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VIBROCARDIOGRAPHIC SYSTEM STUDY

by J. T. Celentano, P. R. Barker, and L. N. Wright

Prepared by
NORTH AMERICAN AVIATION, INC.
El Segundo, Calif.
for Flight Research Center

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • JUNE 1966

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FOREWORD

This document presents the final technical report of Subcontract DSO 1286, "PIAPACS Vibrophonocardiographic System," a part of NASA Contract NAS4-930, "Psychophysiological Information Acquisition, Processing and Control System (PIAPACS)." The technical effort covered by this report was accomplished during the period 24 July 1964 to 15 January 1965 by the Space and Information Division (S&ID) of North American Aviation, Inc.

The following personnel contributed significantly to this program: J. T. Celentano, M. D.; G. D. Kohler, M. D.; L. S. Richman, M. D.; W. F. Scheich, M. D.; H. S. Alexander; P. R. Barker; W. I. Lilley; and L. N. Wright.

All animal handling and procedures were according to the precepts of the Animal Care Panel and the American Medical Association.

This report is submitted to the Space Systems Center, Lear Siegler, Inc., Santa Monica, California.

CONTENTS

ILLUSTRATIONS

INTRODUCTION

The advent of space flight has emphasized the need for new and/or improved techniques for physiological monitoring. The approaching long-term space flights make the retrieval of data during exposure to adverse environments such as acceleration and weightlessness, of primary importance. The development of a monitoring device that can determine the effects of these environments on cardiac activity is a desirable goal. The time relationship between electrical and mechanical activity of the heart is of special interest for assessing cardiac status.

This study program was undertaken to evaluate a commercially available vibrophonocardiographic sensor and to determine the relationship between the record obtained with the sensor and the timing of mechanical cardiac events using animal subjects. This end was approached by comparing vibrophonocardiographic (VCG) data to myocardiographic (MCG), electrocardiographic (ECG), and left ventricular blood-pressure data.

This report describes the sensors used for myocardiographic and vibrophonocardiographic data gathering. A qualitative analysis of data was made, and limited conclusions were drawn.

MYOCARDIOGRAPHIC SENSOR SYSTEM

The objective of this portion of the contract was to modify the myocardial activity sensor designed under NASA Contract NAS_W-923* to provide a method of monitoring mechanical activity of the myocardium for later comparison to the sounds and vibrations generated by this activity. To accomplish this objective, general and specific design goals were established.

DESIGN CONSIDERATIONS

General Goals

Guidelines for the program were established to provide three sensor designs for either acute or chronic implant in canines. These sensor configurations were to be biologically acceptable, were not to interfere noticeably with the well-being of an implanted animal for extended periods, and were to provide a transcutaneous connector for a permanent exterior connection to facilitate postimplant recording of chronic animals.

Specific Goals

Sensor Configuration

The basic sensor design was a corrosion-resistant, stainless steel "arch" with a suture tab located at either end. These arches were used as mounting plates for semiconductor strain gauges. The three configurations fabricated differed in the sumber of strain gauges carried, the size of suture tabs, and the orientation of the electrical leads. The two configurations used for chronic implant are shown in Figures 1 and 2.

Cyclic Life

It was determined that the sensors should be capable of operating for at least 20,000,000 cycles to satisfy the requirements of this program.

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*Development of Vibrocardiographic Instrumentation," Contract NASw-923. Final report published by NAA/S&ID as Report No. SID 64-1221 (30 June 1964).

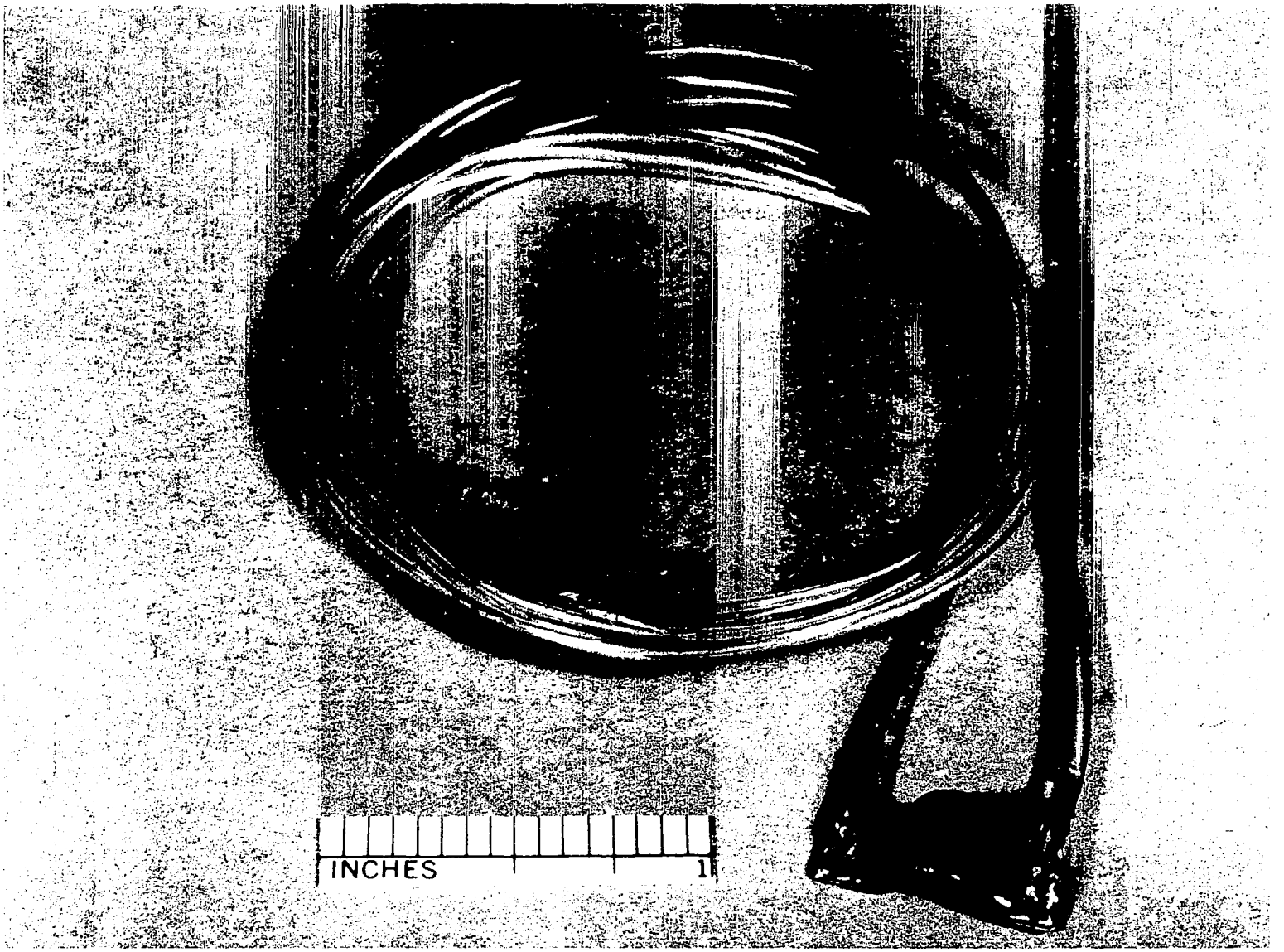

Figure 1. Typical MCG Strain-Gauge Sensor—Inner and Outer Strain Gauge

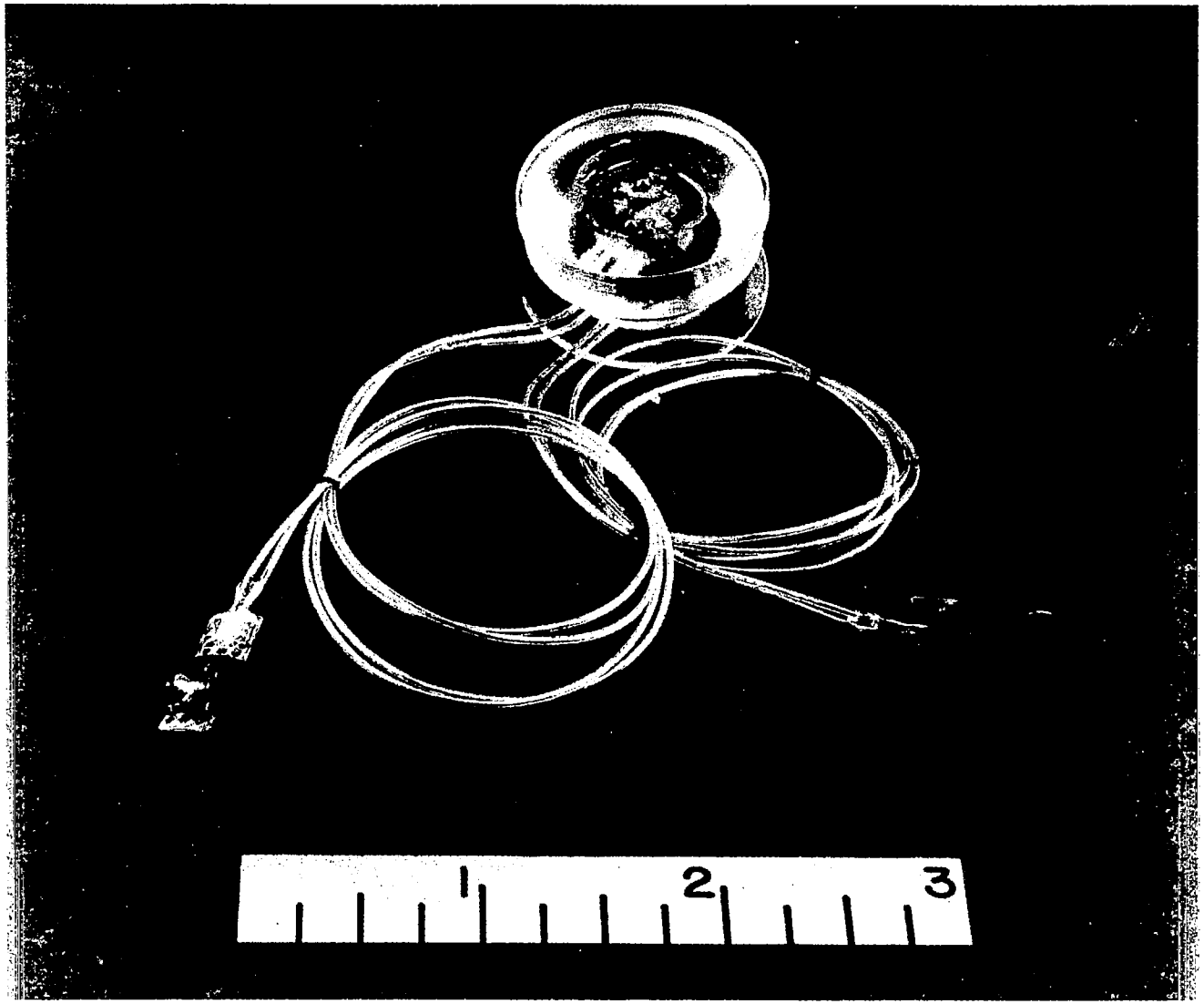

Figure 2. Typical MCG Strain-Gauge Sensor—Two Single Strain-Gauge Sensors and Transtissue Connector

Biological Interface

Materials used in sensor fabrication were selected for biological acceptance and physical properties based on previous experience of the contractor and other researchers. The critical or interface materials were: polyurethane for sensor encapsulation and connector potting; polyethylene insulation for electrical leads; and Plexiglas for transcutaneous connectors.

Electrical Characteristics

The following electrical characteristics were chosen based on sensor sensitivity, cyclic life, and animal safety:

1. Strain Gauges - Silicon semiconductor strain gauges with nominal resistance of 500 ohms ±15 percent were bonded to each metal arch. Individual gauges had their own separate pair of electrical conductors.

2. Power - Bridge bias was established at 6 volts D-C to provide adequate sensor output to permit remote recording without the use of buffer amplifiers and insure animal safety in case of accidental shorting.

3. Strain-Gauge Installation - Three sensor configurations were used. Two groups of five, each had one strain gauge on the outside radius of the metal arch; and one group of five carried two strain gauges, one on the outside radius and the second on the inside radius of the metal arch.

4. Electrical Conductors - An NAA-designed 28-gauge, polyethylene-insulated cable was used for electrical conductors. This cable was designed for: (1) minimum moisture absorption, (2) maximum mechanical flexibility and resiliency properties, and (3) minimum diameter. All electrical conductors used in sensor fabrication were subjected to a wet dielectric test.

SENSOR ASSEMBLY FABRICATION

Metal Details

The metal arches of the sensors were formed from 0.004-inch by 0.250-inch 17-7 PH, condition "C" stainless steel. After the parts were formed, suture holes were drilled in the tabs. The parts were then heat treated in an argon atmosphere and aged to provide a tensile strength of 180,000 to 200,000 psi. Electroplating (nickel, silver, and gold) was applied to the tabs to increase suture hole edge radius.

Strain Gauges and Electrical Conductors

Silicon strain gauges (P/N 110001-001 with a resistance of 500 ohms ±15 percent, Micro Systems, Inc.) with appropriate intermediate conductors and solder tabs were bonded with epoxy (No. 6203, Epoxylite Corporation) to the specified surface (s) of the arch by Micro Systems, Inc. This manufacturer also soldered and cemented with epoxy (No. 6203) a pair of polyethylene-insulated electrical conductors (P/N 3006-28-16-PE, Calmot Wire and Cable) to each strain gauge. The ends of the polyethylene-insulated conductors attached to the sensor were roughened with sandpaper before attachment to enhance the adhesive bond.

Assembly Encapsulation

The entire sensor assembly, including the sanded insulation on the electrical conductors, was cleaned by wiping with trichloroethylene. A two-part, clear polyurethane primer (CS 9937, Chem-Seal Corporation of America) was applied to the cleaned area. When tack-free, the sensors were dipped in a two-part, clear polyurethane (CS 3502, Chem-Seal Corporation of America). This material was mixed, heated, and degassed according to the manufacturer's recommendations. After dipping, the parts were cured for 6 hours at a temperature of 180 degrees F.

Transcutaneous Connectors

Transcutaneous connectors were machined from clear Plexiglas (Rohm and Hass) bar stock. After machining, the flange to underly the skin was heated and curved for anatomical conformity. Holes were drilled through the connector wall adjacent to the subcutaneous flange to permit passage of the electrical conductors into each connector. A four-pin (female) electrical connector was fabricated by modifying a standard five-pin socket (M5S, Winchester or equivalent). After the insulation was sanded, the electrical conductors were passed through the holes in the connector and soldered to the electrical sockets. The connections were then potted with epoxy (Epon 911-F, Shell Chemical Co.). Polyurethane primer (CS 9937) was in turn applied to the mating surfaces of the transcutaneous connector, electrical socket, epoxy, and sanded insulation of the electrical conductors that would remain within the transcutaneous connector. Polyurethane (CS 3502) was then used to pot the electrical connector to the transcutaneous connector. The flange around the upper perimeter of the transcutaneous connector was sized to accept a plastic, snap-on cap.

SENSOR CALIBRATION

Calibration data were obtained for each myocardiographic (MCG) sensor after encapsulation. Measurements of strain-gauge resistance were made

corresponding to changes in compressive and tensile forces applied to the metal arch. These forces were applied by placing the sensor in a calibration fixture. One end was anchored to the fixture, and the other end was attached to a sliding bar from which calibrated weights were hung. Compression and tension were obtained by turning the fixture over. Forces were applied to the sensor which caused resistance changes of approximately 10 percent beyond the anticipated operating range to determine linearity.

In addition to the force versus resistance measurements, the sensors were also calibrated at temperatures of 77, 100, 101, and 105 degrees F to allow evaluation of strain levels at body temperature when implanted.

AUXILIARY EQUIPMENT

Conversion of the mechanical activity of the strain gauge to a recordable electrical signal was achieved by constructing a bridge balance box. This unit contained three D-C bridges that permitted monitoring of up to three strain-gauge elements simultaneously. Provisions were made to allow balancing of each bridge for the various sensors by incorporating a potentiometer in one leg and providing external jacks for a null meter and for substitution resistance.

VIBROPHONOCARDIOGRAPHIC SYSTEM

The objective of the second phase of this program was to procure a commercially available external vibrophonocardiographic (VCG) sensor and compare its output to that obtained from the myocardiographic (MCG) sensors. Ling-Temco-Vought's (LTV) condenser microphone system developed in cooperation with Dr. C. Agress* was procured for this purpose.

The LTV-3B Condenser Microphone System (Figure 3) utilizes a very sensitive condenser microphone in a well-stabilized RF bridge circuit. The system is capable of an over-all flat frequency response (when calibrated on a piston phone) from D-C to beyond 2000 cps; however, the low frequency can be rolled off at any point up to 10 cps by adjusting an air leak to the face of the microphone. The system senses diaphragm displacement at all frequencies of interest above the low-frequency break-over point. At frequencies below this point, velocity rather than displacement is measured. Should there be an additional roll-off incurred either purposely or accidently, then acceleration could be measured. In a hypothetical case, should the microphone system used start its roll-off at 10 cps with -6 db/octave and at 5 cps an additional roll-off of -6 db is added, displacement would be measured above 10 cps, velicity between 5 cps and 10 cps, and acceleration below 5 cps. In other words, each change which makes the slope of the roll-off of the response steeper as frequency goes down is analogous to differentiation and therefore will produce, first, velocity and, secondly, acceleration functions from the displacement function obtained with a tightly coupled, flat pressure response condenser microphone system. Therefore, it the pressure response of any condenser microphone system is known, its output function for any given frequency region can be analyzed in the same way.

As shown in the frequency-response curves in Figure 4, the LTV condenser microphone operated as an element in an RF bridge provides a relatively flat frequency response when subjected to pressure changes. The modified LTV 3-B system used in this study is flat (±1/2 db) from 3 cps to 1700 cps with a roll-off of approximately - 6 db/octave below 3 cps. As discussed above, the sensor measures displacement between 3 cps and 1700 cps and since the roll-off is not a constant slope, both acceleration and velocity are measured below 3 cps.

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*C. Agress, M. D., Institute for Medical Research, Cedars of Lebanon Hospital, Los Angeles, California.

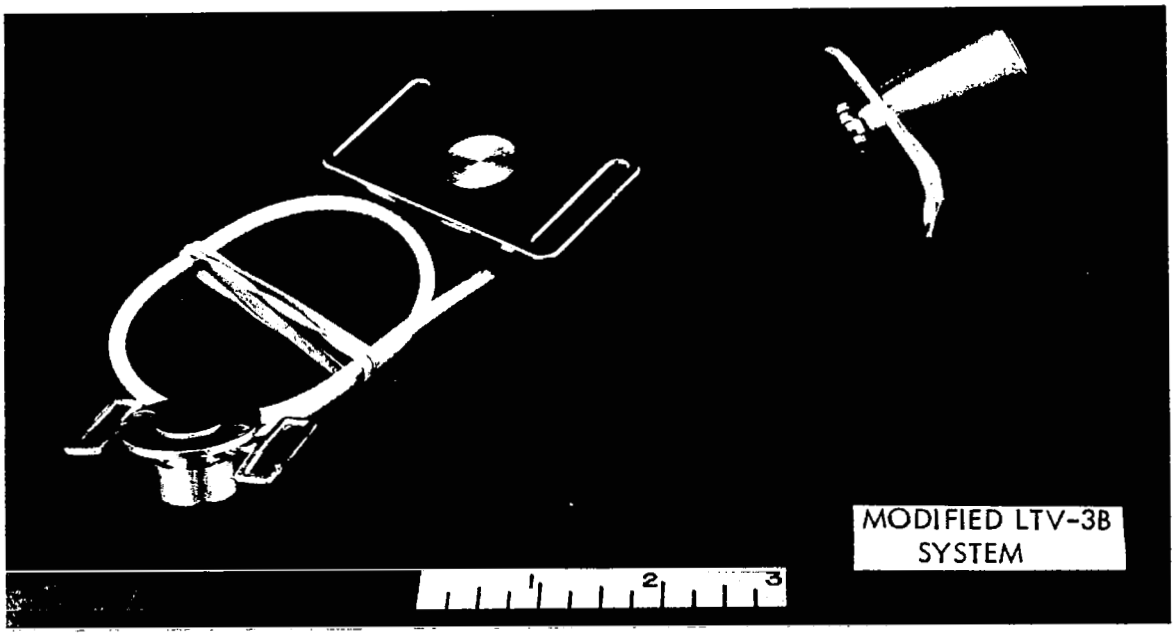


Figure 3. VCG Sensor Assemblies

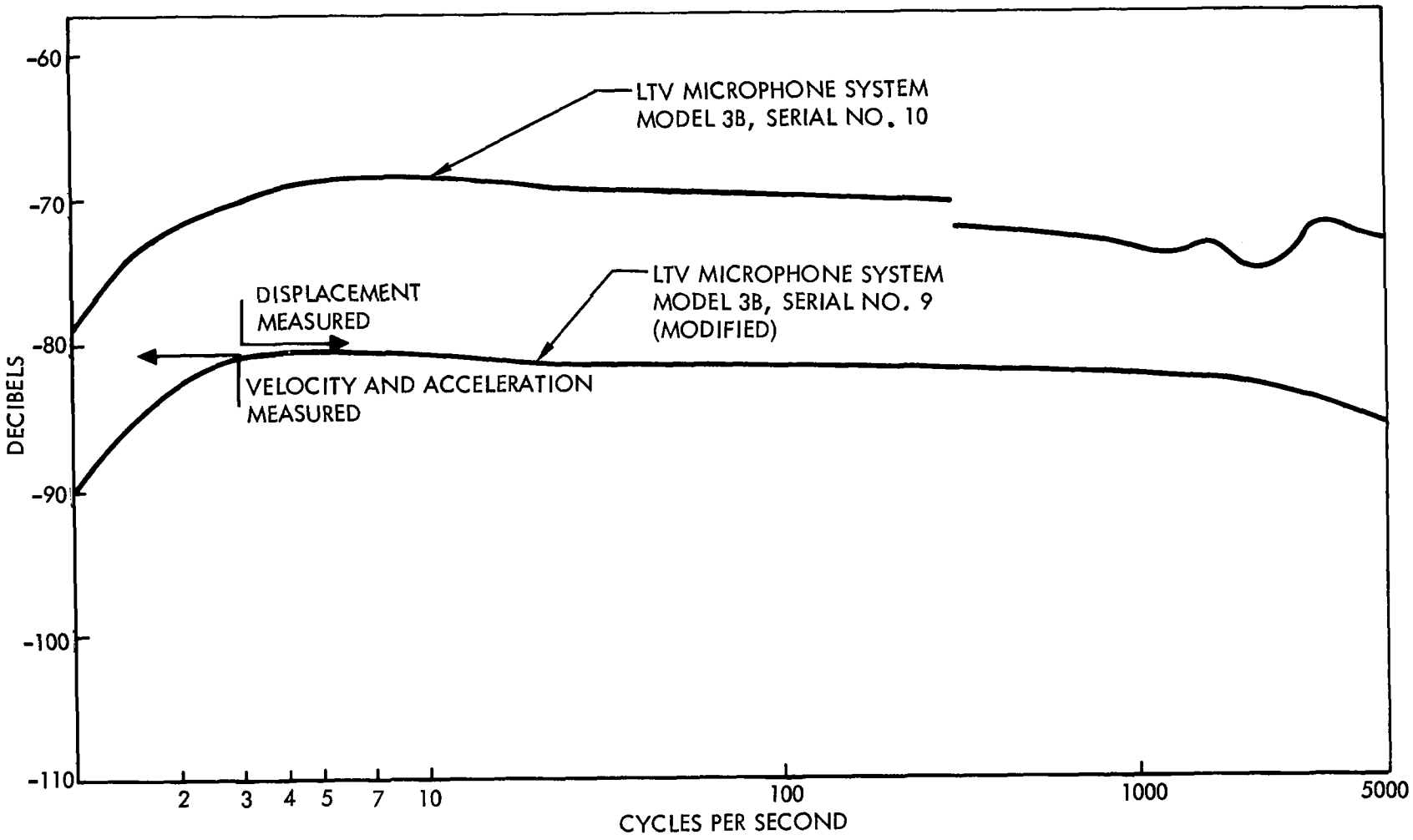


Figure 4. Frequency-Response Curves

DESIGN CONSIDERATIONS

General Goals

The design approach to the development of an external vibrophonocardiograph sensor was to obtain a commercially available unit and modify it to provide a sensor which, by proper mounting, would provide artifact-free recordings from an exercising subject.

