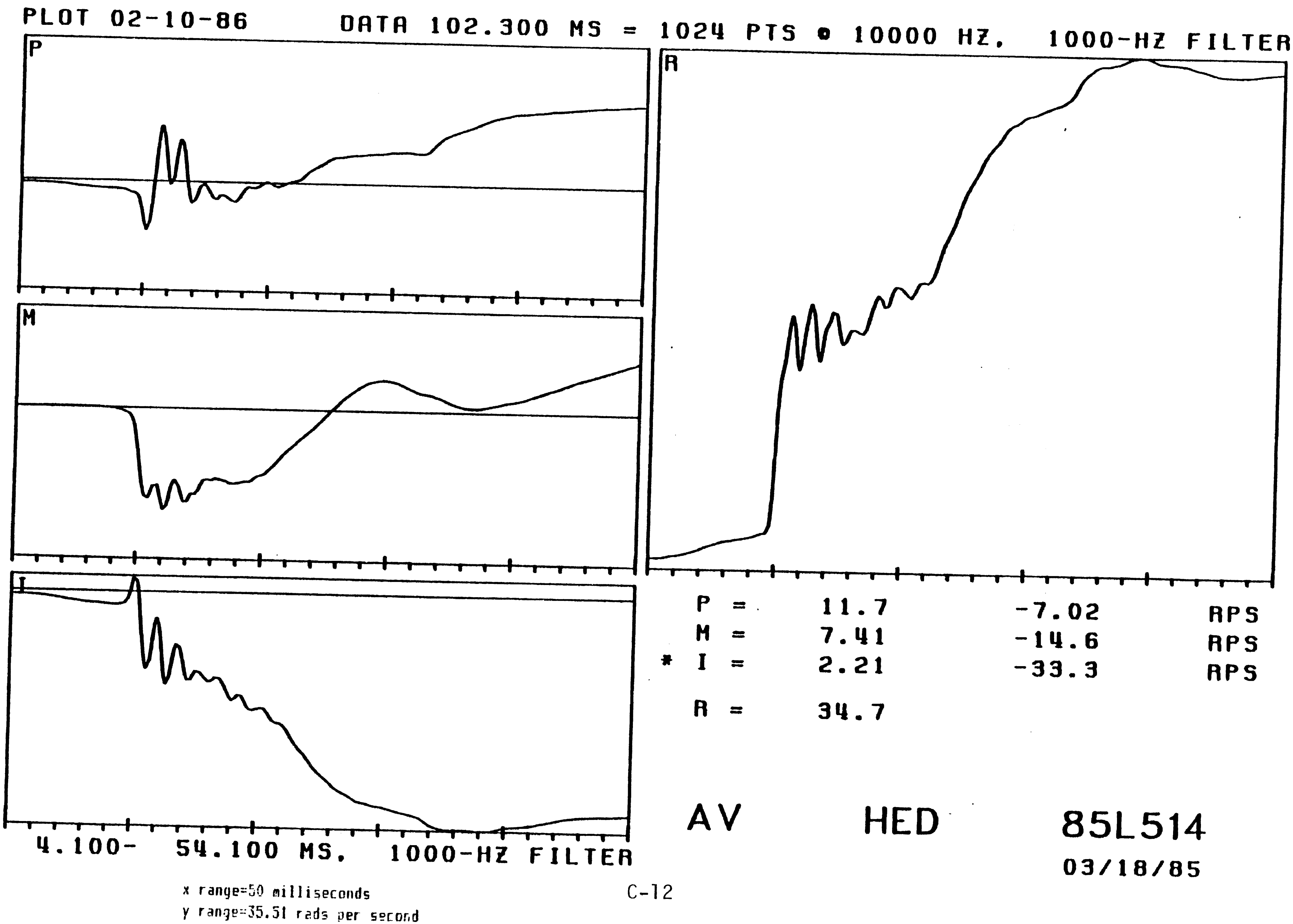
* P	=	922.	-0.639E+04	RP2
M	=	0.302E+04	-0.173E+04	RP2
I	=	0.256E+04	-0.118E+04	RP2
R	=	0.691E+04		