Specific Goals

After selection of the sensor, the following specific design changes were undertaken: (1) remote the sensing element from the electronic package, and (2) provide a sensing element with minimum weight and volume.

In addition to sensor modification, a method of attachment was sought to reduce motion artifacts and provide a maximum of subject comfort.

Sensor Modification

Of the three LTV-3B VCG systems purchased for this effort, one was modified. The original modification was incorporated by the manufacturer and incorporated all of the preset requirements. However, the weight and volume of the pickup was too great and resulted in a cumbersome configuration.

The system was further modified by NAA to incorporate a smaller, lighter pickup at the end of a longer interconnecting cable, as shown in Figure 3. The cable came out the side of the electronic component housing allowing the base plate to lay flat against the subject. At the completion of this modification, the sensor pick-up assembly weighed 13.1 grams.

Sensor Calibration and Testing

Prior to the collection of animal data, the microphone systems were calibrated for sensitivity and frequency response (Figure 4). Low-frequency calibration from 0.1 cps to 300 cps was accomplished using a Neuman Piston Calibrator. Frequencies from 200 cps to 5000 cps were applied in an acoustic chamber and monitored by a Bruel and Kjaer 3rd Octave Analyzer, and the output was compared to a standard microphone of known sensitivity and response.

The modified sensor system has a basic sensitivity of -81 db (ref/volt/dyne/cm^2), and a typical unmodified system has a sensitivity of -74 db. The over-all frequency response is better in the modified system since it is flat (±1 db) from 2.3 cps to 2000 cps. The unmodified system that was calibrated

shows a response that is flat within ±1.5 db from 2 cps to 500 cps. It should be noted that the 2-db drop between 300 and 500 cps most likely resulted from a mismatch of calibration apparatus.

Environmental testing of the modified sensor included operation in a calculated 100-percent oxygen environment over a pressure range of 0 to 20 psia. This was performed in a sealed chamber and accomplished by pulling a vacuum on the chamber and then filling with oxygen. This technique was utilized four (4) times with the system operating. At the last saturation of oxygen the pressure was held at 20 psia and the microphone system operated for a period of thirty (30) minutes.

Sensor Attachment

The standard VCG sensor was attached to the animal subjects by placing a standard Sanborn rubber chest strap (ECG) through the loops provided in the base plate of the sensor (Figure 5). The strap was placed around the chest of the subject, and sensor placement and strap tension were adjusted to provide the optimum output. This scheme worked satisfactorily on anesthetized animals; however, in the case of unanesthetized subjects, the left foreleg impinged upon the sensor assembly, forcing it off the apical beat.

Several approaches were taken to provide a mounting for the modified sensor. Two techniques were finally evolved that provide some degree of success in obtaining recordings from active animal subjects. The first approach utilized silicone rubber mounting pads molded to the individual animal's rib cage, over the apical beat. Pads were, in turn, housed in a plastic cup and were strapped to the animal. A problem occurred, however, when the animals were standing; the left foreleg would force the microphone off of the point of apical beat, causing a reduction in signal output.

To overcome this problem, an adapter plate was made to thread onto the end of the microphone element, which reduced the size of the microphone attachment assembly. Two loops were attached to this plate to provide for attachment by a rubber strap. Good data were obtained from unanesthetized animals in both sitting and standing positions.

Figure 5. MCG Strain-Gauge Sensor Implantation

EXPERIMENTAL PROCEDURES

SUBJECTS

Mongrel dogs were used for acute procedures, and mature male Beagles (Rockridge Kennels, Rockridge, Missouri) were used for chronic experiments. The animals were maintained in appropriate stainless steel and/or fiber glass cages, and exercised daily in runs. The routine diet consisted of "Prescription Diet" Dietary Animal Food (Hill Packing Company). All Beagles were quarantined a minimum of 21 days prior to chronic implantation of myocardiographic (MCG) sensors. Animals were immunized against distemper and hepatitis at the Rockridge Kennels. All animal handling and procedures were according to the precepts of the Animal Care Panel and the American Medical Association.

PROCEDURES

Implantation of Myocardiographic Sensors

MCG sensors were sutured to the myocardium (Figure 5) with the connecting electrical conductors leaving the pleural cavity and coursing under the skin to a transcutaneous connector that was fixed through the skin, over the back musculature.

Catheterization

A cardiac catheter was inserted into the femoral artery and introduced into the left ventricle, while the animal was anesthetized, to provide aortic and ventricular pressure data.

Rib Resection

A procedure involving resection of two inches of the left fifth rib to the sternum was performed. The MCG sensor was sutured to the skin, then to the rib musculature, then to the pleural peritoneum after the rib was removed. Each site was simultaneously sampled with the vibrophonocardiograph (VCG).

Reinsertion/Replacement of Transcutaneous Connectors

Several transcutaneous connectors had to be reinstalled and/or replaced after spontaneous rejection. Reinsertion methods varied. The connector was

sutured to the musculature over the spinal column or directly to the skin. Reinsertion was successful when the connector was sutured to a clean wound area and fixed to the underlying musculature.

Recordings

Recordings were done under anesthesia, during surgical procedures and also postoperatively when animal motion was undesirable. Recordings were otherwise made without anesthesia. Figure 6 shows an example of recording from an ambulatory animal.

MCG data were acquired by using the sensor as one leg of a balanced bridge and feeding the output signal into a Sanborn Model 2700 preamplifier. The VCG and ECG were also monitored by a Model 2700 preamplifier.

During implant and/or catheterization, the waveforms of the ECG and/or blood pressure were monitored on a Tektronix Model 555 Oscilloscope.

OPERATIVE TECHNIQUE AND SURGICAL COURSE OF EXPERIMENTAL ANIMALS

Acute Experiments

Criteria for MCG sensor suturing, orientation, and location were evolved from four acute experiments with mongrel dogs. Primary importance was placed on determining the MCG sensor placement technique necessary to provide the earliest indication of cardiac mechanical activity.

Animals No. 1 Through 4

The weight of the dogs ranged from 11 to 20 kilograms. The anesthesia was accomplished by injecting sodium pentobarbital intraperitoneally and/or intravenously at a level of 27 to 28 mg/kg of body weight. The rib cage was opened on the first animal by resecting the entire sternum and on the other three canines by resecting the fourth and the fifth ribs on the left side. The pericardial sac was opened, and the MCG sensor(s) was (were) sutured to the myocardium on multiple locations, changing their positions from a minimum of 9 times to as many as 27. Subsequently, these animals were terminated by injecting intravenously lethal doses of sodium pentobarbital.

Chronic Experiments

Upon completion of the acute experiments, six mature male Beagles were instrumented with MCG sensors. Postimplant calibration catheterizations were undertaken on all animals. In addition, transcutaneous connector

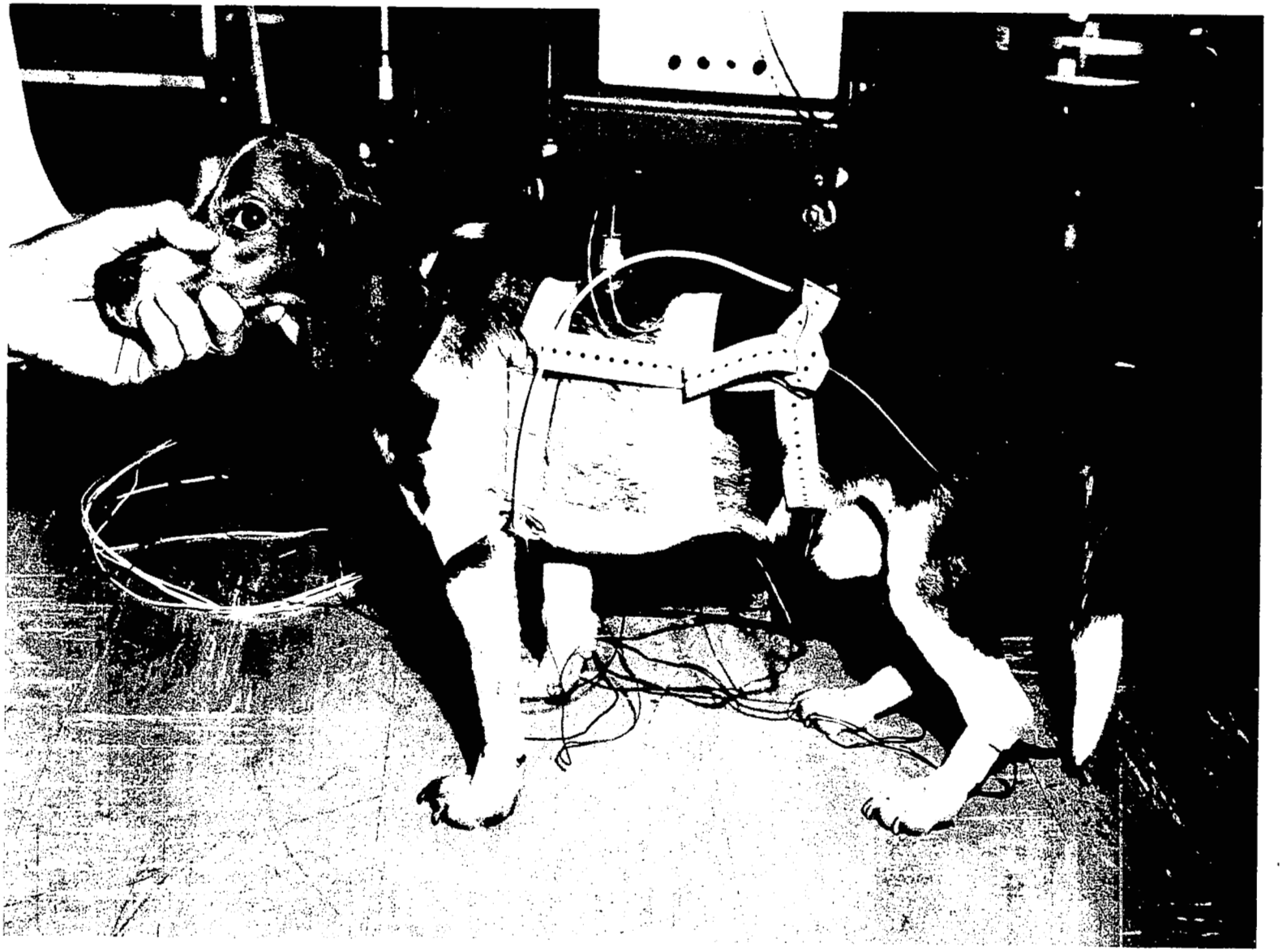


Figure 6. Animal 11 (Ambulatory), VCG, MCG, and ECG Recording Session

reinstallation and/or replacement were/was required in some instances. After completion of the six implants, one Beagle rib resection was accomplished (Animal No. 12).

Animal No. 5

The surgical procedure for implantation of the MCG sensor was attempted on 16 October 1964. The anesthesia was accomplished by administering sodium pentobarbital intraperitoneally at a level of 27 to 28 mg/kg of body weight. The skin of the animal was prepared by shaving the hair, thoroughly scrubbing with Phisohex, and, finally, washing with benzalkonium chloride. An intratracheal tube was inserted and connected to a Bird respirator. The skin incision was made over and along the fifth right rib. The rib was exposed, the periosteum peeled back, and a 7-cm section of the rib resected without penetrating the pleura. After the pleural cavity was opened, the lung tissue was held back by moist sponges and the heart exposed. At this point the intratracheal tube came out of the trachea without being recognized immediately. Cardiac resuscitation (internal cardiac massage and administration of oxygen) was unsuccessful, and the animal expired because of anoxia.

Animal No. 6

The anesthesia and skin preparation was accomplished in the same manner as for Animal No. 5. After the intratracheal tube was inserted and positive respiration was established, a skin incision was made in the same site as previously described. The rib was exposed, the periosteum peeled back, and a 7-cm section of the rib resected without damaging the pleura. After the pleural cavity was opened, the lung tissue was held back by moist sponges and the heart exposed. The pericardial sac was opened wide, and the heart was elevated slightly with the help of Allis clamps attached to the pericardium edges. The MCG sensor was sutured with a 5-0 Mersilene (P/N R-870, Ethicon, Inc.) to the myocardium of the left ventricle on the central aspect near the apex perpendicular to the longitudinal sulcus. The pericardium was left open. The fourth and sixth ribs were approximated with a stainless steel suture. The pleura was closed with 3-0 silk running sutures. The electrical conductors were buried in the subcutaneous tissue, and the transcutaneous connector was secured in an area between the shoulder blades over the thoracic spine with a purse string suture. Skin closure, over the electrical conductors, was accomplished with 00 silk interrupted mattress sutures. A sterile dressing was applied consisting of gauze sponges and stockinette. Postoperatively, Demerol was given for pain and antibiotics (penicillin and streptomycin) for seven consecutive days. The recovery was uneventful. A cardiac catheterization was performed on 6 November 1964; reinsertion of the plug was necessary at the same time. The animal exhibited no postoperative complications and no evidence of wound infection.

Animal No. 7

A similar implant procedure as on Animal No. 6 was carried out on 22 October 1964. The MCG sensor in this case was attached to the right ventricle at the apical region perpendicular to the longitudinal sulcus. A left ventricular calibration catheterization was successfully carried out on 10 November 1964; again the transcutaneous plug had to be replaced. No postoperative complications developed, and the animal exhibited an excellent postoperative course.

Animal No. 8

A similar implant procedure as on Animal No. 6 was carried out on 29 October 1964, in which the MCG sensor was located in an identical position over the left ventricle. A fistula that developed at the abdominal end of the skin incision postoperatively closed up in approximately two weeks after daily irrigation with saline/peroxide and an antibiotic topical ointment. The course subsequently was uneventful.

Animal No. 9

A similar implant procedure was carried out on this animal on 5 November 1964, with the MCG sensor placed perpendicular to the longitudinal sulcus close to the apex over the left ventricle. The first calibration catheterization was terminated because of equipment failure on 24 November. A procedure to obtain calibration catheterization information in addition to resection of a portion of the left fifth rib was undertaken on 11 December 1964; however, the animal expired during the procedure. Autopsy indicated that the catheter tip had punctured the thoracic aorta, followed by death by exsanguination. The autopsy report was as follows:

On opening the thoracic cavity, no free exudate was found. There was a massive hemorrhage surrounding the aortic arch and within the upper one-third of the mediastinum. The left lung was extensively adherent to the ventral aspect of the heart. There were tent-like strands of fibrotic tissue connecting the apex of the heart with the left semidiaphragm. The sensor was found to be completely encased in fibrotic tissue involving the major part of the ventral aspect of the heart and adjoining parts of the left lung. However, the sensor was not adherent to these parts. On opening the left ventricle of the heart, a small amount of granulation tissue was found at the central portion of the aortic valve. The thoracic aorta was opened, and two perforations measuring one-eighth of an inch and one-quarter of one inch apart were found between the origin of the brachiocephalic and the left brachial artery; probing of these perforations led into the center of the blood clot surrounding the aortic arch.

Animal No. 10

A similar implant procedure was carried out on 17 November 1964, except for the following: a pair of MCG sensors was sutured to the myocardium at a 90-degree angle to the longitudinal sulcus of the heart—one over the right ventricle 4-cm cranially from the apex and the other 3-cm cranially over the left ventricle. Postoperatively, this animal developed an extensive necrosis of the skin of the back and both flanks, probably as a result of reaction to the benzalkonium chloride solution used for surgical preparation. This skin condition cleared up eventually with daily dressing changes and medication with systemic and topical antibiotics, and the animal recovered.

Animal No. 11

A similar implant procedure as on Animal No. 10 was carried out on 24 November 1964. A pair of MCG sensors was sutured to similar locations over the left and right ventricles. The animal underwent cardiac calibration catheterization on 9 December. There were no postoperative complications.

Animal No. 12

The surgical procedure on this animal consisted of resecting approximately 7-cm's of the sixth left rib in order to test sensors on several tissue layers from the intact skin down to the unopened parietal pleura. Initially, an MCG sensor was sutured to the skin of the left thoracic wall over the point of maximum intensity (PMI) of the heart. Then the sensor was implanted to the rib musculature over the PMI. After removal of a rib, the sensor was fixed to the parietal pleura over the PMI. These sites were tested simultaneously with the modified VCG. This animal recovered uneventfully despite extended time of anesthesia (five hours).

DATA COLLECTION

All data were recorded simultaneously on a direct writing or optical oscillograph and on magnetic tape. Most records were taken on a Sanborn Model 350 oscillograph with appropriate preamplifiers. The oscillograph power amplifier output was fed to a Sanborn Model 2007 FM Magnetic Tape Recorder. This system provided an instantaneous recording with frequency response of dc to 125 cps and a magnetic tape recording with a frequency response of dc to 2500 cps.

To observe the higher frequency characteristics of the instantaneous recordings, several records were made with a Sanborn Model 568M optical recorder. This provided a visual record with frequency response flat to 500 cps.

Blood pressure recordings were obtained with a system consisting of a Statham P23b pressure transducer; Goodale-Lubin single lumen, birdseye tip, 6FX100CM cardiac catheter; B-D syringe; and appropriate stopcocks.

RESULTS

A large amount of data were collected during the study, and representative samples appear in the Appendix. Since much detailed discussion is presented with these figures, only a summary of the results obtained is presented here. The purpose of the several acute surgeries was to provide preliminary information for the chronic implant procedures. The purpose of the chronic implants was to provide data about the external vibrophonocardiograph (VCG) using the myocardiograph (MCG) as the basic index of mechanical activity, and obtaining these results in an animal well recovered from surgery and with an intact left chest wall.

ACUTE ANIMAL PROCEDURES

The first three acute surgeries were performed to determine the effect of depth and placement of sutures upon MCG sensor output. As long as the angle of the sutures did not stray too far from the vertical and were tight so that there was no motion of the MCG sensor with respect to the heart surface, the output of the sensor was relatively constant. If the sutures were loose, or if the angle was very great, tending to pull a suture away from the sensor or bunch the cardiac muscle under the sensor, the response was greatly distorted. A snugly tied suture with a depth of one to several millimeters gave uniform response.

The third surgery involving the use of three MCG sensors sutured to multiple sites was undertaken to study the effect of position upon the anterior surface of the heart and orientation with respect to the vertical and horizontal axes of the heart. During the three and a half hours that the heart was exposed, numerous placements were examined. The results of this study appear in Figures A-1 through A-7. From this study, the best locations for giving the earliest indication of mechanical activity as well as the wave form providing easiest identification of events were determined. Two sites were identified: (1) approximately 1 to 2 cms from the point of the apex on the left ventricle parallel to the diaphragmatic surface; (2) the middle of the right ventricle with one leg of the sensor sutured to the longitudinal surface and parallel to the diaphragmatic surface.

CHRONIC ANIMAL PROCEDURES

Myocardiograph

Figures A-8 through A-37 are records obtained during the implant surgeries and the chronic period thereafter. The wave shapes obtained from

the implant day, whether right or left ventricle, were generally the same in all cases. Electromechanical delay generally varied between 0.04 to 0.06 seconds and was related to sensor location. However, in any one animal, the electromechanical delay has been shown to be relatively constant in all succeeding recordings. Figure A-47 shows records obtained from an animal implanted during a previous study program. Although one of these records was obtained 12 days after the implant surgery and the other 214 days later, the electromechanical delay is the same as well as the general shape of the wave. In this regard, after the immediate postimplant period, some degradation in wave generally occurred; however, this amounts to a flattening, not a change in character, leaving identifiable events.

In all records examined, respiration appears to have no effect upon electromechanical delay, nor does heart rate. Any variation in timing between left ventricular pressure and electrocardiogram (ECG) among different animals does not appear to be reflected in the MCG. Positioning of the animal appears to have no effect upon MCG response. In one case, as shown in Figures A-24 through A-27, an MCG sensor was sutured to the external chest wall at the apex of one of the animals with an implanted MCG. In this case, the response of the external MCG was opposite to that of the implanted MCG; that is, when one was compressed the other extended. However, as can be seen from the record, there is no time phase shift; that is, there is no lag between the event occurring in the myocardium and the equivalent response at the chest wall. The opposite action of the two sensors may have been due to the adhesions formed between the heart and the chest wall, as this record was obtained many weeks after implant.

The final chronic surgery consisted of a procedure involving resection of several inches of the left fifth rib to the sternum in order to assess the effect of the chest wall on both the VCG and MCG response. Records were made with both sensors externally placed on the intact chest wall and then at several depths with the final placement on the external pleura after the rib was resected. The results of this surgery are shown in Figures A-38 through A-46. Although minor changes in wave shape occurred at the various levels, cardiac events of interest could be identified. It is most significant that the electromechanical delay with both MCG and VCG sensors remained relatively constant from the record obtained on the external chest wall to that of the pleural surface.

Vibrophonocardiograph

Numerous vibrophonocardiograms are shown with events of interest labeled. Using the ECG and the MCG as indices for timed relationships, VCG records were examined. Electromechanical delay is slightly longer with the VCG than the MCG but it is also relatively constant in nature. With

the MCG as an absolute index of mechanical activity, the major VCG deflections can be correlated to cardiac mechanical events. There appears to be no question that the VCG interpretation of isometric contraction, in addition to opening and closure of the semi-lunar valves, is correct (J_1, J_2, and L waves).