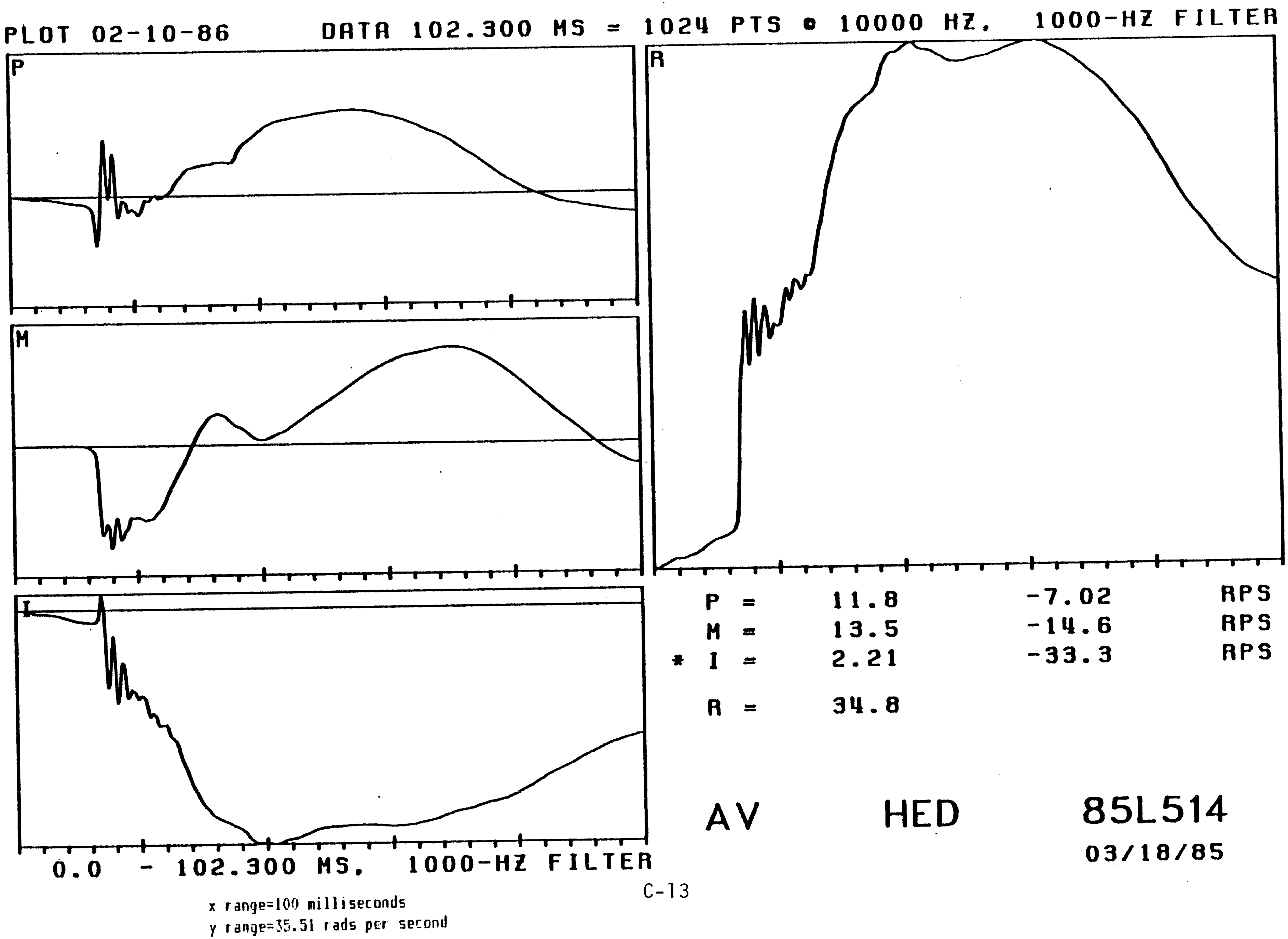
AA HED 85L518

10/01/85

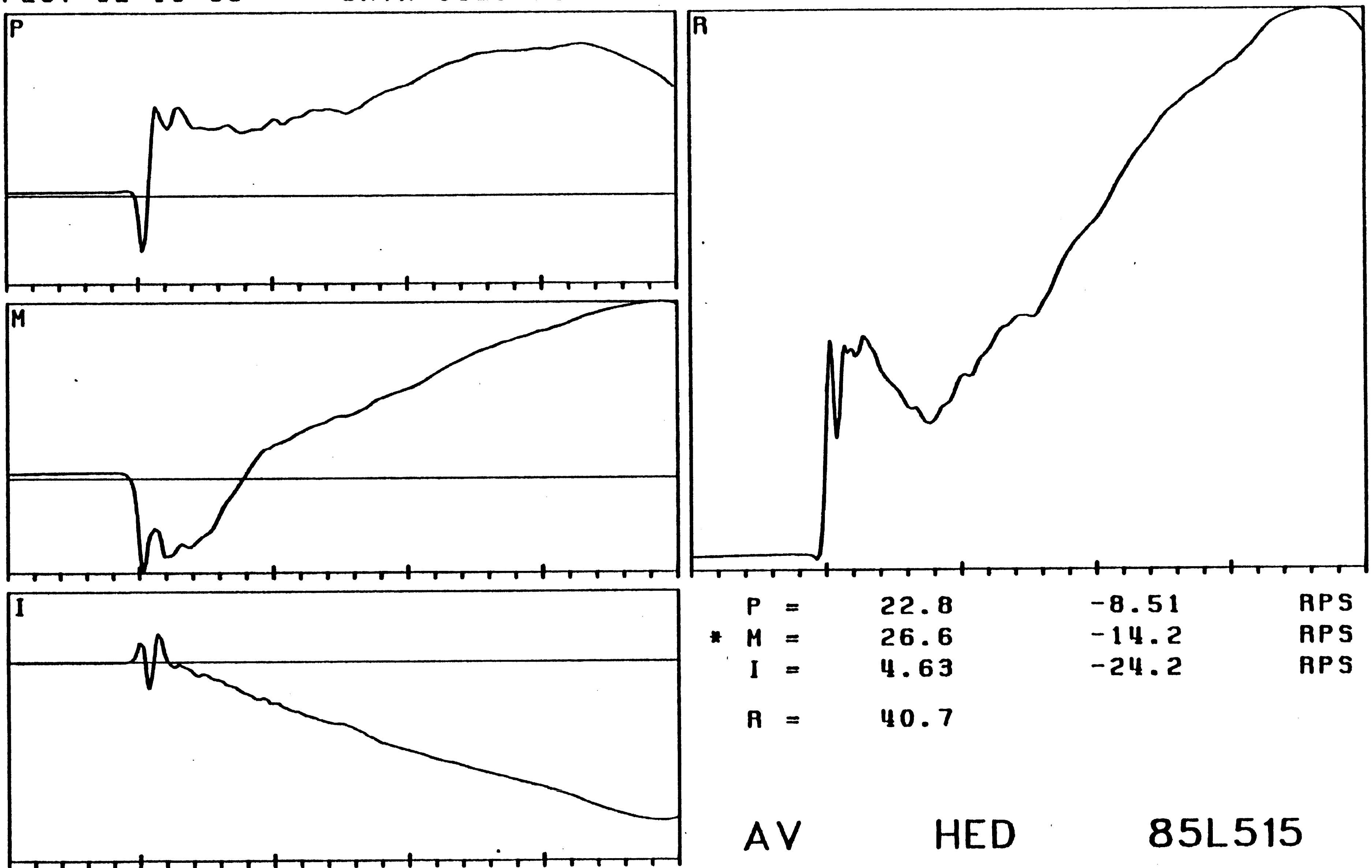
x range=50 milliseconds

y range=0.731E+04 rads per second^2


PLOT 02-10-86
DATA 102.300 MS = 1024 PTS @ 10000 HZ. 1000-HZ FILTER
P
M
I
R
4.100- 54.100 MS. 1000-HZ FILTER
x range=50 milliseconds
y range=35.51 rads per second
P = 11.7 -7.02 RPS
M = 7.41 -14.6 RPS
* I = 2.21 -33.3 RPS
R = 34.7
AV
HED
85L514
03/18/85


PLOT 02-10-86
DATA 102.300 MS = 1024 PTS @ 10000 HZ. 1000-HZ FILTER
P
M
I
R
P = 11.8 -7.02 RPS
M = 13.5 -14.6 RPS
* I = 2.21 -33.3 RPS
R = 34.8
AV
HED
85L514
03/18/85
0.0 - 102.300 MS. 1000-HZ FILTER
x range=100 milliseconds
y range=35.51 rads per second