Two major problems present themselves when using and interpreting the VCG. First, noise and motion artifacts easily distort the pure apical signal and, unfortunately, most of this interference is in the range of interest. Second, different body positions, especially where the heart is moved away from the left chest wall, change the wave shape and can make interpretation difficult. Of the several mounting techniques, those that allow transmission of body motion to the sensor such as a rubber strap give the greatest problem, although the use of a dampening interface medium, such as plasticene modeling clay, serves to attenuate motion artifact. On one occasion, two LTV microphones were used, one on the apex and the other on the right chest, and the signals fed to a differential amplifier in an attempt to reduce the noise level. This procedure was not successful because the sensors were overdriven and proper phasing could not be obtained.

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

1. Sufficient data have been obtained during this program to establish the myocardiographic (MCG) sensor as a basic tool for studying mechanical activity of the heart. The greatest asset of this device lies in the fact that animals can be chronically instrumented and subsequently studied under a variety of conditions for a long period of time and thus can have valuable application in applied research.

2. Physical position of the animal has no effect upon the MCG signal.

3. Electromechanical delay does not change for a particular animal even after extended chronic implantation of an MCG sensor.

4. A problem with the use of the chronic MCG implant is in the rejection of the transcutaneous connector by the animal subjects. Once the connector is well accepted, however, this is no longer of concern.

5. The MCG sensor mounted on a suitable template could provide a tool for studying external apical vibrations when positioned on the apex. In this mode it would approximate a point sensor.

6. In the vibrophonocardiographic (VCG) and MCG recordings obtained, changes in electromechanical delay are not apparent during the respiratory cycle.

7. Although the data are limited, time phase shifts across the chest wall are not apparent with either the VCG or MCG. This preliminary information suggests that, as far as transmission of the apical impulse across the chest wall is concerned, the wall acts as a piston. Thus, the interpretation of cardiac events from the external apical vibration would be in phase with the corresponding event of the heart itself. This justifies the use of an external sensor, such as the VCG, for studying mechanical activity of the heart.

8. The VCG events can be correlated to the actual mechanical events of the heart as identified by the MCG. The major events of the VCG—isometric contraction and semi-lunar valve opening and closing—have been correctly identified (J_1, J_2, and L waves). It is thus most feasible to use VCG for determining the electromechanical delay of isometric contraction and the rejection time.

9. Noise and motion artifact must be eliminated if the VCG is to become a practical tool for studying electromechanical delay when a subject is active. Electrical filtering, transducer attachment techniques, and noise canceling procedures should all be pursued.

10. If qualitative evaluation of large quantities of analog material is to be made, analog-digital techniques should be employed. If quantitative evaluation or statistical determination are to be made, analog-digital techniques are essential.

RECOMMENDATIONS

1. The time phase relationship of apical vibrations across the chest wall should be examined in more detail to establish beyond question or refute the concept that the chest wall acts as a piston. In conjunction with this, an attempt should also be made to establish the transfer function of the chest wall.

2. In order to make the VCG a usable device for flight and applied research, transducer interface material, attaching techniques, and noise canceling procedures must be studied.

3. The MCG and other similar displacement sensors should be evaluated for use on the external chest.

4. Design techniques for transcutaneous connectors to be used in animal implant experiments should be studied to devise optimal configuration and material to reduce/overcome rejection problems.

APPENDIX

RECORDED DATA

Recorded data derived from the acute and chronic animals during this program are presented in Figures A-1 through A-47.

NOTE: Prior to the chronic surgeries, four acute surgeries were performed. The purpose of these procedures was to ascertain the effect of suture position, depth, tightness, and myocardiograph (MCG) sensor location upon electro-mechanical timing relationship. The first three acute surgeries indicated that suture depth need only be to the extent required to provide certain and continued positioning of the MCG sensor. A bite of several millimeters or more was found to be adequate and variations in depth did not affect sensor output. However, placement of a loose suture provided an erratic and frequently uninterpretable sensor signal. In addition, as long as the direction of the suture was generally perpendicular to the point of insertion, no variation in sensor response was noted.

The series of following figures (A-1 through A-7) relate to the fourth acute surgery, which was accomplished to determine the best location and orientation of the MCG sensor for earliest indication of mechanical activity in order to study electromechanical delay. A wave shape was also desired that would allow relatively easy location of cardiac mechanical events. In the succeeding figures, the times of electromechanical delay are given from the bottom of the "Q" wave on the ECG to the peak of the MCG, which indicates end of isometric contraction and semi-lunar valve opening. The results of this acute study indicated that the best location for chronic implants would be: (a) in a region on the anterior surface of the heart about 1 to 2 cm from the tip of the apex on the left ventricle in a direction parallel to the diaphragmatic surface; and (b) on the right ventricle about half way from the diaphragmatic surface on the anterior surface, with one leg of the sensor attached to the longitudinal sulcus and in a direction parallel to the diaphragmatic surface.

The heart illustrations, on this figure and also A-2, depict sensor location, orientation, and serial number used to obtain the recordings shown in Figures A-3 through A-7. Each channel of MCG data is cross-referenced to the heart diagrams by sensor serial number.