PLOT 02-10-86 DATA 102.300 MS = 1024 PTS @ 10000 HZ. 1000-HZ FILTER



35.800- 85.800 MS. 1000-HZ FILTER

	P =	22.8	-8.51	RPS
*	M =	26.6	-14.2	RPS
	I =	4.63	-24.2	RPS
	R =	40.7		

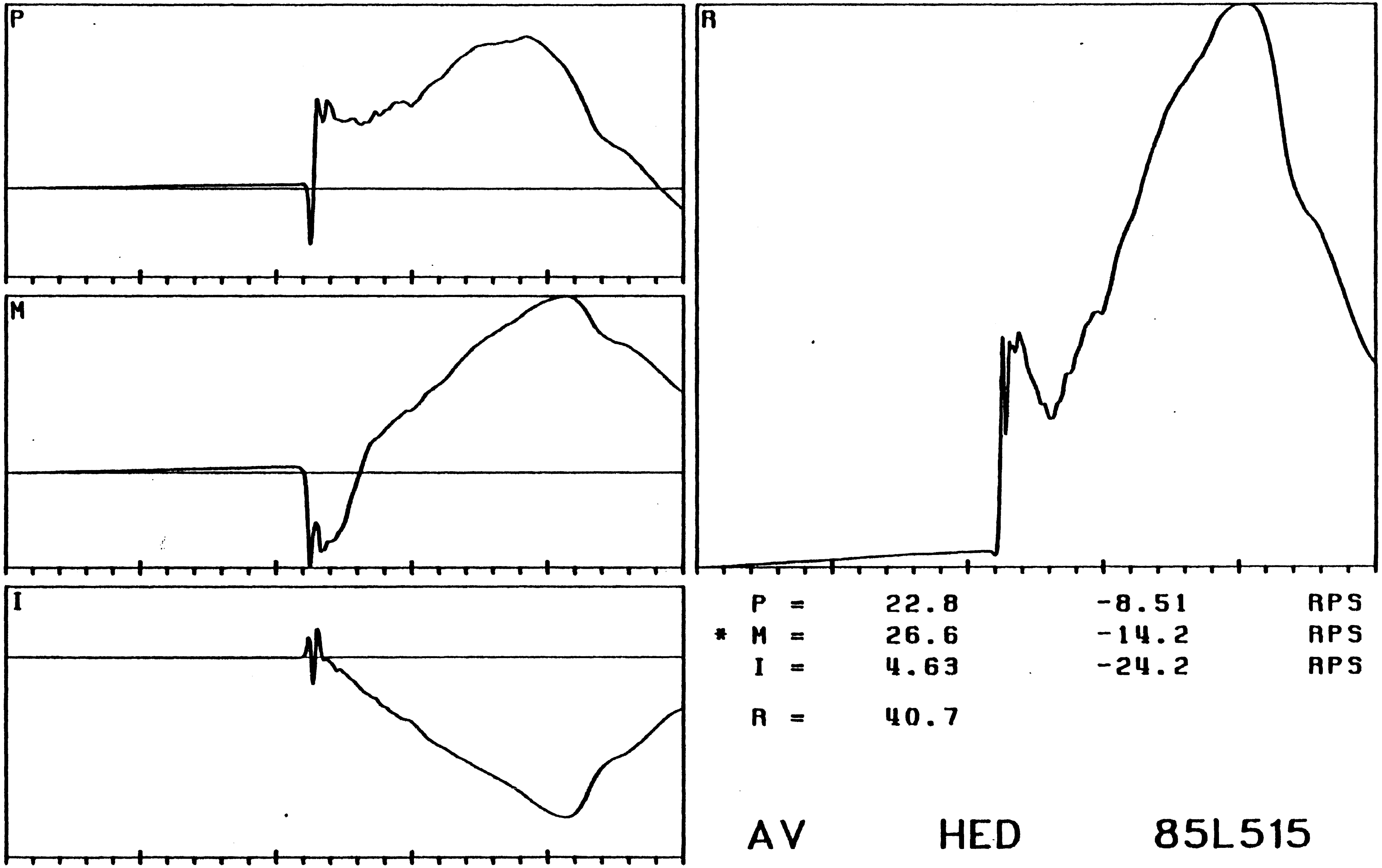
AV HED 85L515

04/12/85

x range=50 milliseconds

y range=40.8 rads per second

PLOT 02-10-86 DATA 102.300 MS = 1024 PTS @ 10000 HZ, 1000-HZ FILTER



0.0 - 102.300 MS, 1000-HZ FILTER

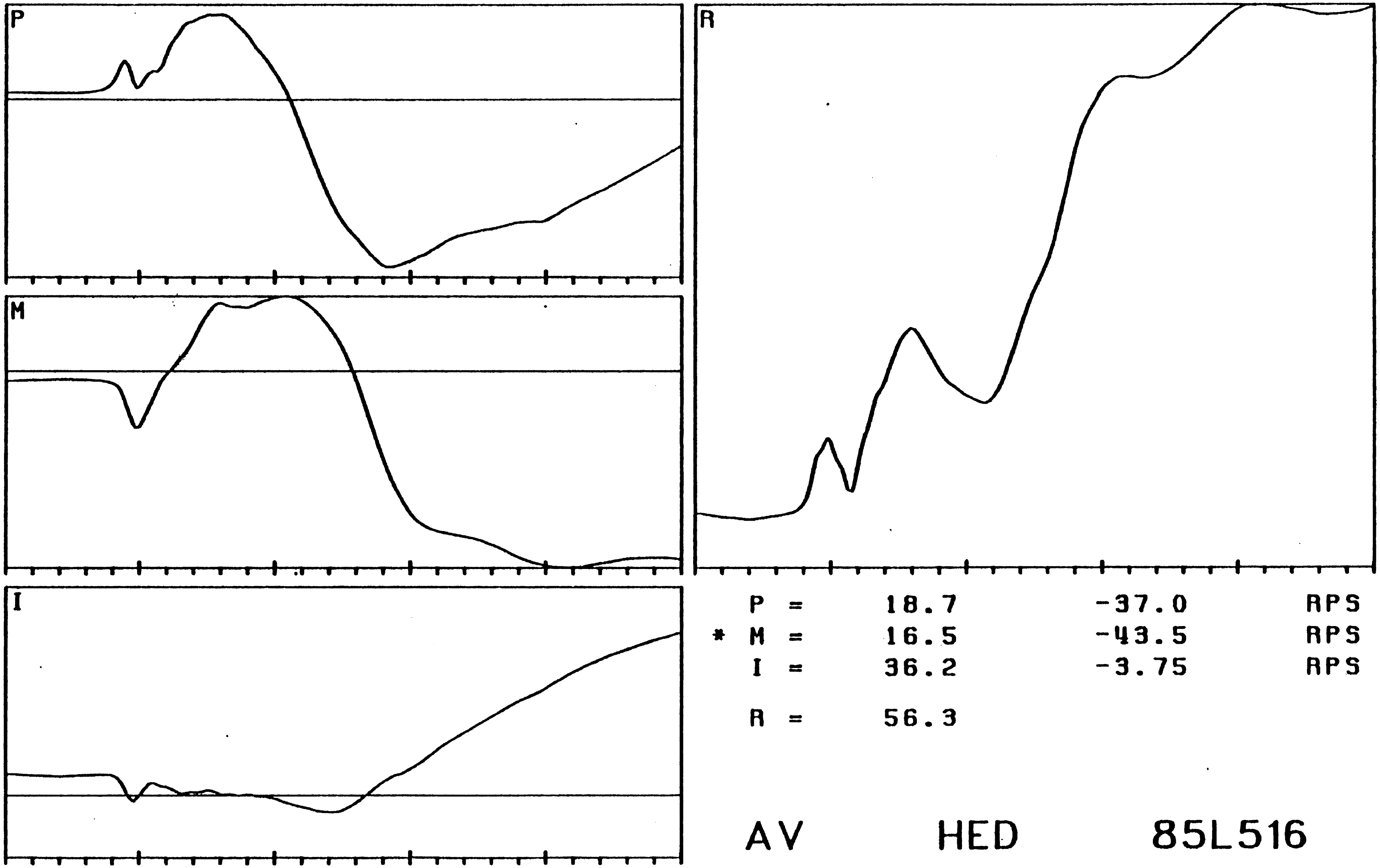
	P =	22.8	-8.51	RPS
*	M =	26.6	-14.2	RPS
	I =	4.63	-24.2	RPS
	R =	40.7		