KEY TO SENSOR PLACEMENT

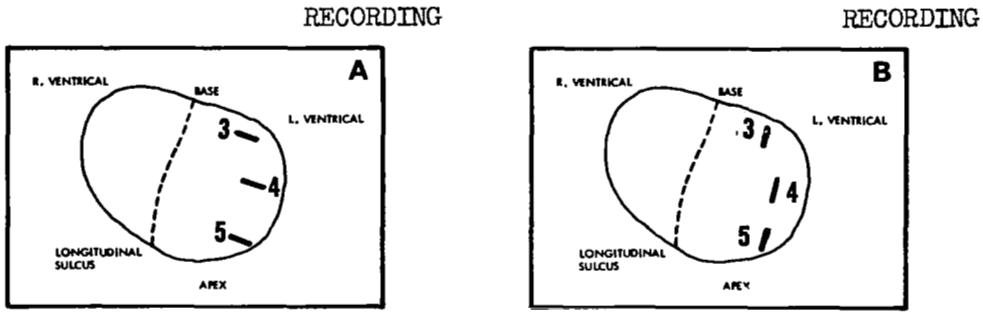


Figure A-1. Animal 4 (Anesthetized), MCG Sensor Placement Study

KEY TO SENSOR PLACEMENT

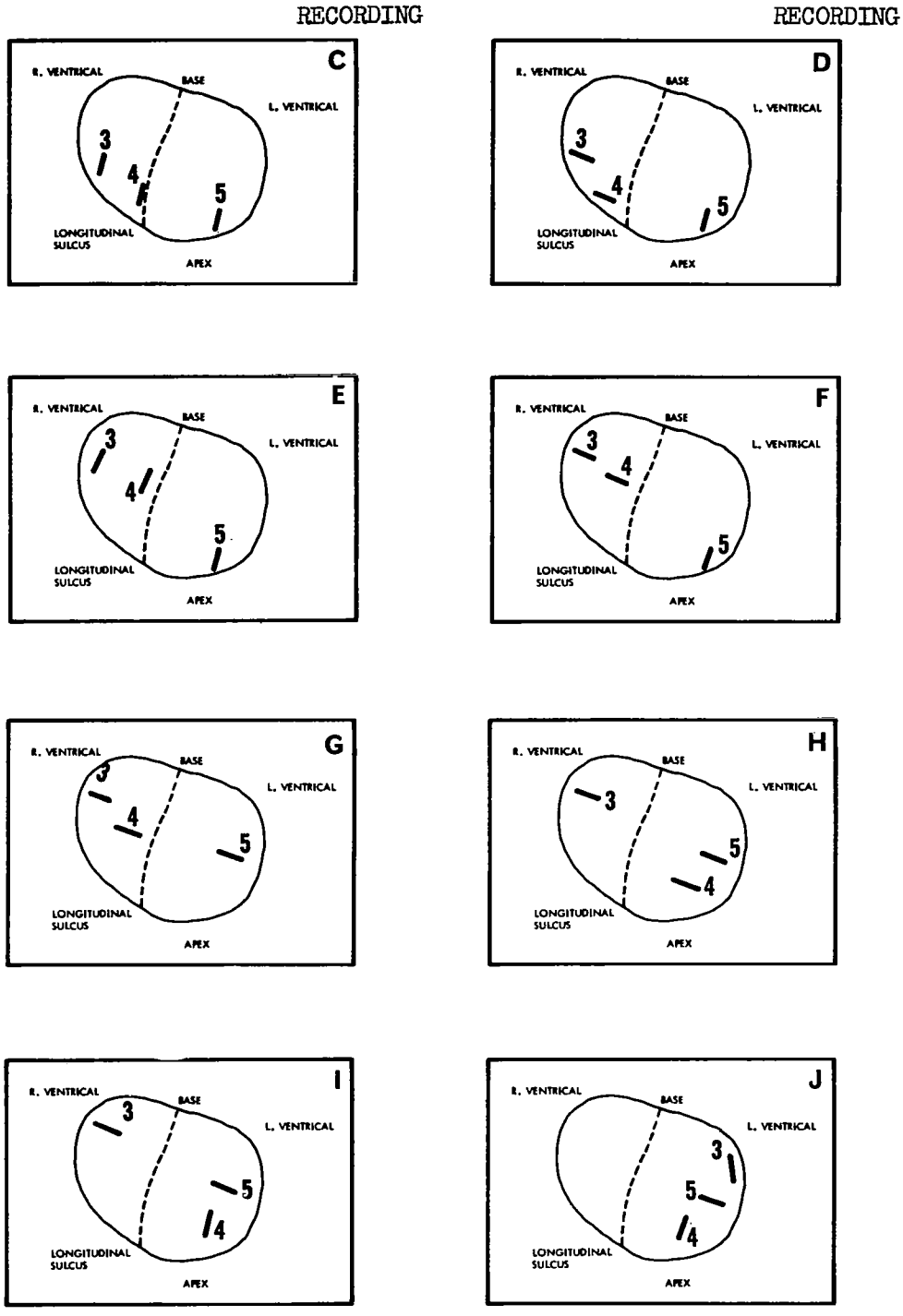


Figure A-2. Animal 4 (Anesthetized), MCG Sensor Placement Study

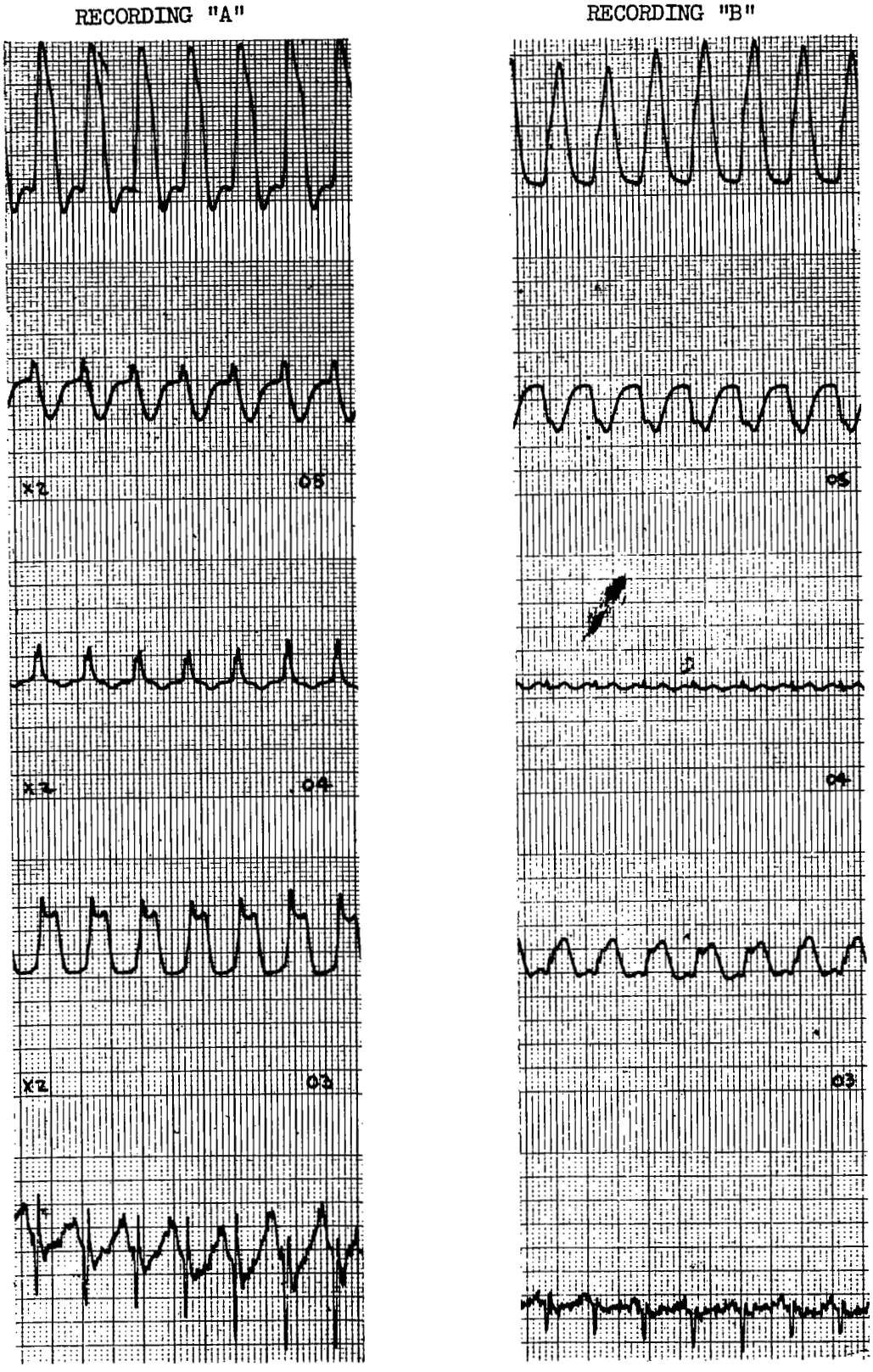


Figure A-3 Animal 4 (Anesthetized), MCG Sensor Placement Study

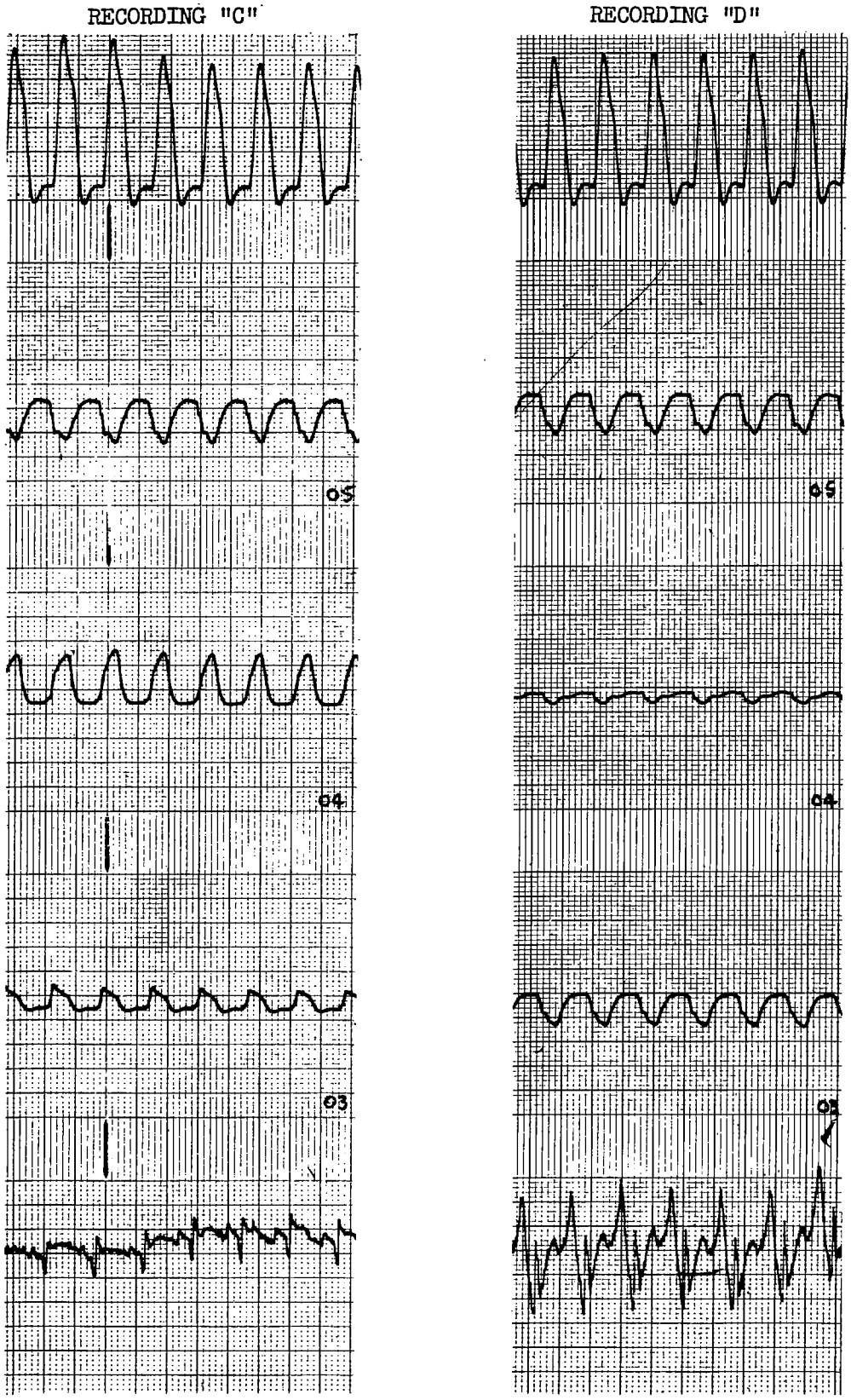


Figure A-4. Animal 4 (Anesthetized), MCG Sensor Placement Study

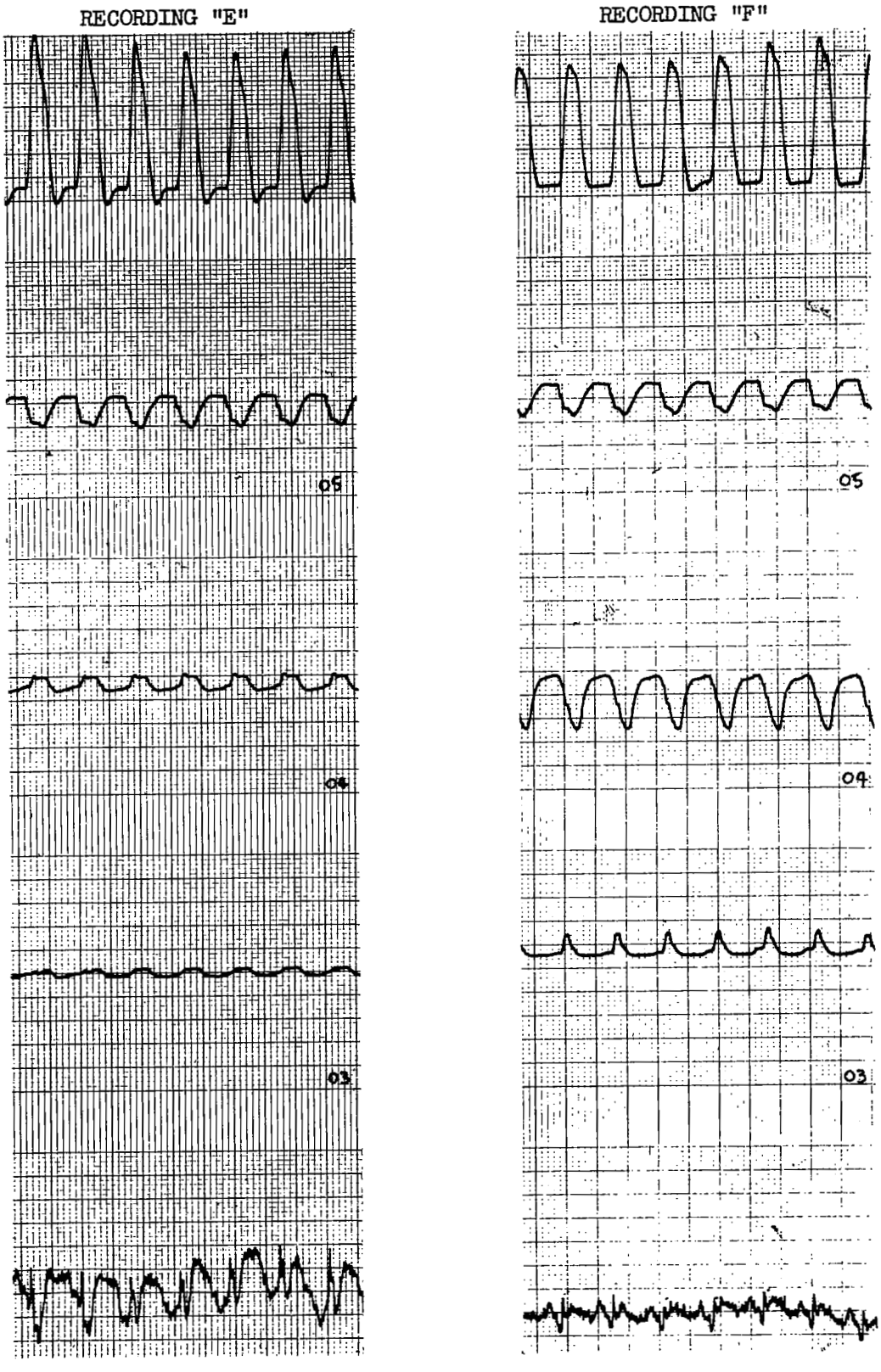


Figure A-5. Animal 4 (Anesthetized), MCG Sensor Placement Study

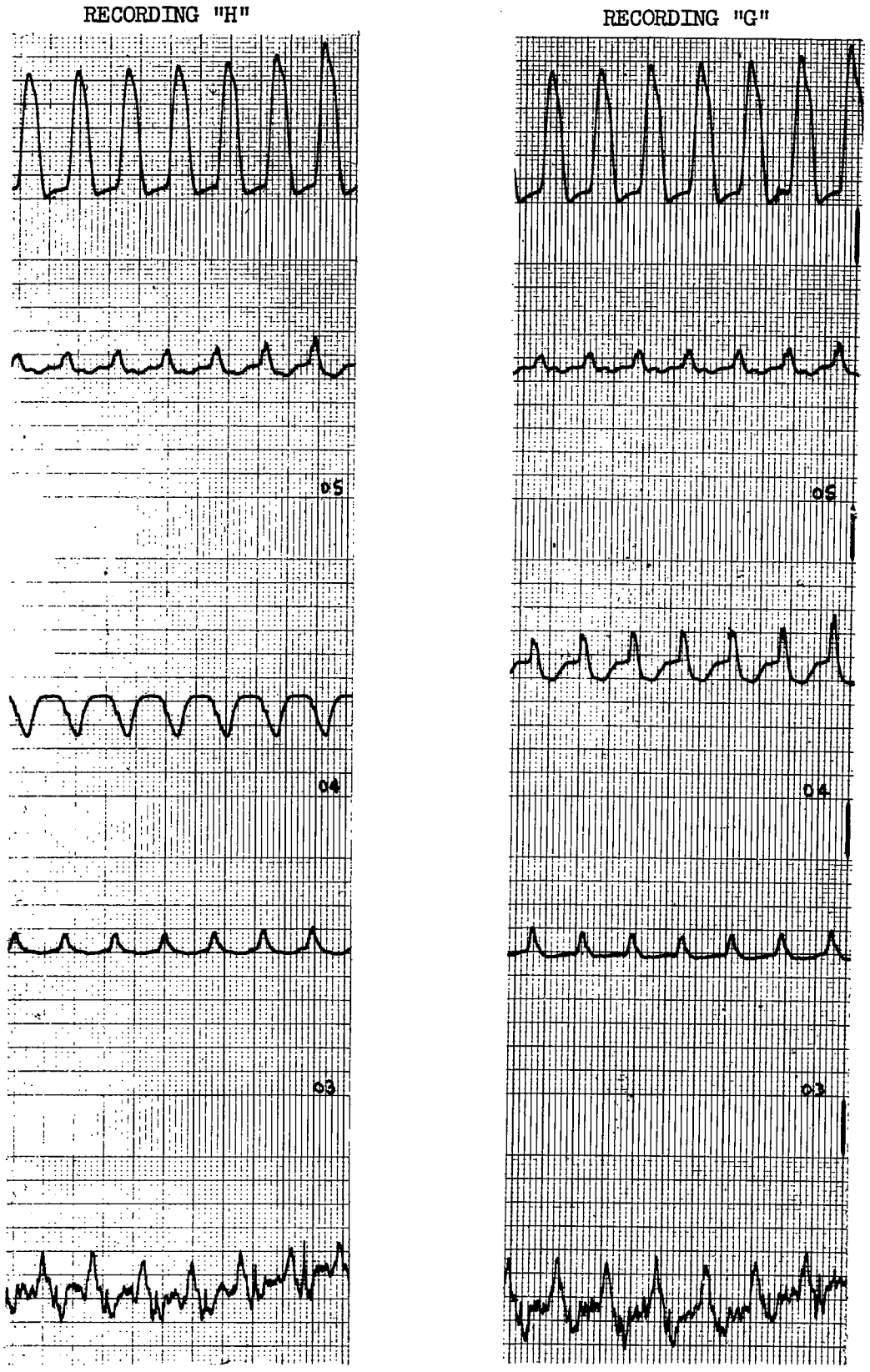


Figure A-6. Animal 4 (Anesthetized), MCG Sensor Placement Study

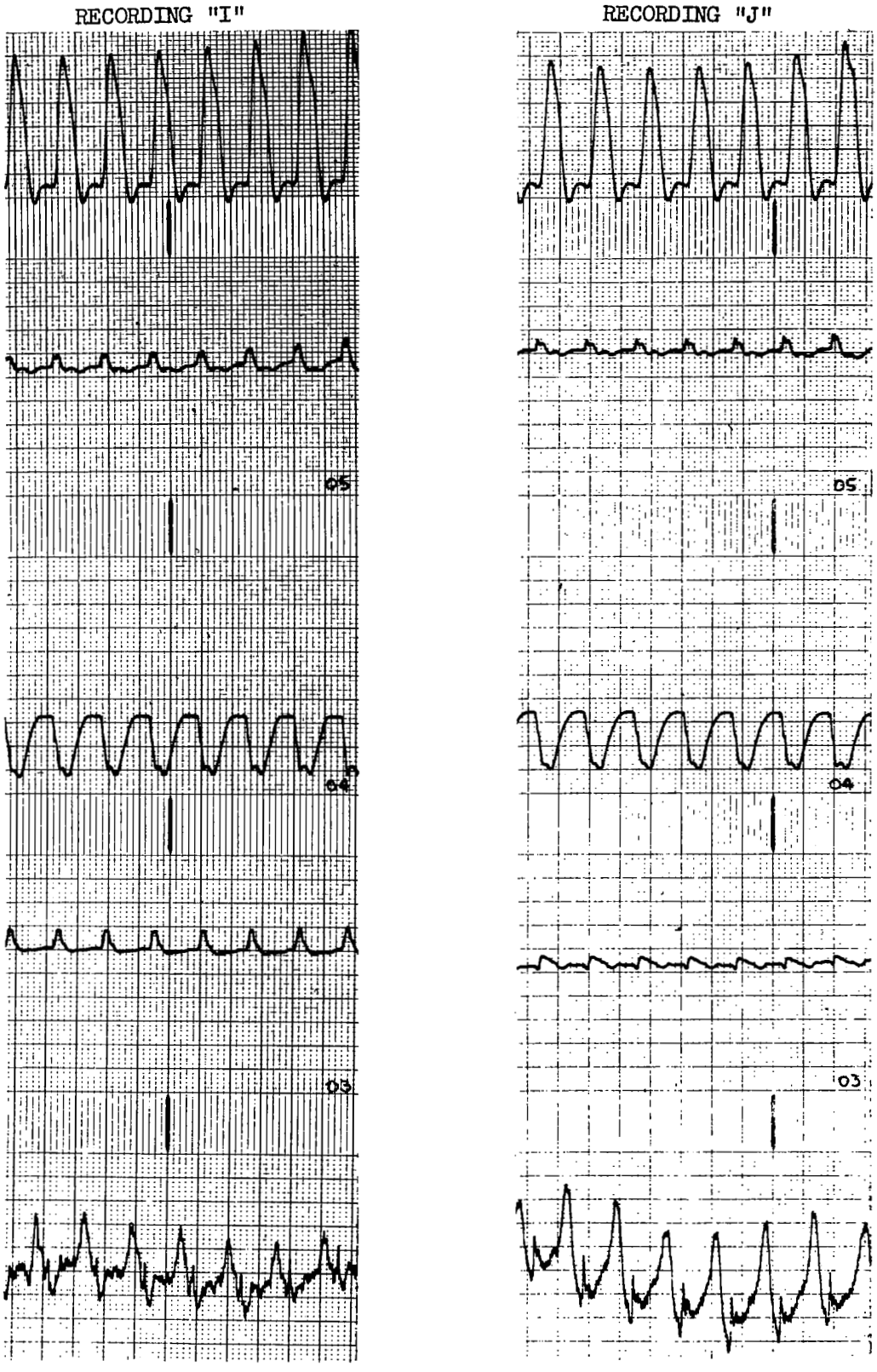


Figure A-7. Animal 4 (Anesthetized), MCG Sensor Placement Study

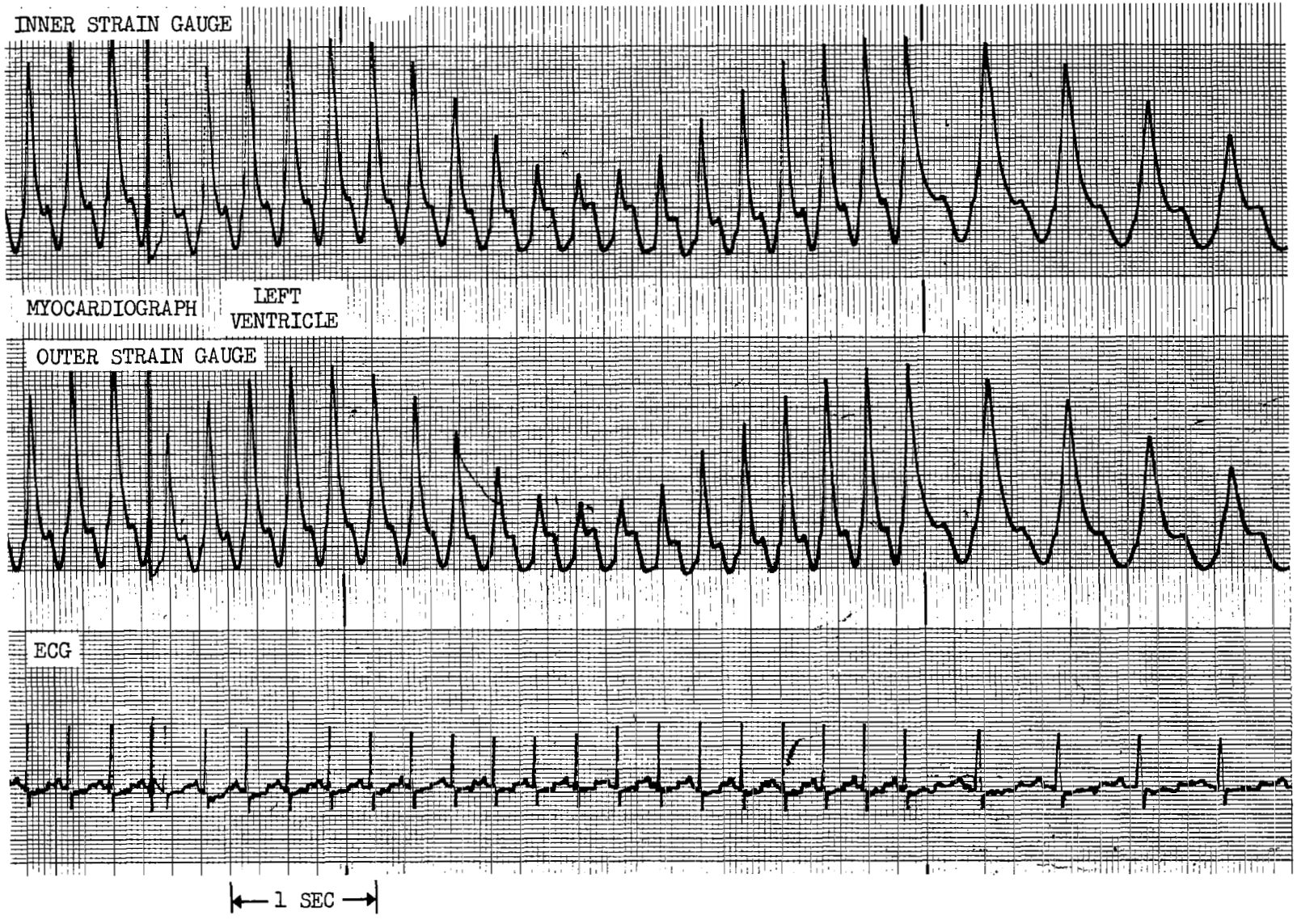


Figure A-8. Animal 6 (Anesthetized), Day of Implant. Record taken after surgical closure before respirator was disconnected, displayed to show the effect of respiration on myocardiograph (MCG) output.

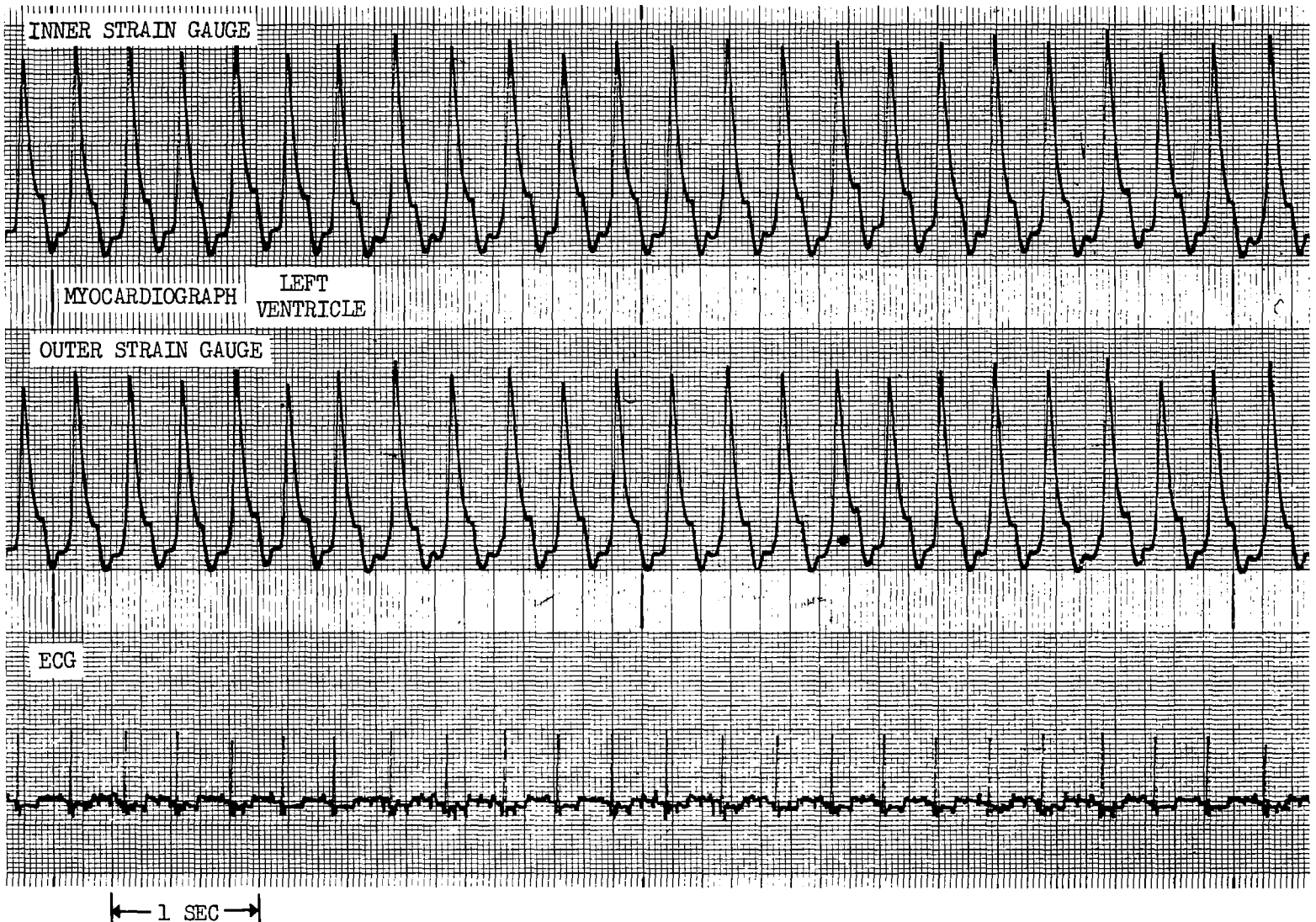


Figure A-9. Animal 6 (Anesthetized), Day of Implant. Record obtained after the respirator was disconnected, displayed to show a normal MCG record typical of the period immediately after surgery. Time interval from the peak of the ECG "R" wave to the peak of the MCG wave is 0.04 seconds.

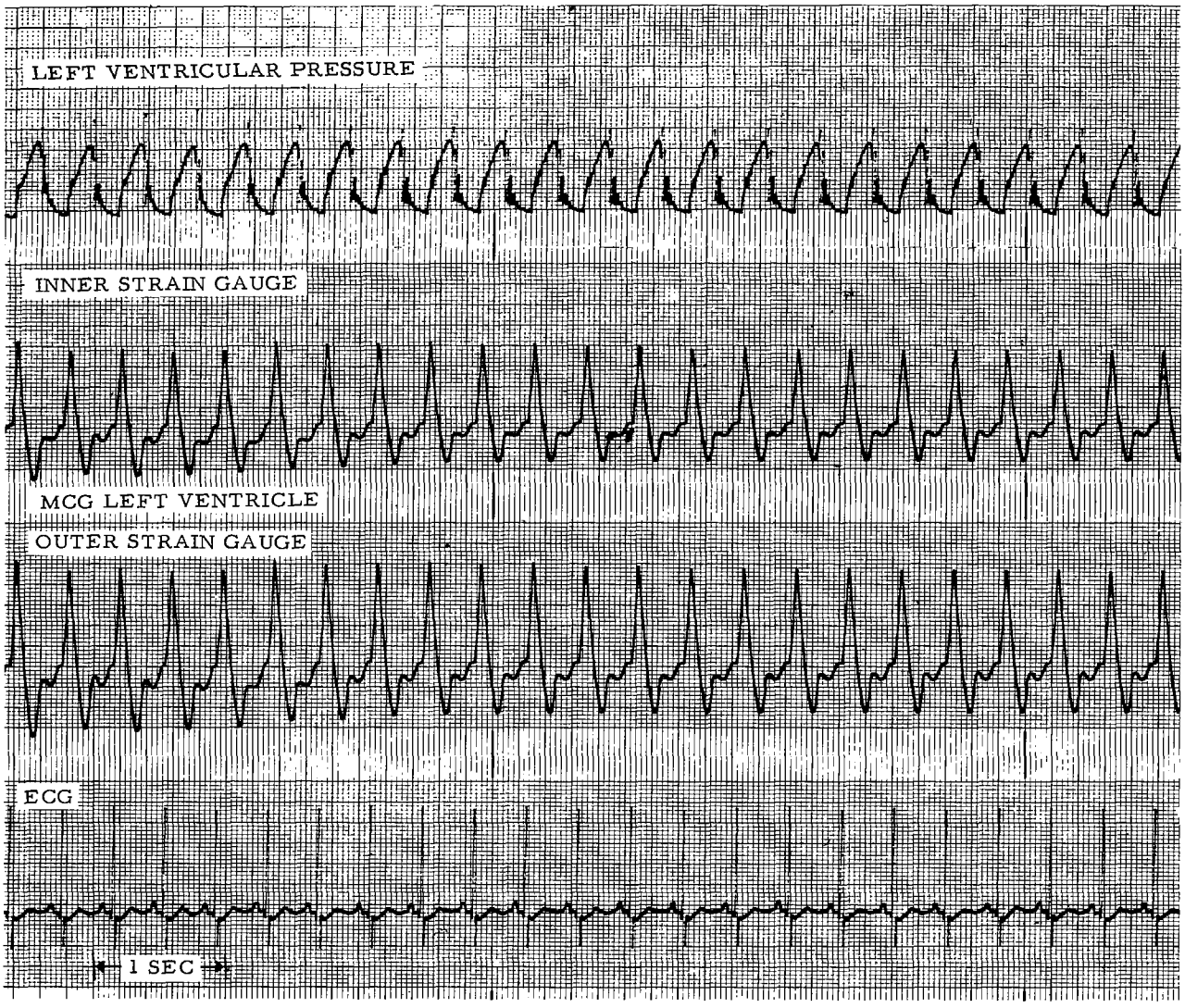


Figure A-10. Animal 6 (Anesthetized), Catheterization, 18 Days Postimplant. Catheterization record indicates that MCG response precedes equivalent left ventricular pressure response by 0.04 seconds. This is due to the placement of the strain gauge and, as discussed in the text, was to give the earliest indication of mechanical activity; that is, the shortest interval of electromechanical delay.

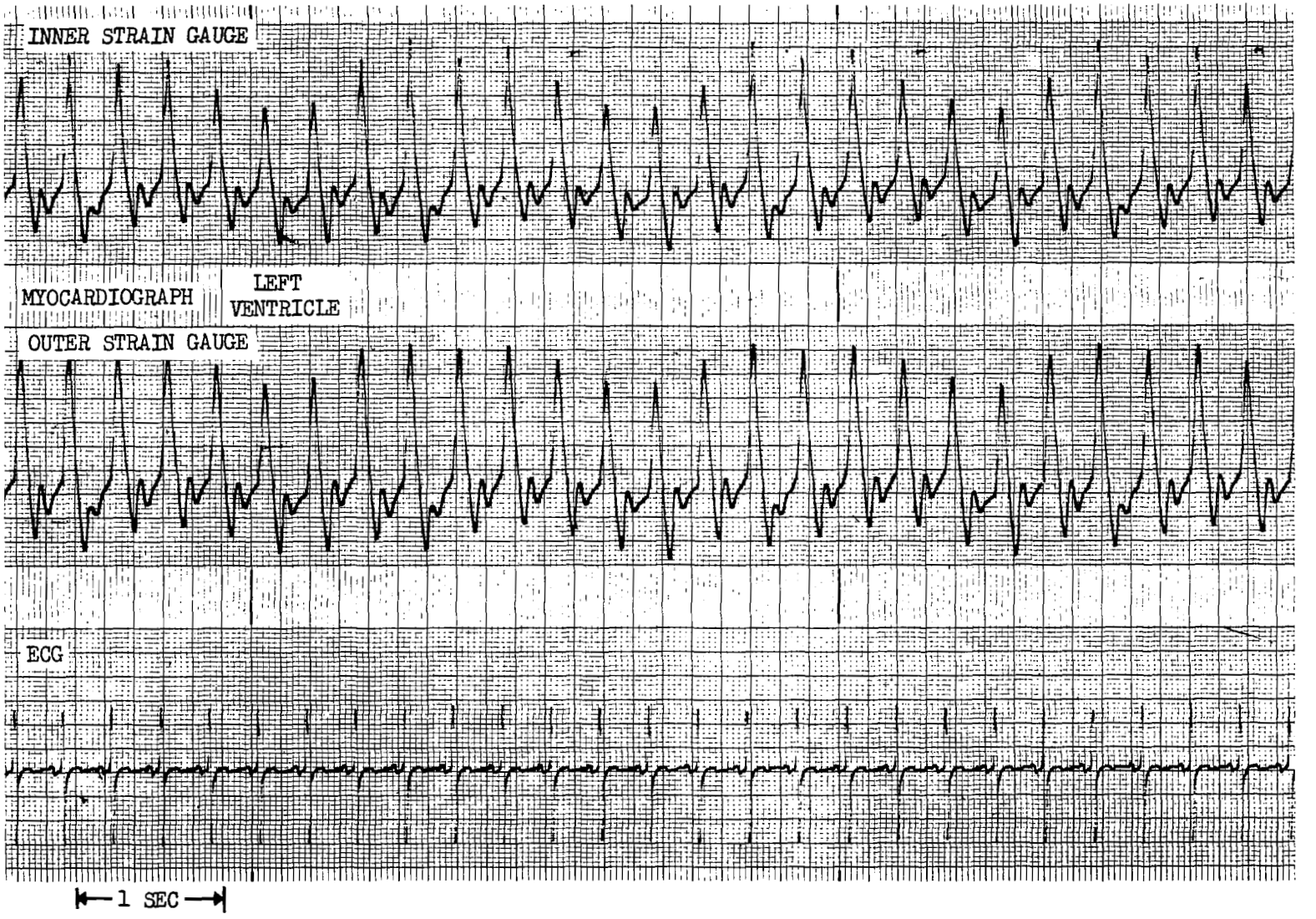


Figure A-11. Animal 6 (Anesthetized), Routine Check, 31 Days Postimplant. Record displayed to indicate that electromechanical interval is the same (e. g., 0. 04 seconds) from peak of ECG "R" wave to peak of MCG response. There has occurred some change in the over-all wave shape; however, events of interest are still identifiable as on the day of catheterization. The amplitude of the signal is relatively the same. It is interesting to note that there is no noticeable change in electromechanical delay with respiration.