AV HED 85L515

04/12/85

x range=100 milliseconds
y range=40.8 rads per second

PLOT 02-10-86 DATA 102.300 MS = 1024 PTS @ 10000 HZ. 1000-HZ FILTER



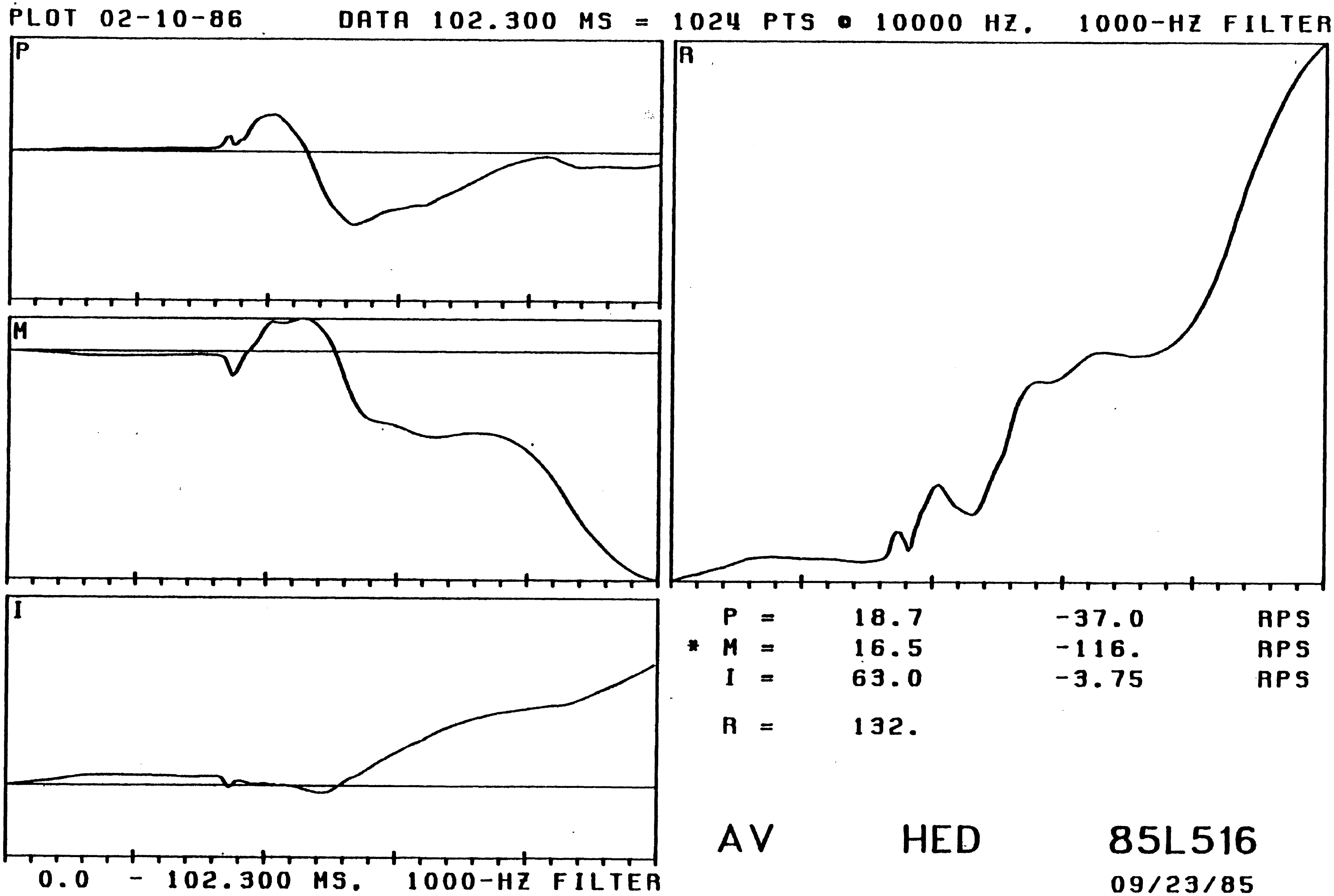
25.800- 75.800 MS. 1000-HZ FILTER

	P =	18.7	-37.0	RPS
*	M =	16.5	-43.5	RPS
	I =	36.2	-3.75	RPS
	R =	56.3		

AV HED 85L516

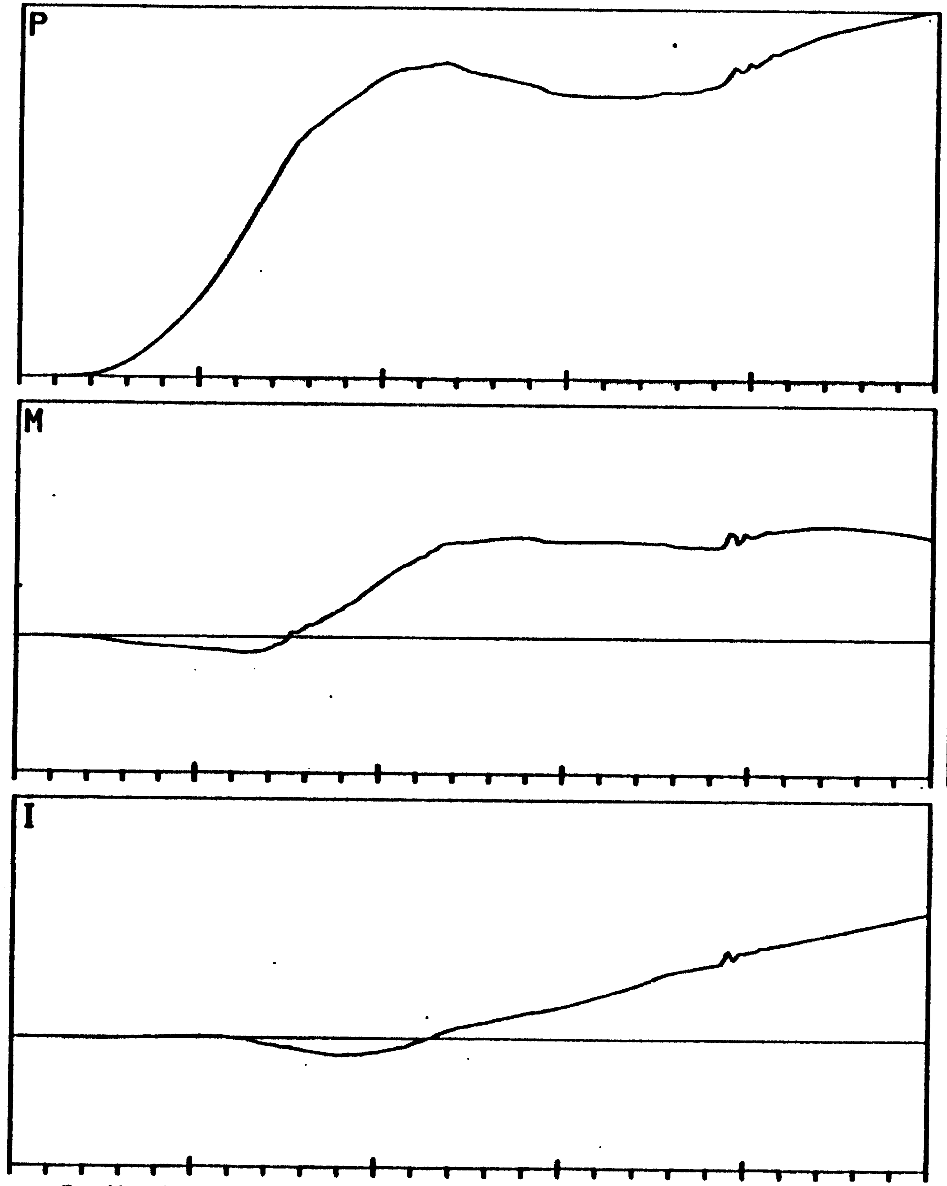
09/23/85

x range=50 milliseconds
y range=60.0 rads per second



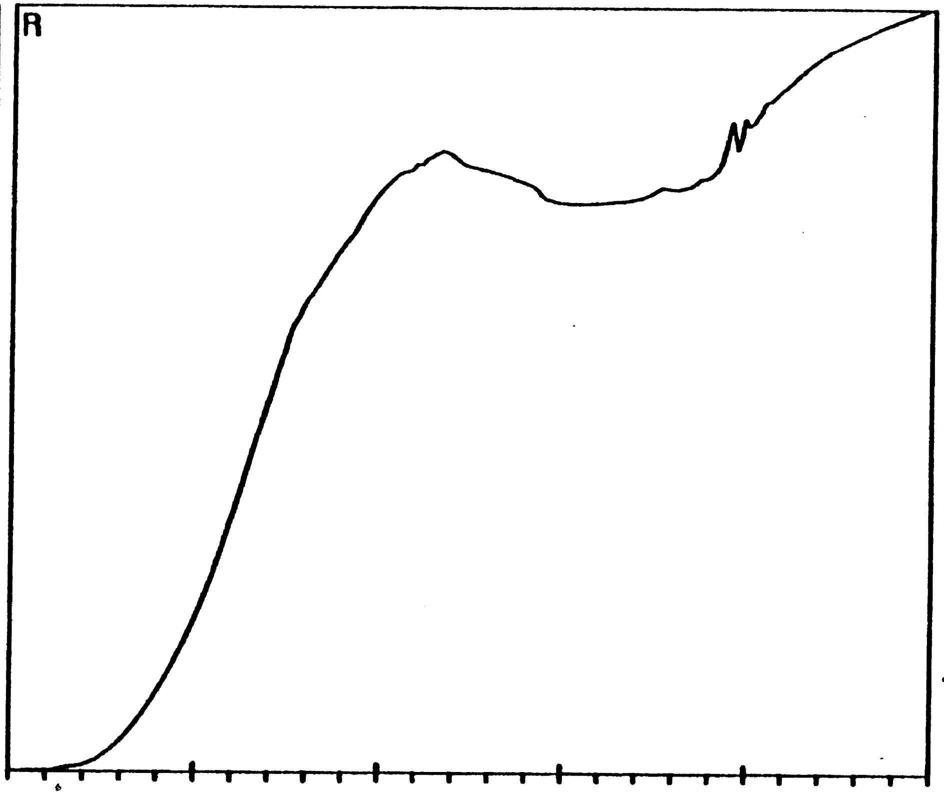
x range=100 milliseconds
y range=132.5 rads per second