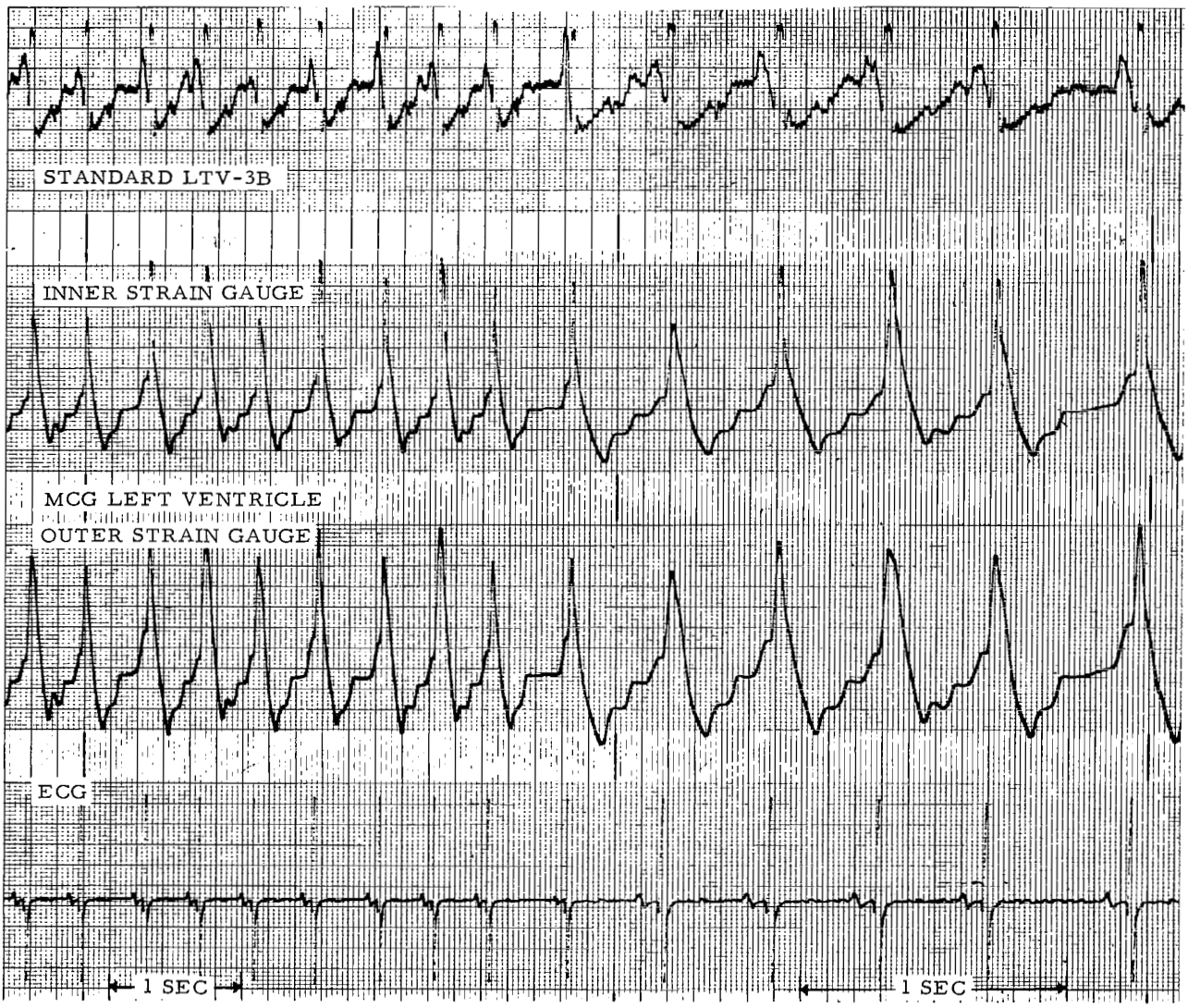


Figure A-12. Animal 6 (Unanesthetized), Vibrophonocardiograph Recording, 37 Days Postimplant. Although this is not a typical vibrophonocardiograph tracing as shown in Figure , the events of interest can be identified as the H, J_2, and L waves.

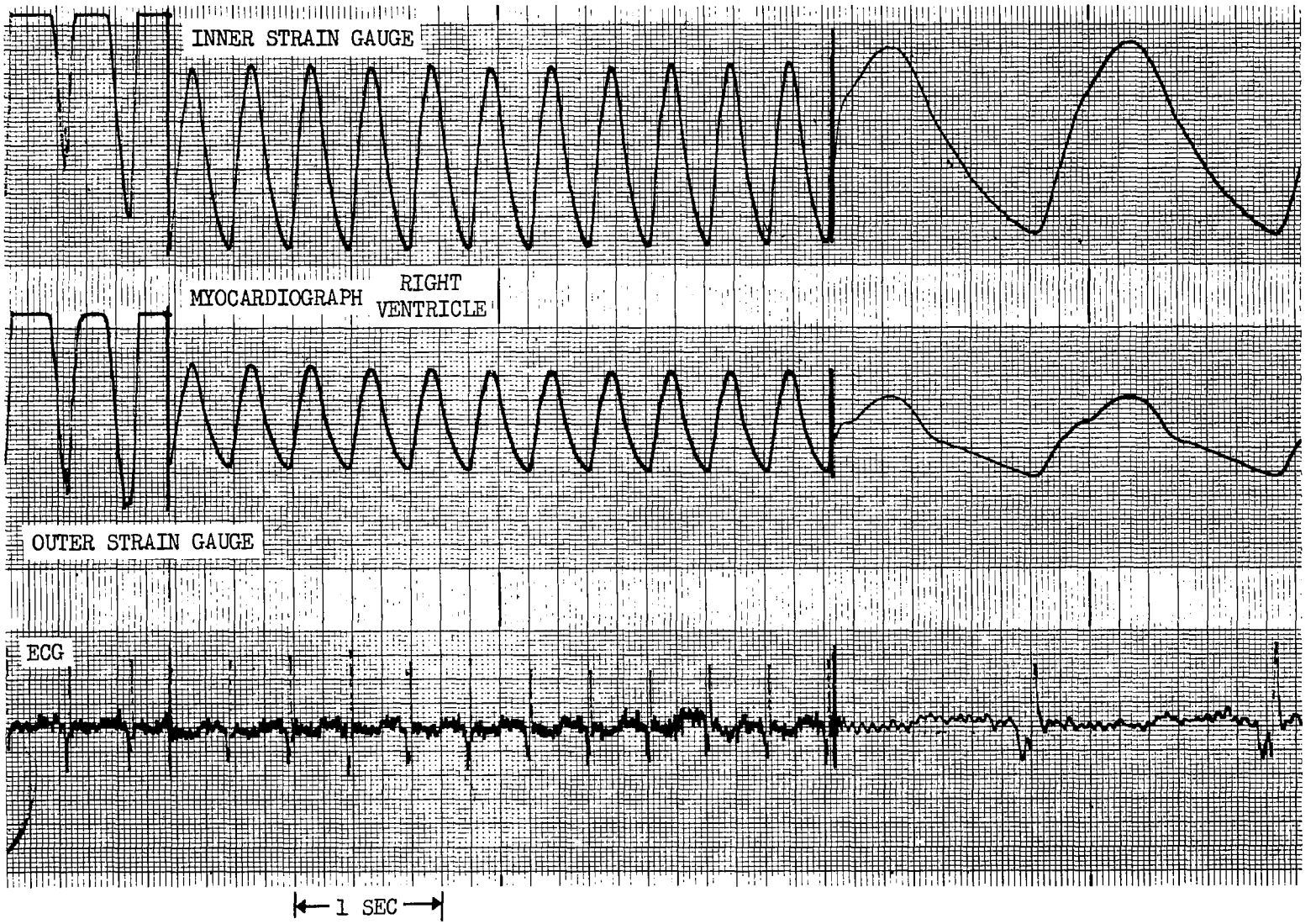


Figure A-13. Animal 7 (Anesthetized), Day of Implant. Occasionally, because of position of the MCG after placement on the heart, it was found that MCG sensor output was poor, thus not sensitive to the many events that good placement would show. This record is such an example. It is typical of MCG sensors that respond poorly to the various mechanical events occurring at the heart surface. When such a placement was found, the MCG sensor was reimplanted in a slightly different orientation or location. In this case, the final implant involved a right ventricular placement.

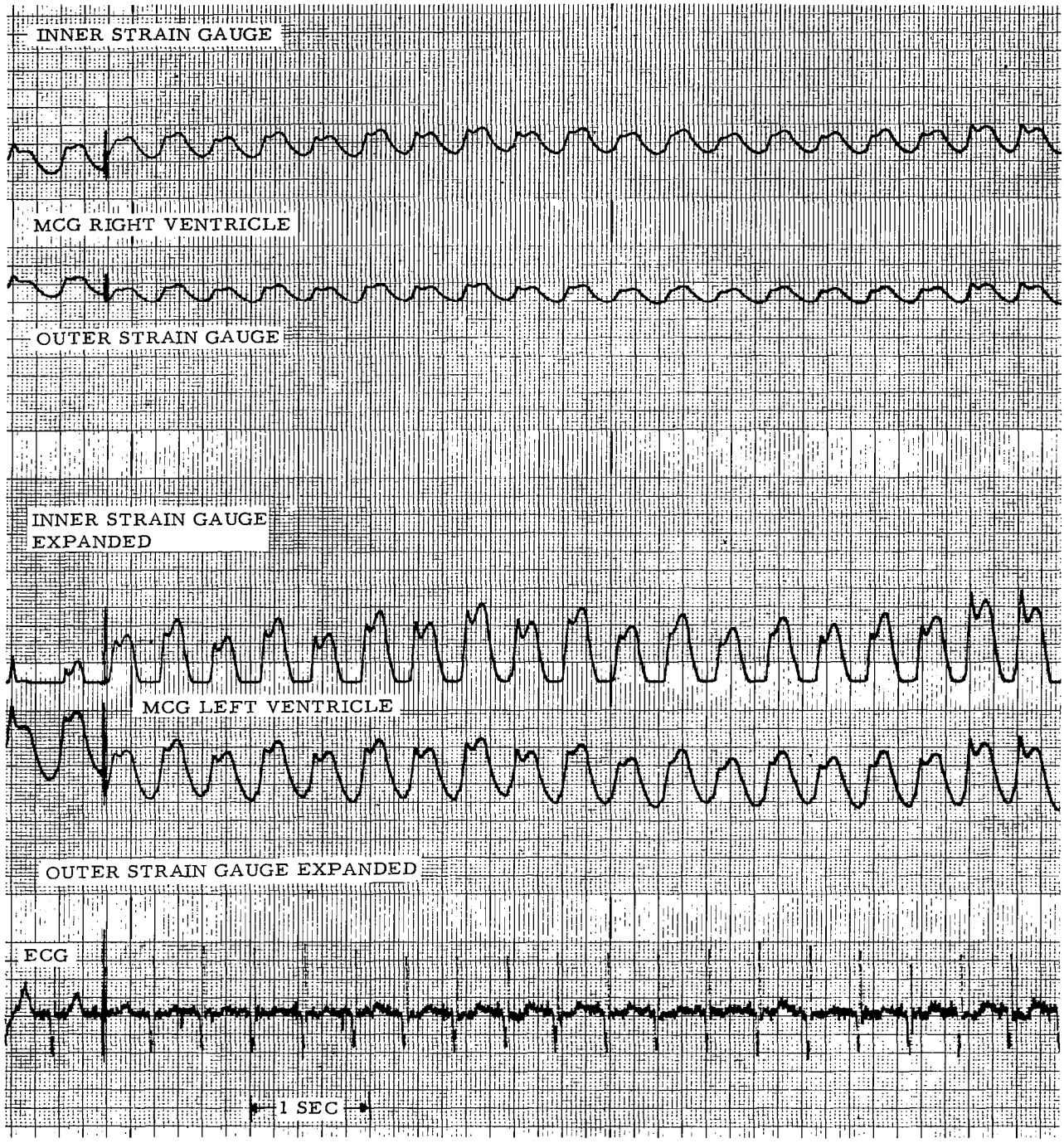


Figure A-14. Animal 7 (Anesthetized), Final MCG Sensor Placement, Day of Implant. This record is shown to indicate a typical tracing immediately following implant but prior to closure.

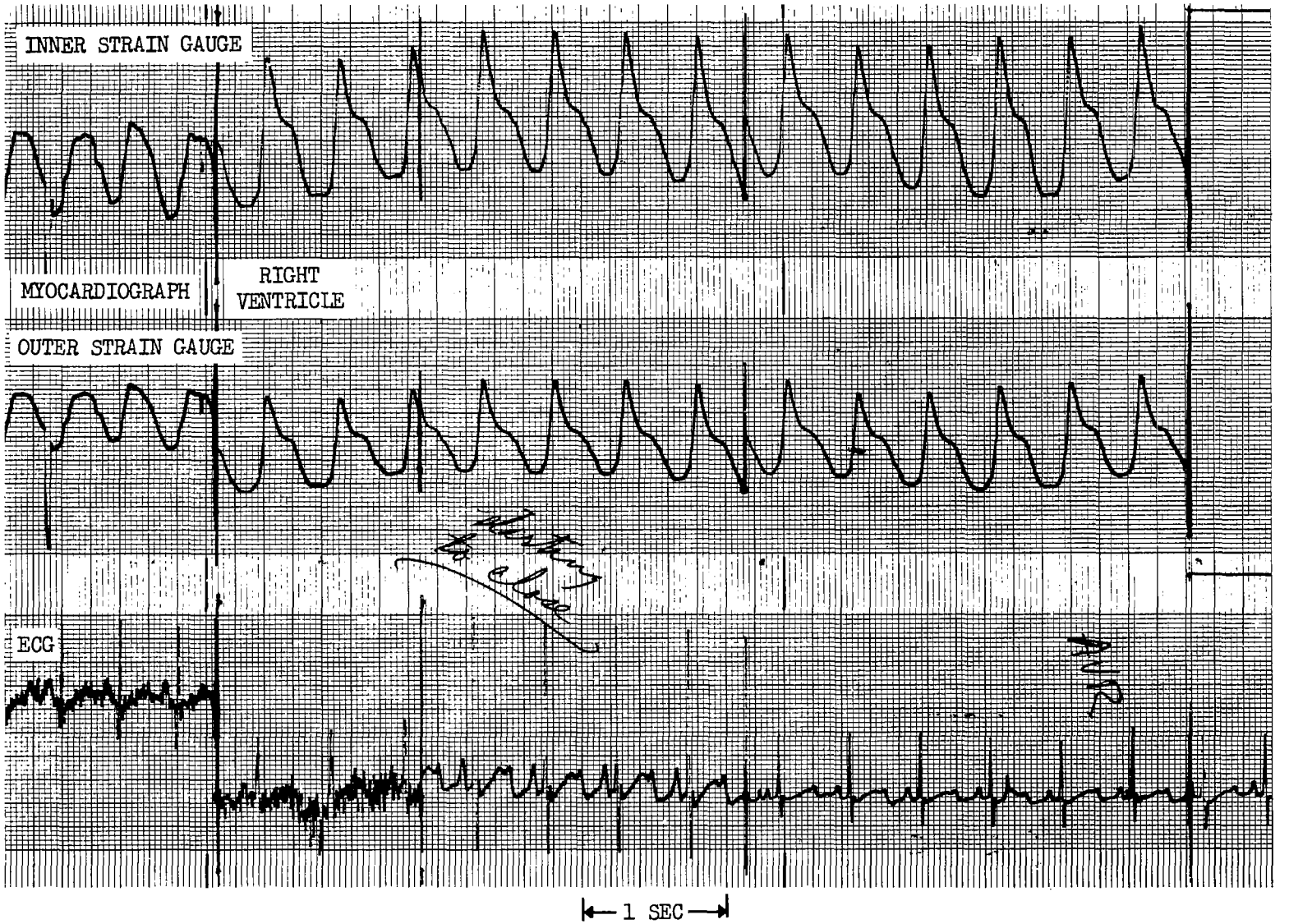


Figure A-15. Animal 7 (Anesthetized), Day of Implant. This is a typical record immediately following closure. Note the high amplitude of the peak of the MCG recording. This differs considerably from the preceding figure where the peak was relatively small. This phenomenon occurred occasionally with the chronic implants. It may be related to the interaction of the chest wall and the heart; however, animal orientation does not seem to affect MCG response. The electromechanical interval between the peak of the ECG "R" wave and the peak of the MCG is 0.05 seconds.

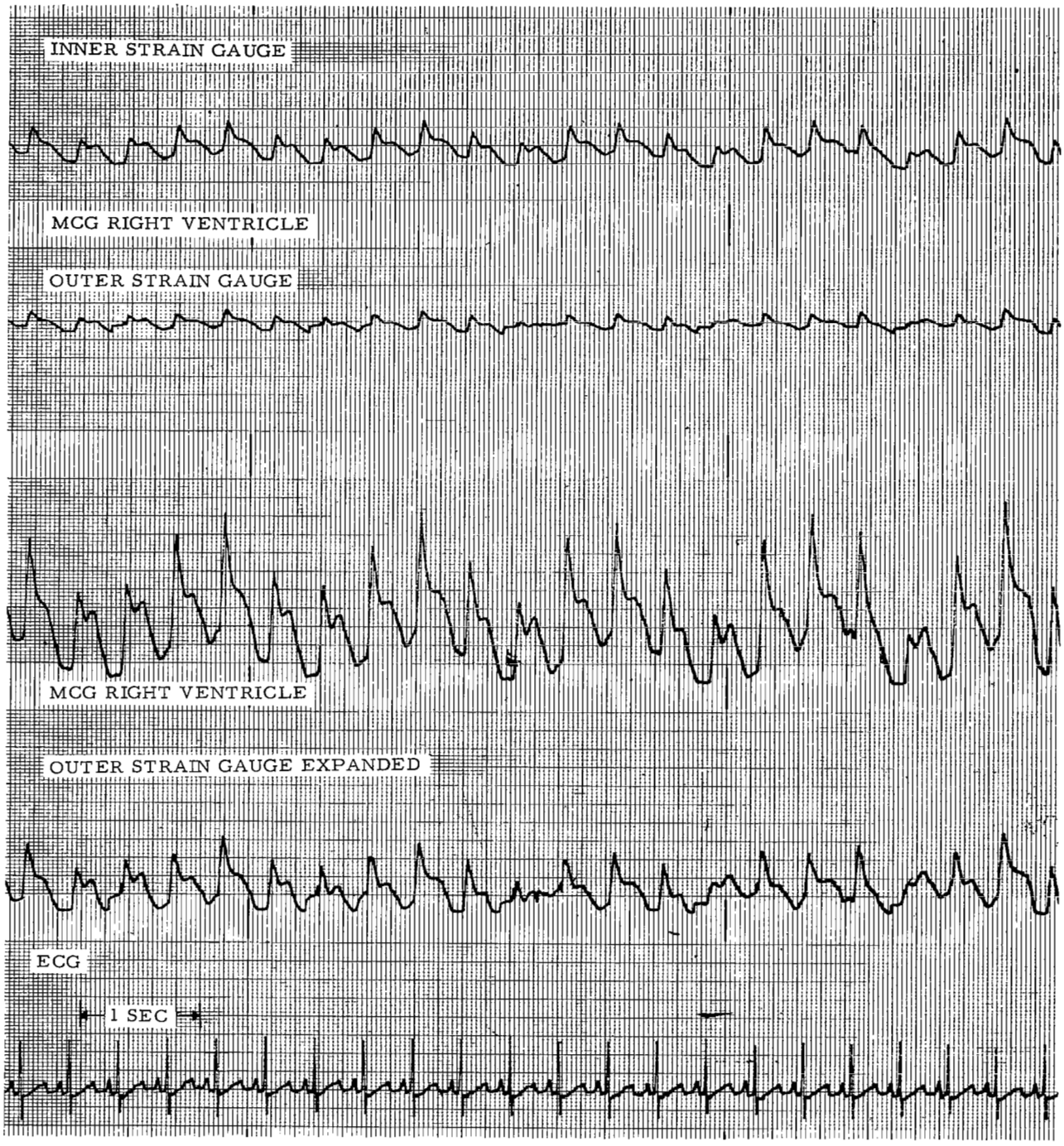


Figure A-16. Animal 7 (Anesthetized), Day of Implant. This figure shows in more detail the change in MCG wave shape with respiration. There still appears to be no electromechanical time change during the respiratory cycle.