PLOT 02-10-86 DATA 102.300 MS = 1024 PTS @ 10000 HZ, 1000-HZ FILTER



3.400- 53.400 MS, 1000-HZ FILTER

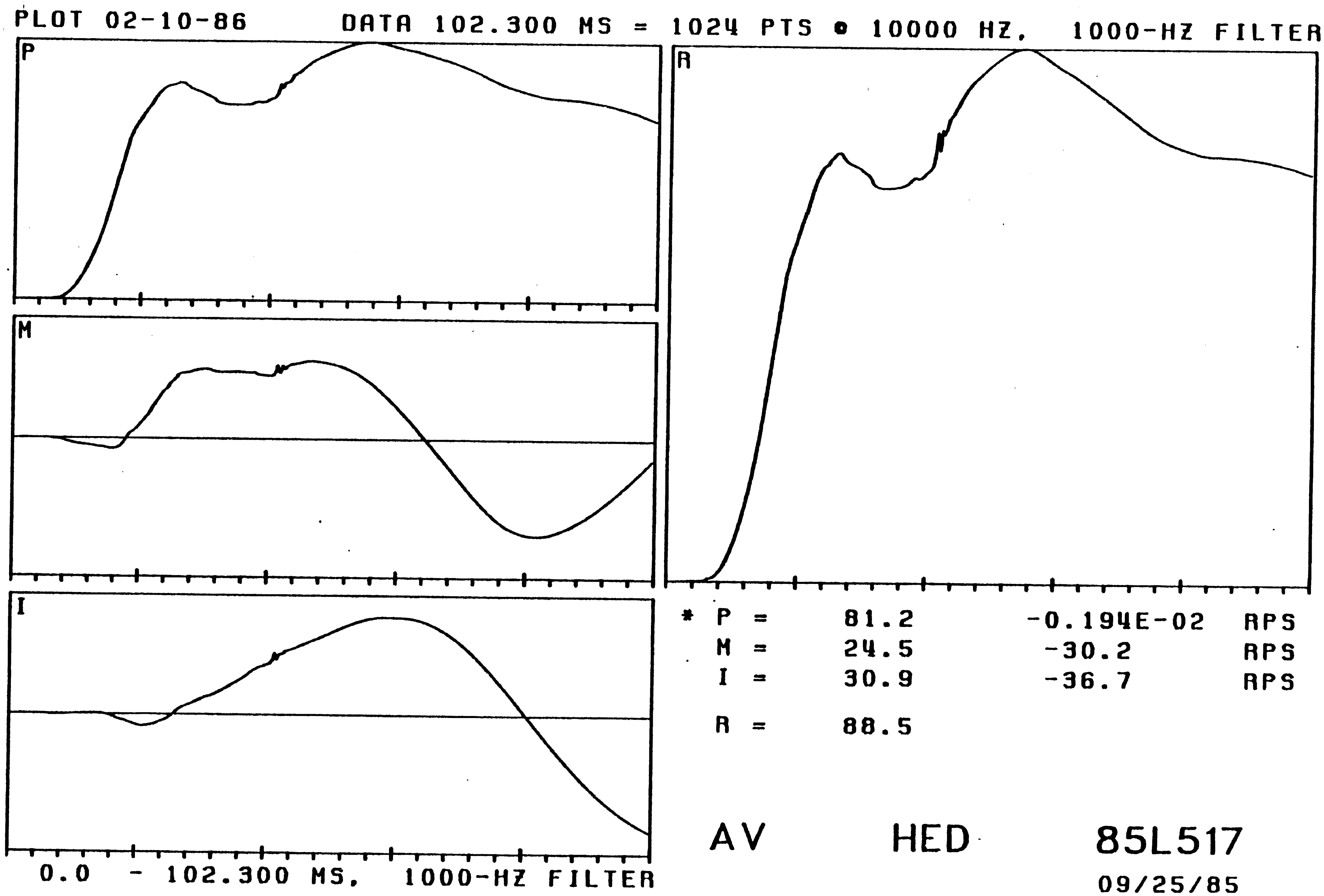
x range=50 milliseconds
y range=80.16 rads per second



* P	=	80.1	0.610E-01	RPS
M	=	24.5	-3.43	RPS
I	=	27.7	-3.86	RPS
R	=	87.6		

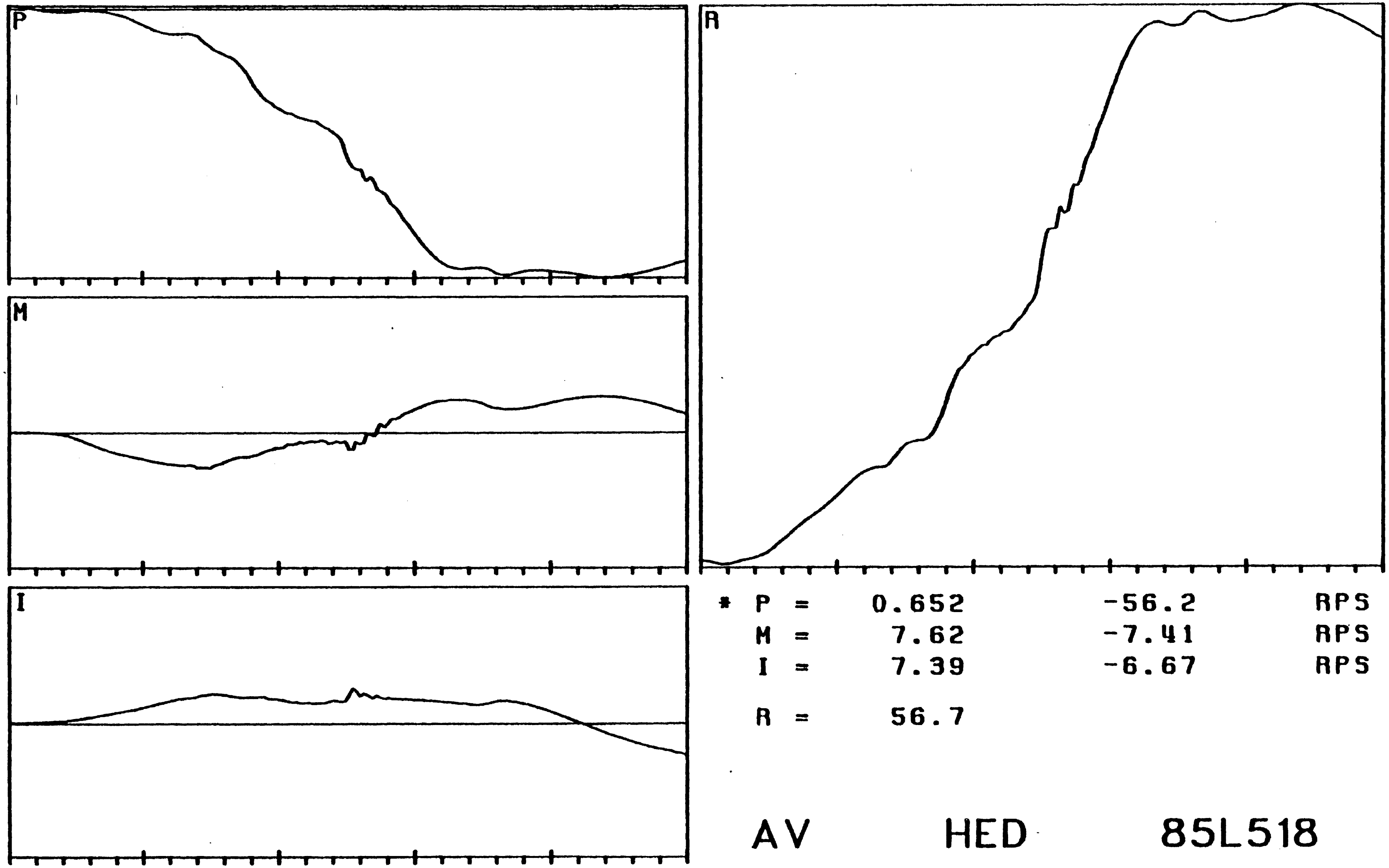
AV HED 85L517

09/25/85



x range=100 milliseconds
y range=81.2 rads per second

PLOT 02-10-86 DATA 102.300 MS = 1024 PTS @ 10000 HZ, 1000-HZ FILTER



24.800- 74.800 MS, 1000-HZ FILTER

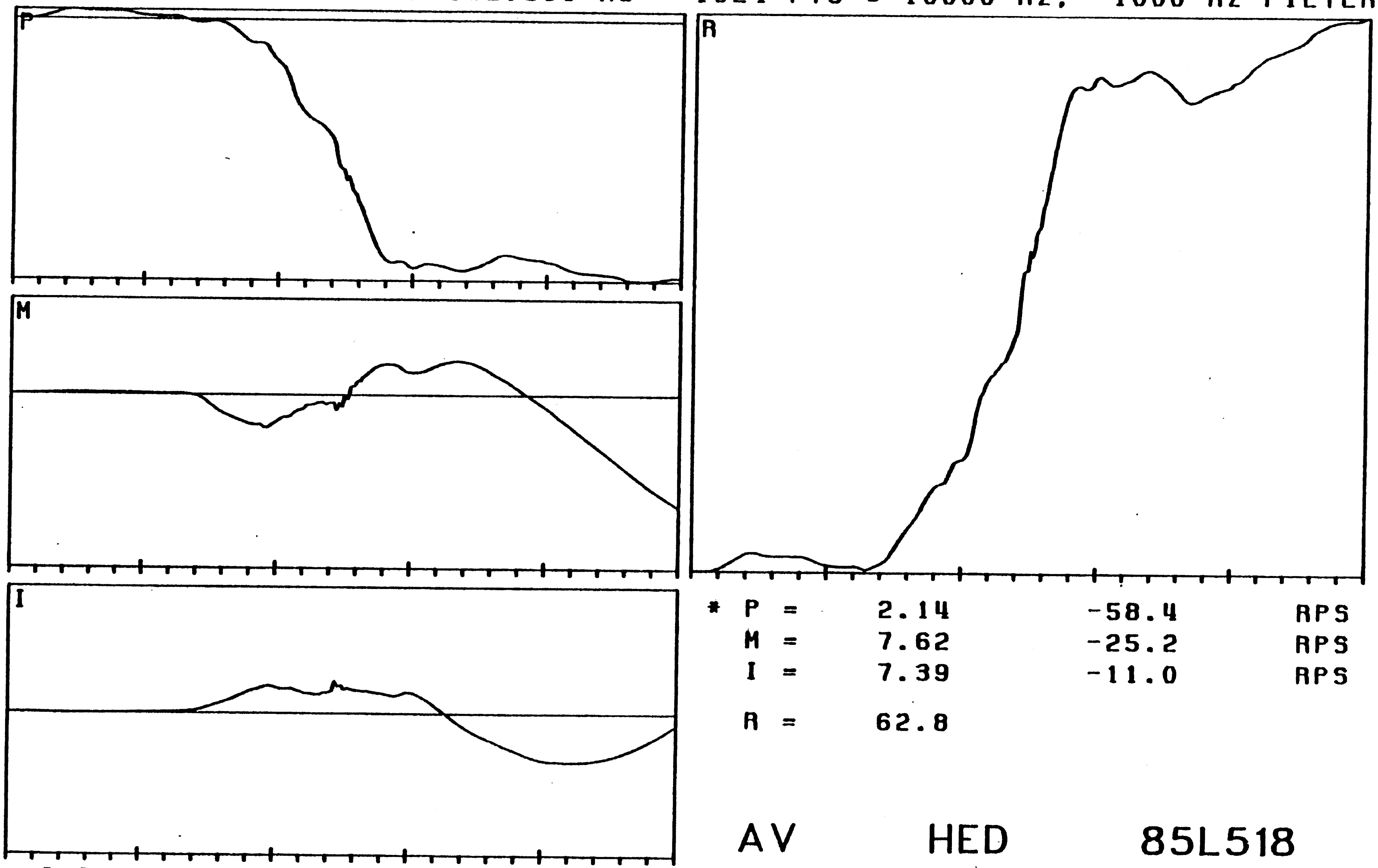
* P	=	0.652	-56.2	RPS
M	=	7.62	-7.41	RPS
I	=	7.39	-6.67	RPS
R	=	56.7		

AV HED 85L518

10/01/85

x range=50 milliseconds
y range=56.85 rads per second

PLOT 02-10-86 DATA 102.300 MS = 1024 PTS @ 10000 HZ, 1000-HZ FILTER



*	P =	2.14	-58.4	RPS
	M =	7.62	-25.2	RPS
	I =	7.39	-11.0	RPS
	R =	62.8		

AV HED 85L518

10/01/85

x range=100 milliseconds
y range=60.54 rads per second