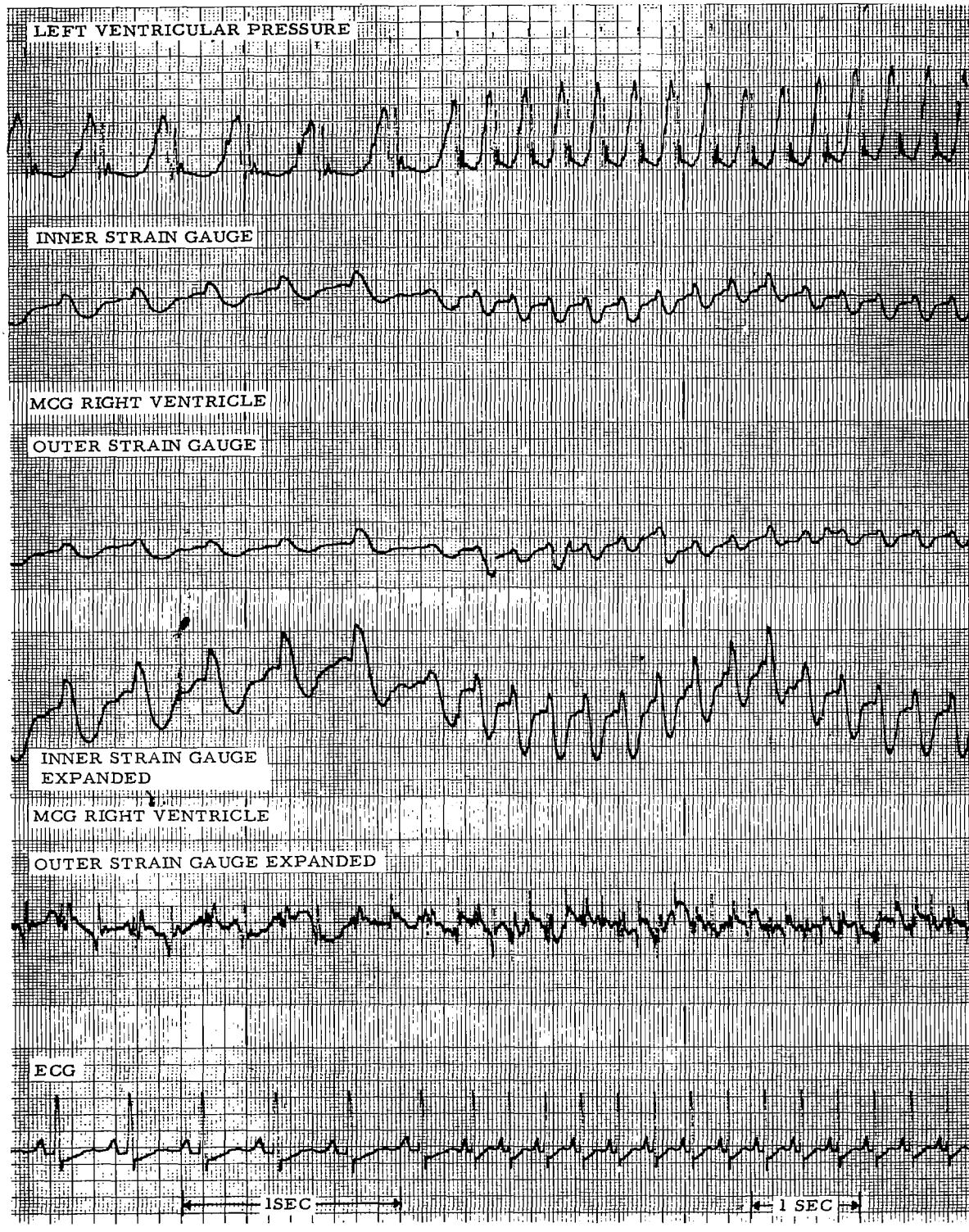


Figure A-17. Animal 7 (Anesthetized), Day of Catheterization, 19 Days Postimplant. A progression in over-all shape of the wave is evident in this recording as noted with Animal 6 with greater prominence of the ventricular filling portion of the record. The electromechanical delay between peak of ECG "R" wave to peak of MCG is still 0.05 seconds. The myocardiograph events precede the equivalent events of the ventricular pressure curve by 0.05 seconds.

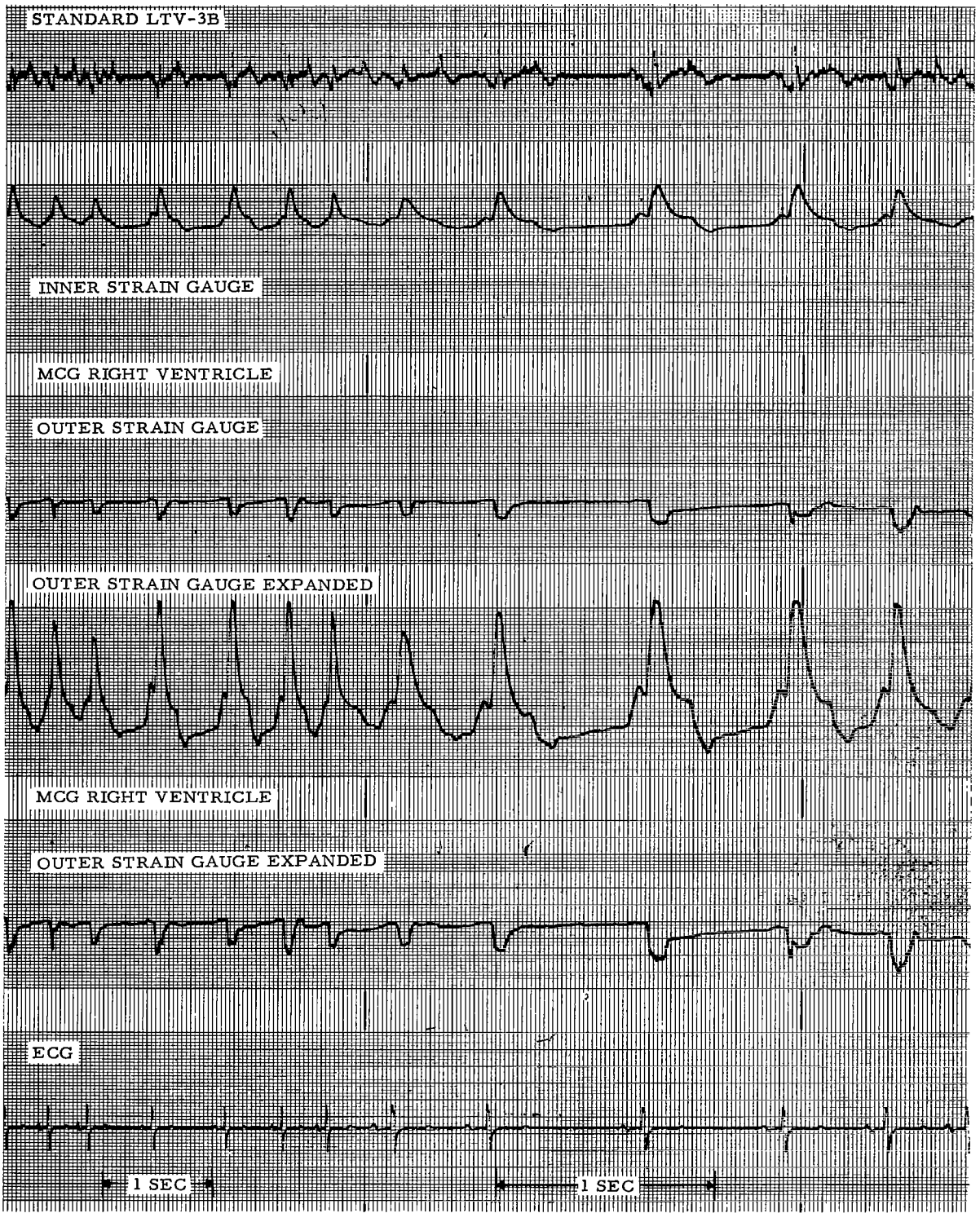


Figure A-18. Animal 7 (Unanesthetized), Vibrophonocardiograph Recording, 34 Days Postimplant. Taken with the standard VCG sensor, shows results are similar to those with Animal 6. One can not only identify the H, J, and L waves, but can also note a peak corresponding to the P wave (biphasic) of the EKG which is probably a reflection of atrial contraction at the apex.

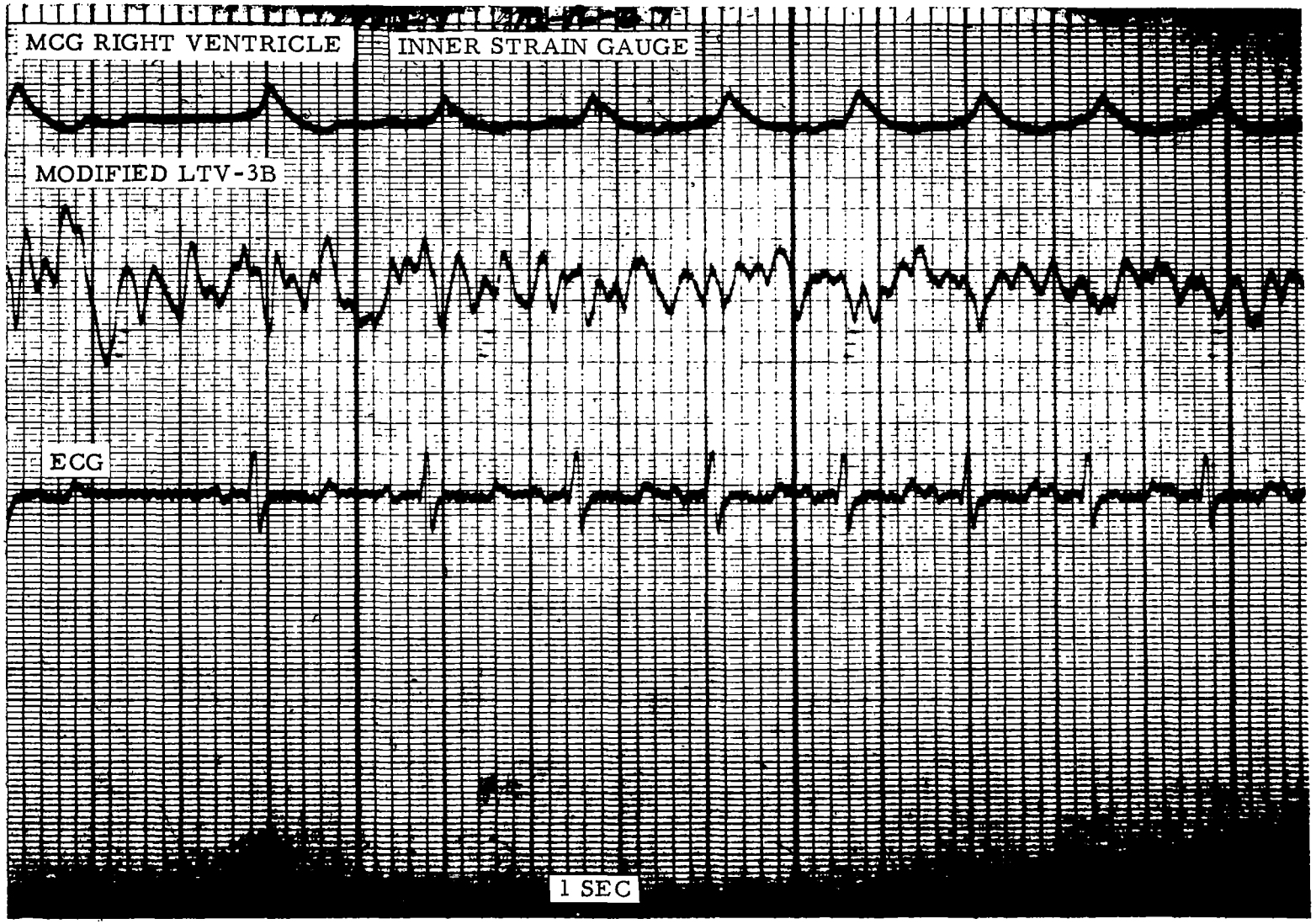


Figure A-19. Animal 7 (Unanesthetized), Vibrophonocardiograph Recording, 55 Days Postimplant. This and the succeeding record were made with a Sanborn 568 Optical Recorder. Included only to show the effect of shivering upon the Vibrophonocardiogram.

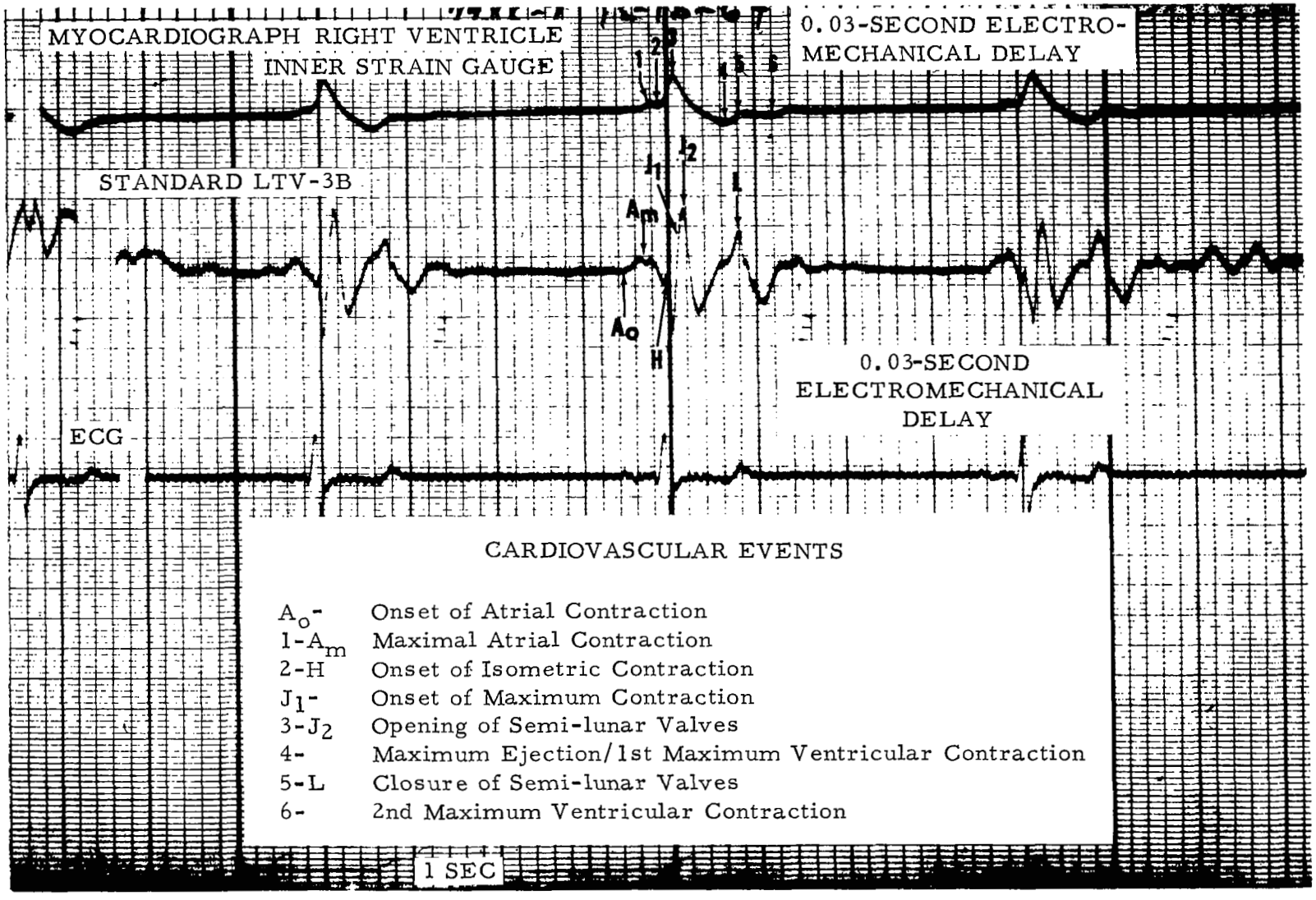


Figure A-20. Animal 7 (Unanesthetized), Vibrophonocardiograph Recording, 55 Days Postimplant. Shown to exemplify in detail a vibrophonocardiograph record corresponding to ECG and MCG and with important events identified. Electromechanical delay between peak of ECG "R" wave and peak of MCG is still 0.05 seconds. It should be remembered again that this is a right ventricular MCG placement.

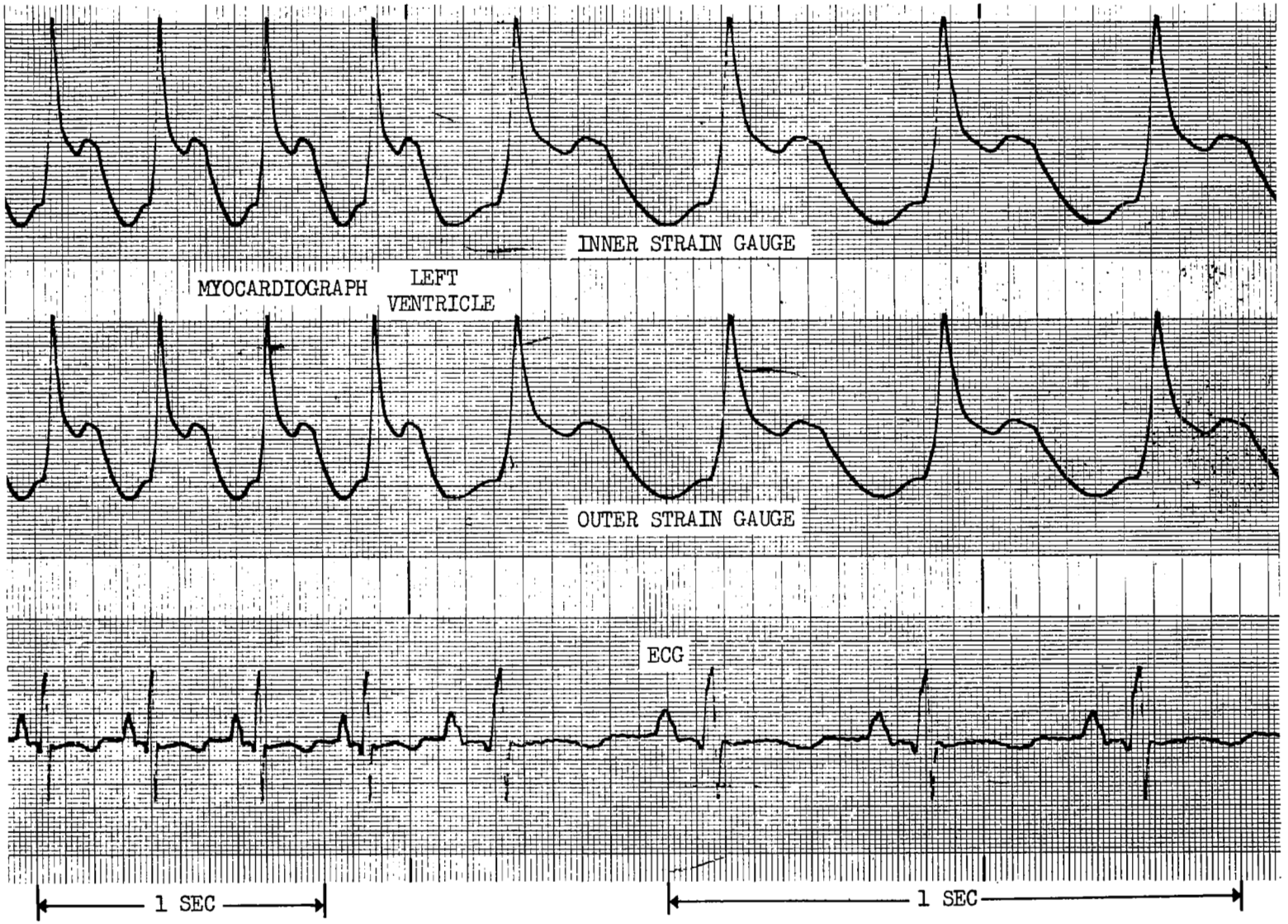


Figure A-21. Animal 8 (Anesthetized), Day of Implant. This was an implant of a double-gage sensor MCG placed on the apex of the left ventricle. The wave shape is similar to other implants of this placement. The electromechanical delay between the peak of the ECG "R" wave and the peak of the MCG is 0.03 seconds.

CARDIOVASCULAR EVENTS

1 Atrial Contraction
2-I Onset of Isometric
3-N Opening of Semi-lunar Valves
4-P 1st Maximum Contraction/Max. Ejection
5-R Closure of Semi-lunar Valves

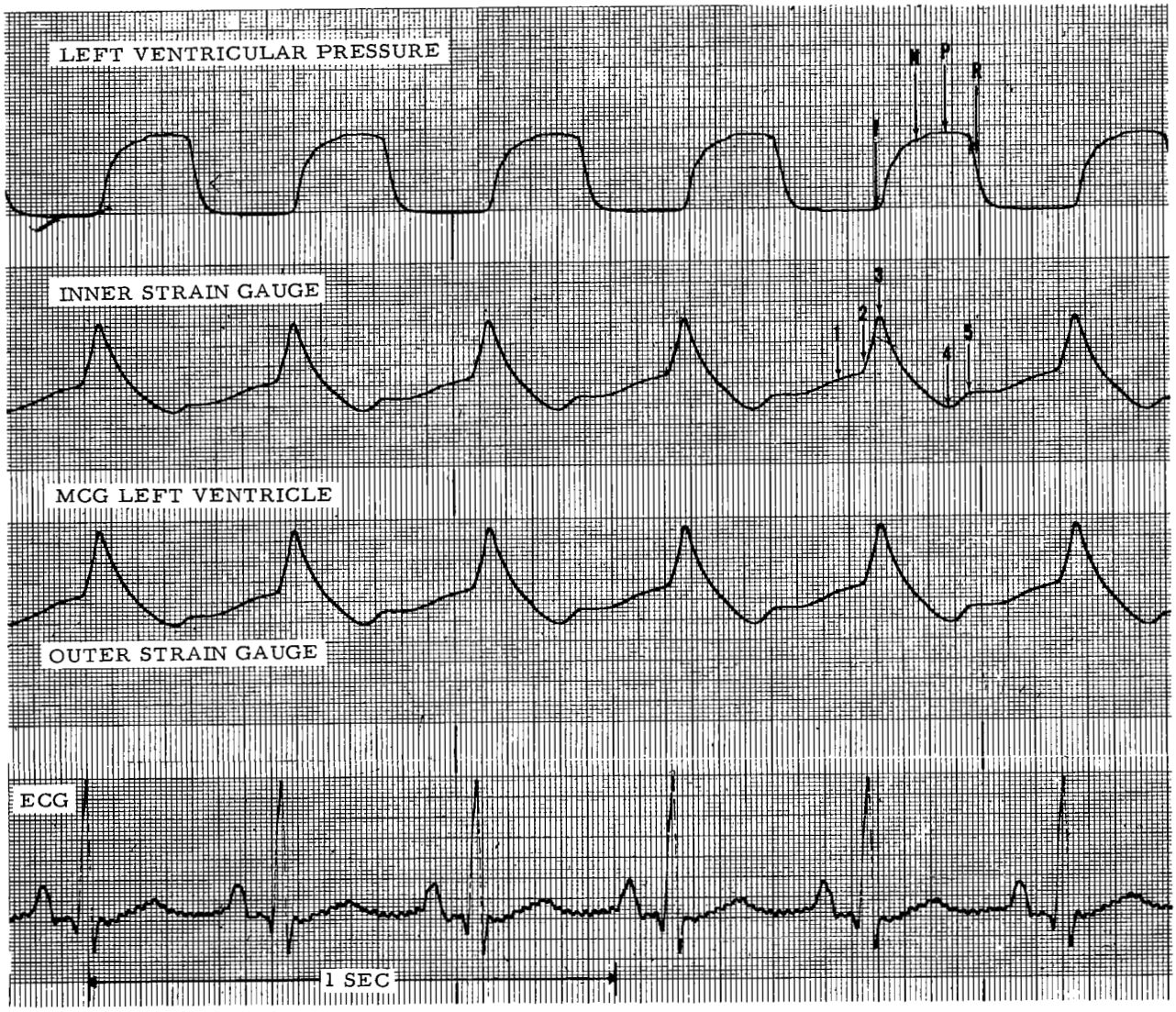


Figure A-22. Animal 8 (Anesthetized), Catheterization, 14 Days Postimplant. The modification of the wave shape as noted for Animals 6 and 7 again is apparent here. Cardiographic events of interest are identified on the elctrocardiogram, the myocardiogram, and the left ventricular pressure records. The electromechanical delay between the peak of the "R" wave and the peak of myocardiogram is seen to be 0.03 seconds; the delay between the myocardiogram and the left ventricular pressure record is also approximately 0.03 seconds.

CARDIOVASCULAR EVENTS

1- Atrial Contraction
2-H Onset of Isometric Contraction
J- Onset of Maximum Contraction
3-J_2 Opening of Semi-lunar Valves
4- 1st Maximum Right Ventricular Contraction
5-L Closure of Semi-lunar Valves
6- 2nd Maximum Ventricular Contraction

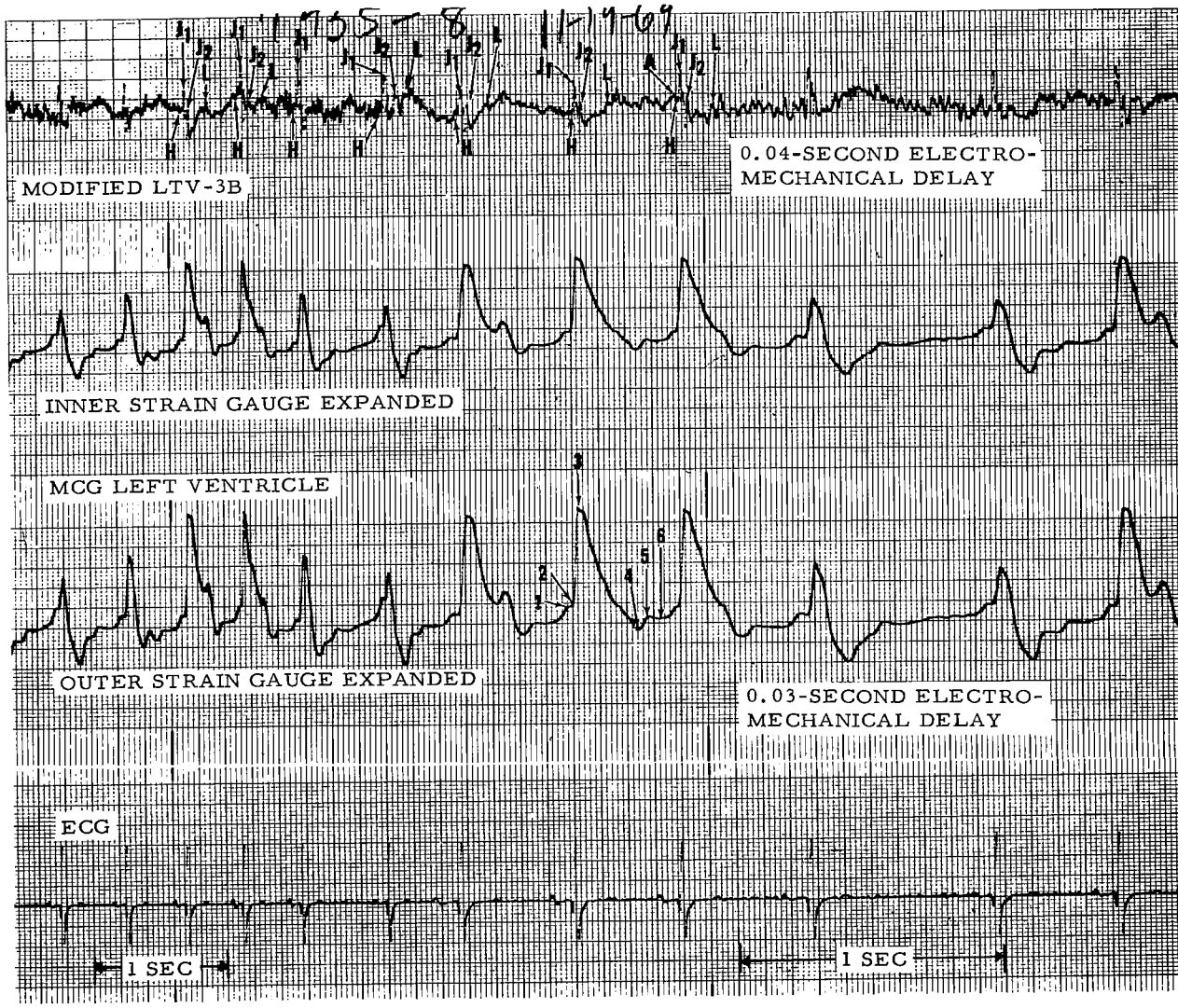


Figure A-23. Animal 8 (Unanesthetized), Vibrophonocardiograph Record, 21 Days Postimplant. Obtained with the use of the modified VCG sensor. The VCG pattern is similar to that of Animal 7 obtained under similar conditions. Although there is considerable noise apparent, the events of interest can be identified as shown.

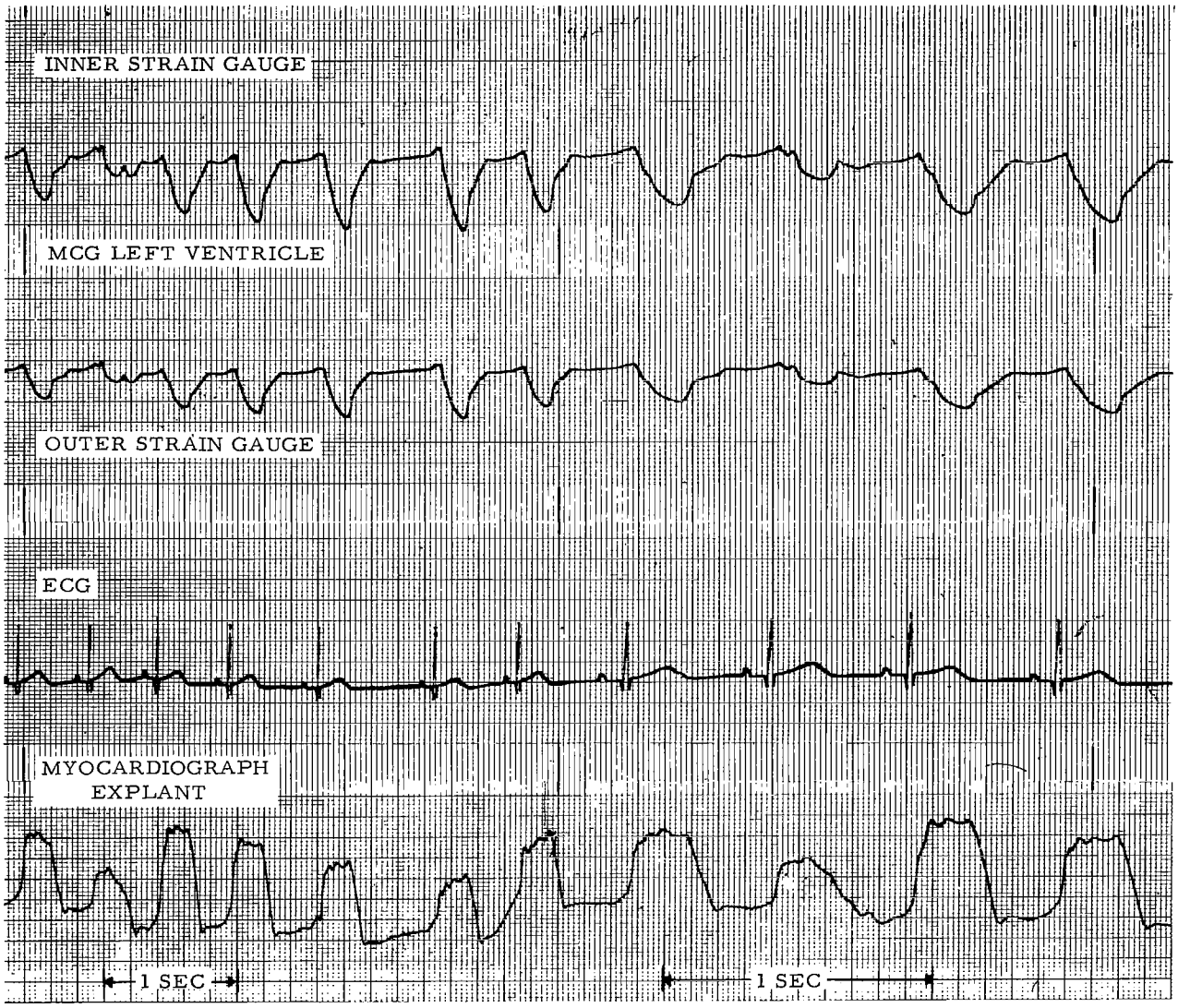


Figure A-24. Animal 8 (Anesthetized), Explant MCG, 55 Days Postimplant, Animal on Right Side. A MCG sensor was sutured to the external chest wall in the region of the apex to relate the external apical vibration to the implanted MCG. This figure and the succeeding three figures show some representative samples of data obtained during this procedure. The implanted MCG response has degraded considerably from the early postimplant wave shape; however, the significant myocardiograph events are identifiable. The electromechanical delay time is still 0.03 seconds. The response of the explant MCG is opposite to that of the internal MCG, but time relationships appear to be in phase. The explant MCG was sutured to the fifth interspace dorsal to the apical vibration such that the ventral leg rested on the apical beat.

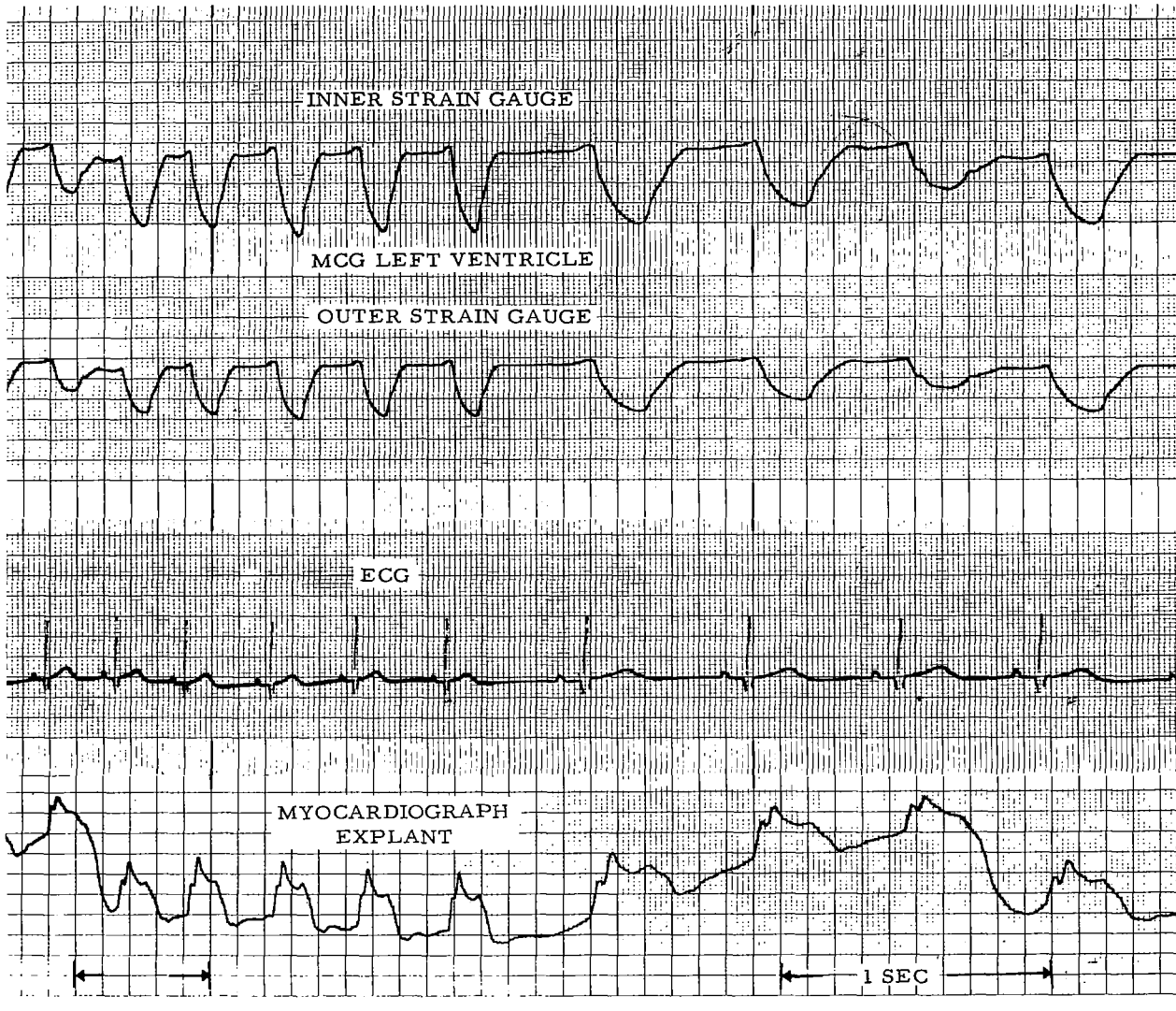


Figure A-25. Animal 8 (Anesthetized), Explant MCG, 55 Days Postimplant, Animal on Left Side. Same as preceding figure but animal on left side.

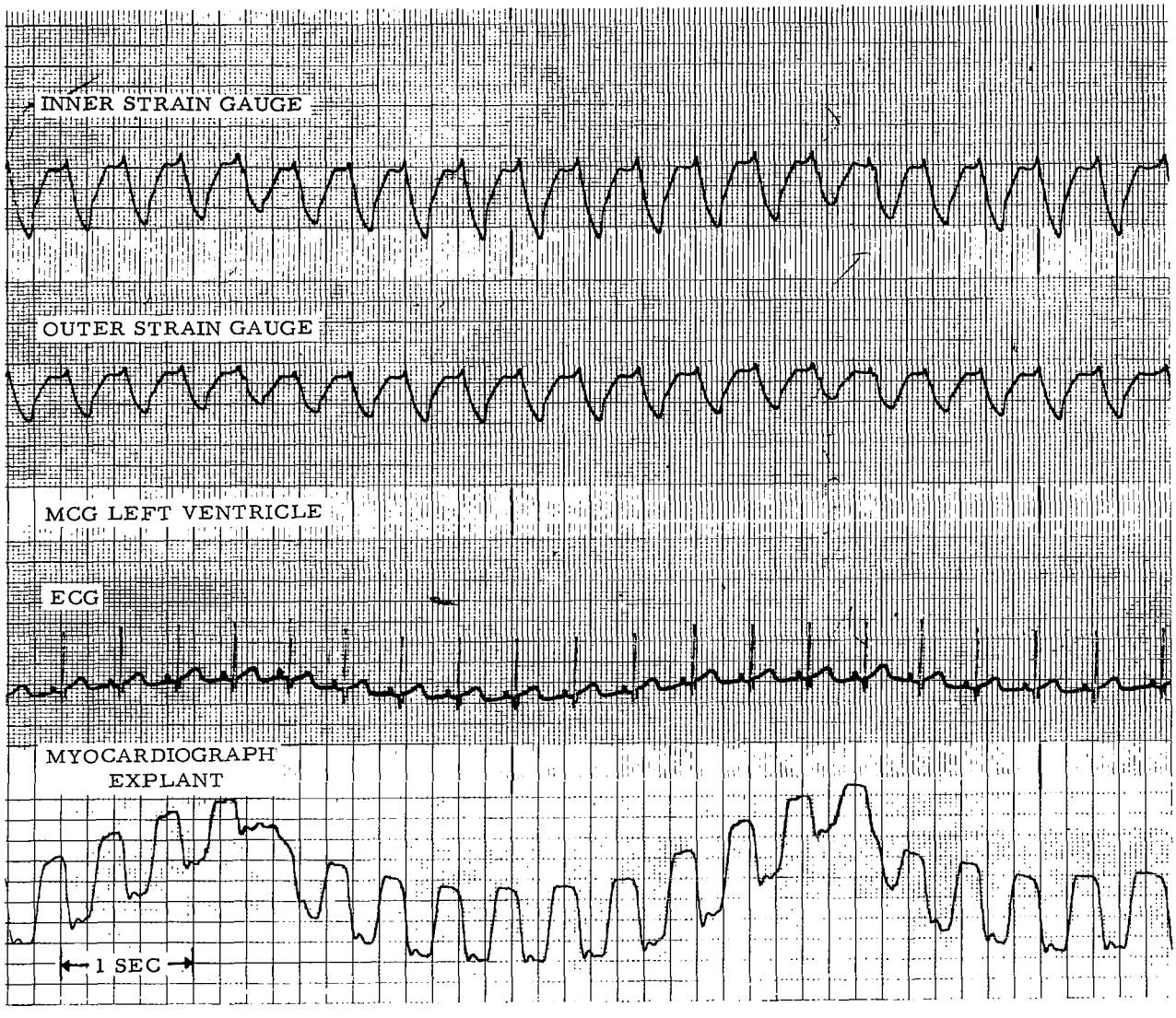


Figure A-26. Animal 8 (Anesthetized), Explant MCG, 55 Days Postimplant, Animal on Right Side. The explant MCG was repositioned 90 degrees to the preceding placement, and the record indicates that the response is considerably reduced, as the sensor is resting partly over the ribs and partly over the interspace.

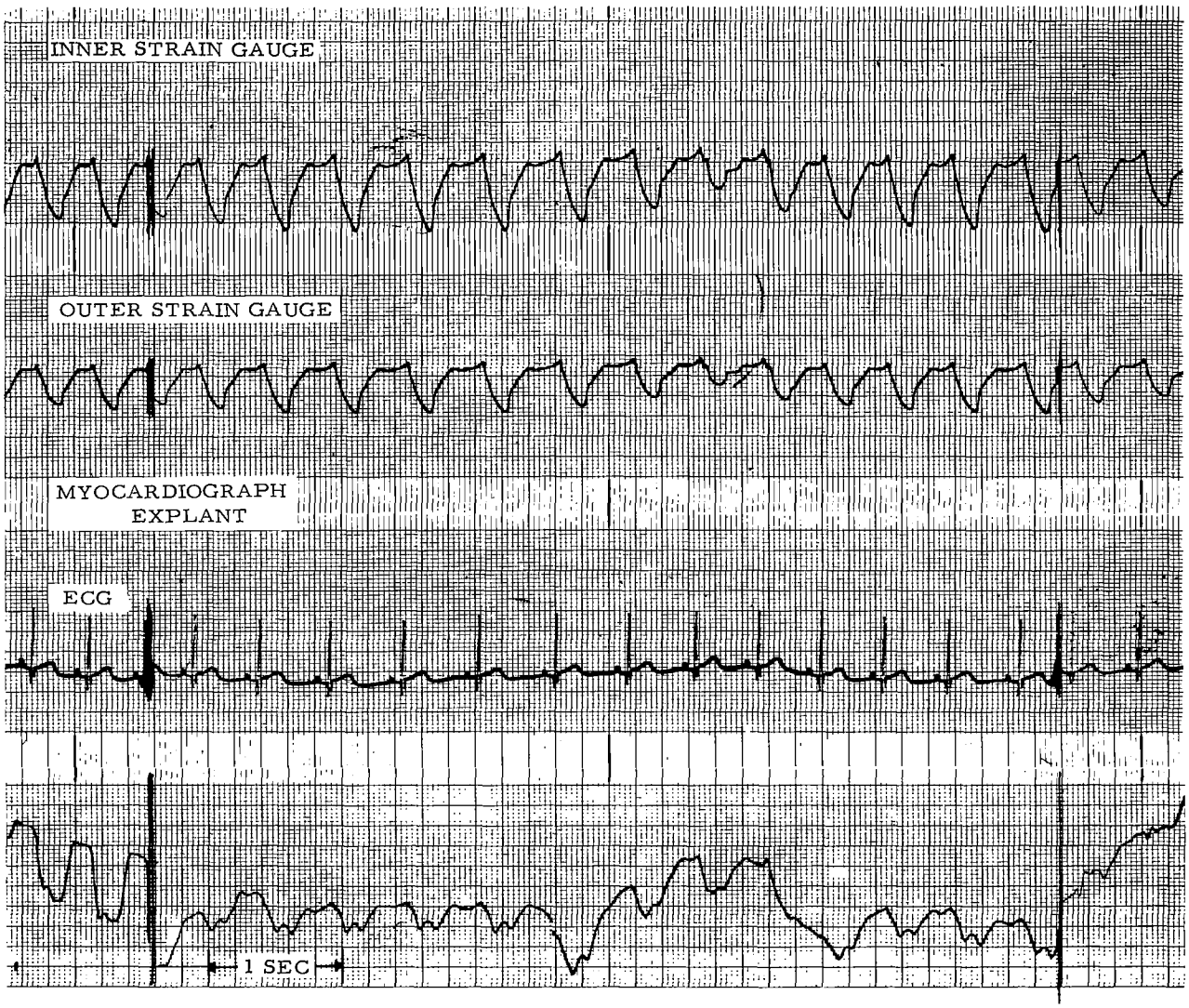


Figure A-27. Animal 8 (Anesthetized), Explant MCG, 55 Days Postimplant, Animal on Left Side. Same as preceding figure but animal on left side.

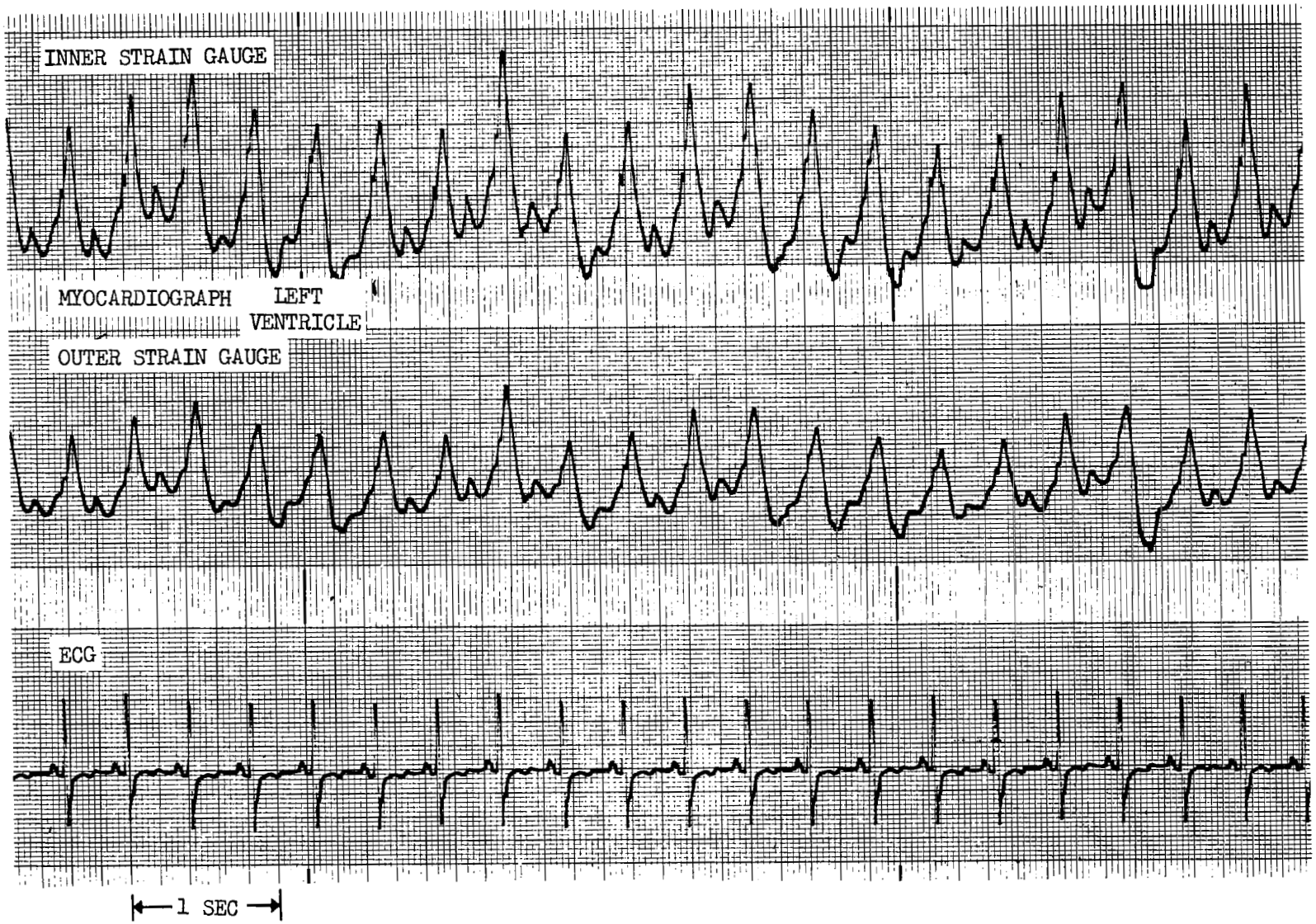


Figure A-28. Animal 9 (Anesthetized), Day of Implant. A somewhat typical sensor response was obtained with this implant. Although several positions and orientations were attempted, MCG events of interest are identifiable. However, electromechanical delay is 0.08 seconds.

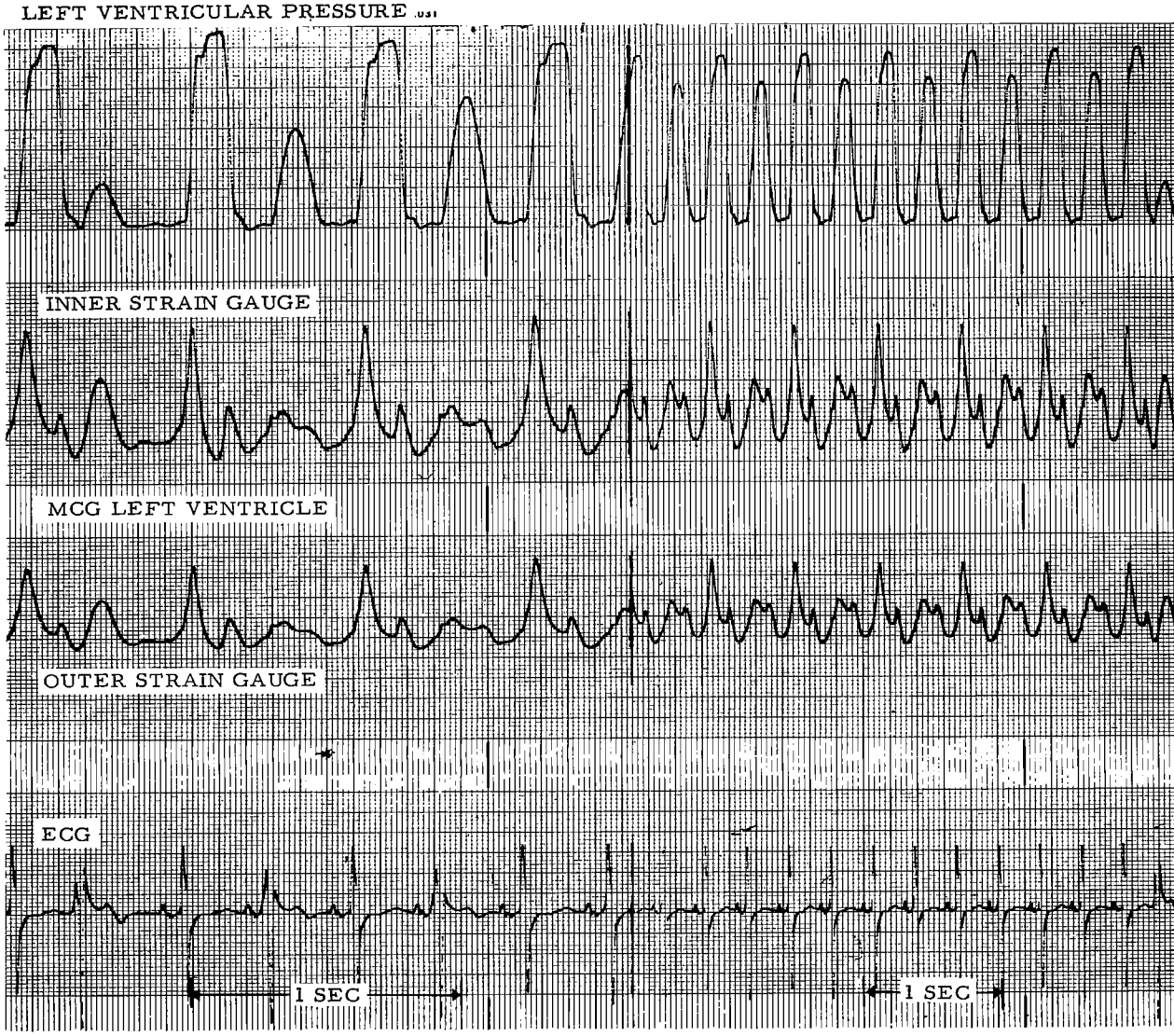


Figure A-29. Animal 9 (Anesthetized) Catheterization, 20 Days Postimplant. MCG response and left ventricular pressure response are in phase. Although the heart rate is regular, the mechanical response of the heart is not as indicated by the irregular MCG output and the irregular ventricular pressure. This dog expired during a later procedure.

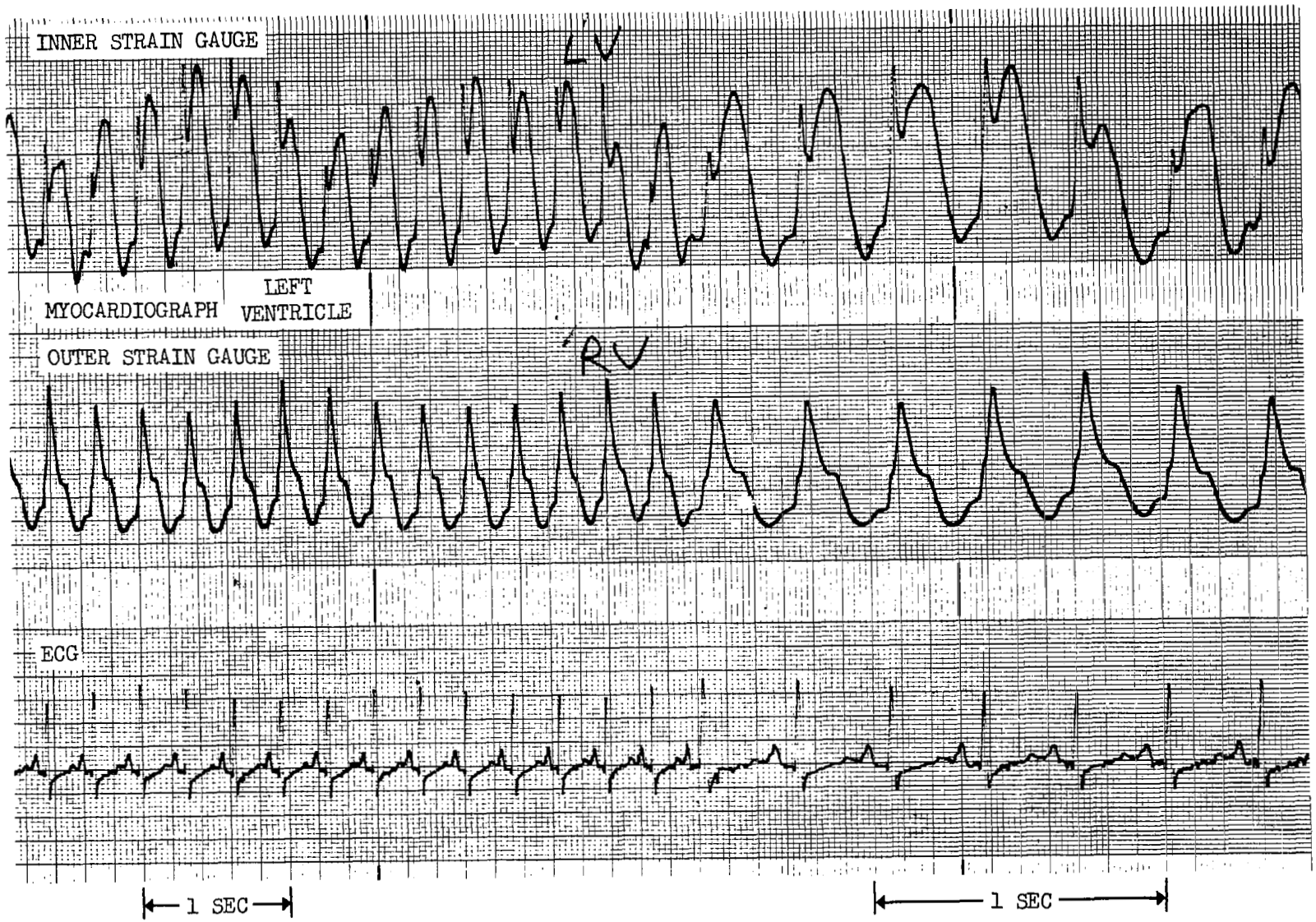


Figure A-30. Animal 10 (Anesthetized), Day of Implant. Two single-gage sensors were implanted, one on the right and one on the left ventricle. Electromechanical delay is 0.04 seconds in both cases. Considerable difficulty with rejection of the connector was experienced with this animal. Fluid leakage around the plug was such that succeeding records could not be obtained.

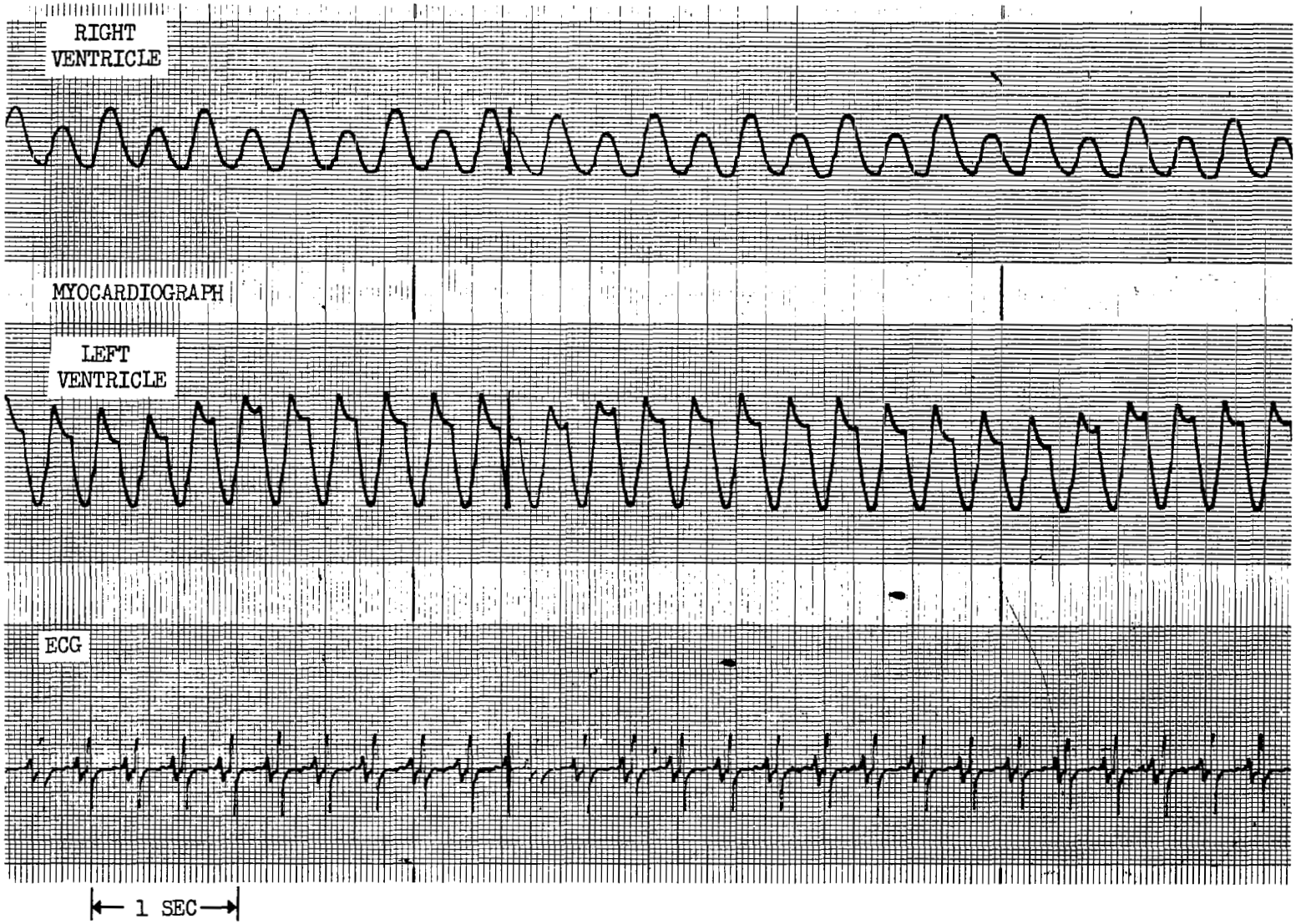


Figure A-31. Animal 11 (Anesthetized), Day of Implant. As with Animal 10, this animal had MCG sensors implanted, one on the right ventricle and one on the left ventricle. This first record is of interest because the right ventricular sensor was placed at a point near the diaphragmatic surface at a place where the earliest indication of contraction was thought to occur by observation during surgery and during motion pictures of other dog heart action. It can be seen from this record, however, that while the wave shape is somewhat different, the initiation of contraction does not precede that of the apical placement in time.

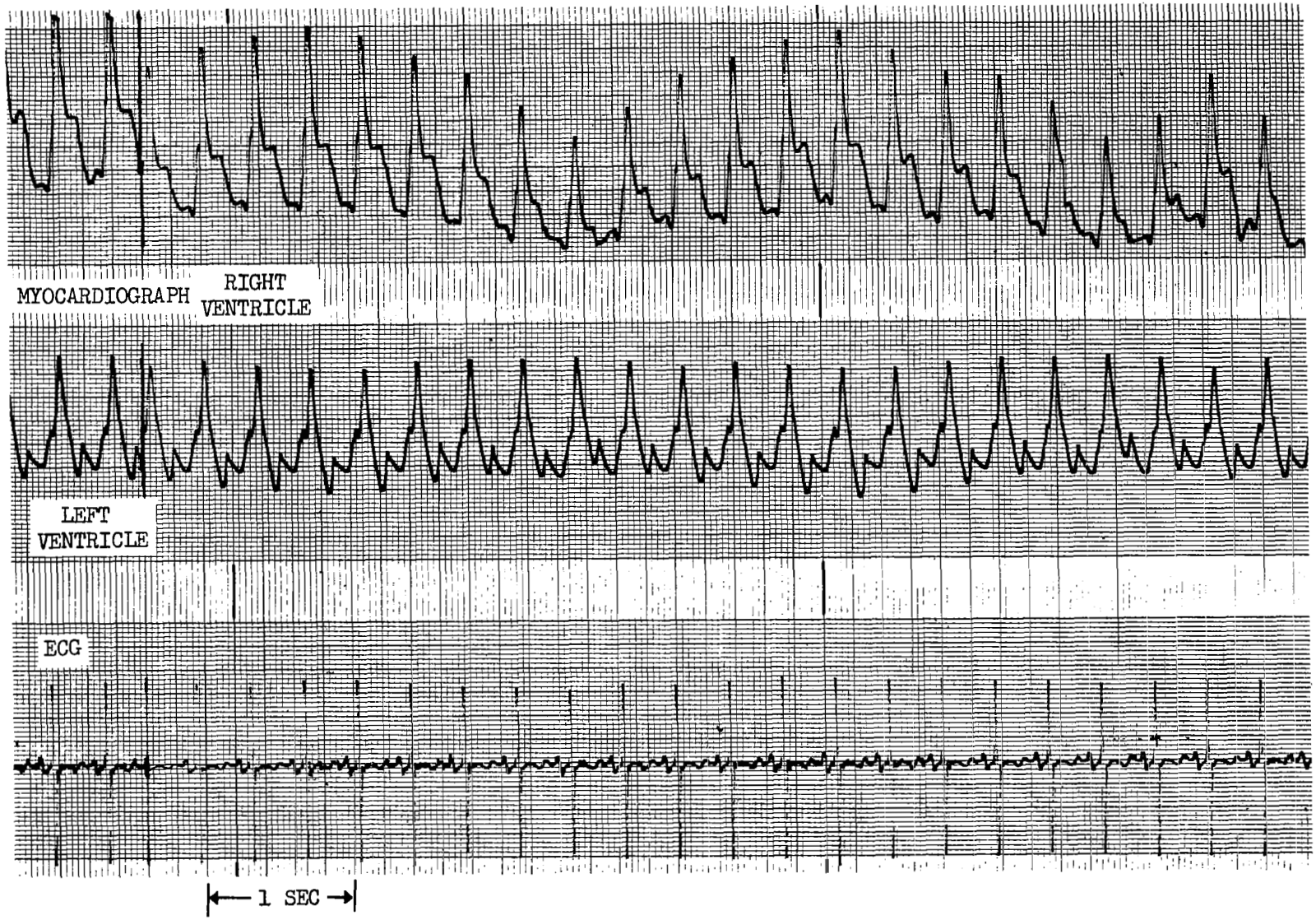


Figure A-32. Animal 11 (Anesthetized), Day of Implant. The right ventricular gage was placed at the predetermined location for a chronic MCG implant. Electromechanical delay is 0.06 seconds for both right and left ventricle sensors.

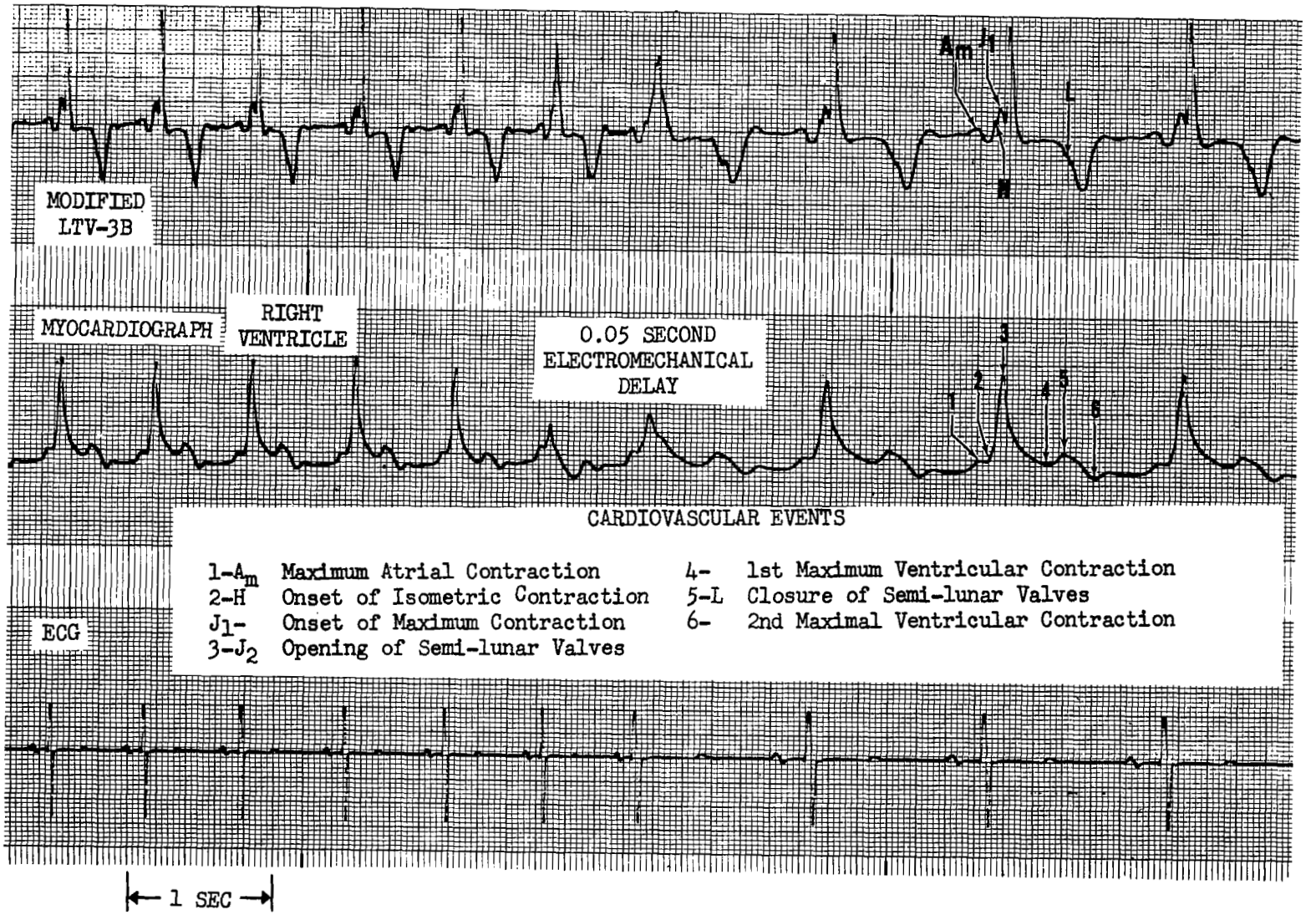


Figure A-33. Animal 11 (Anesthetized), VCG Recording, 9 Days Postimplant. This record was obtained using the modified VCG sensor. The significant points of interest are identified. The left ventricular gage was no longer functioning properly and does not appear on succeeding records. Electromechanical delay is 0.04 seconds.

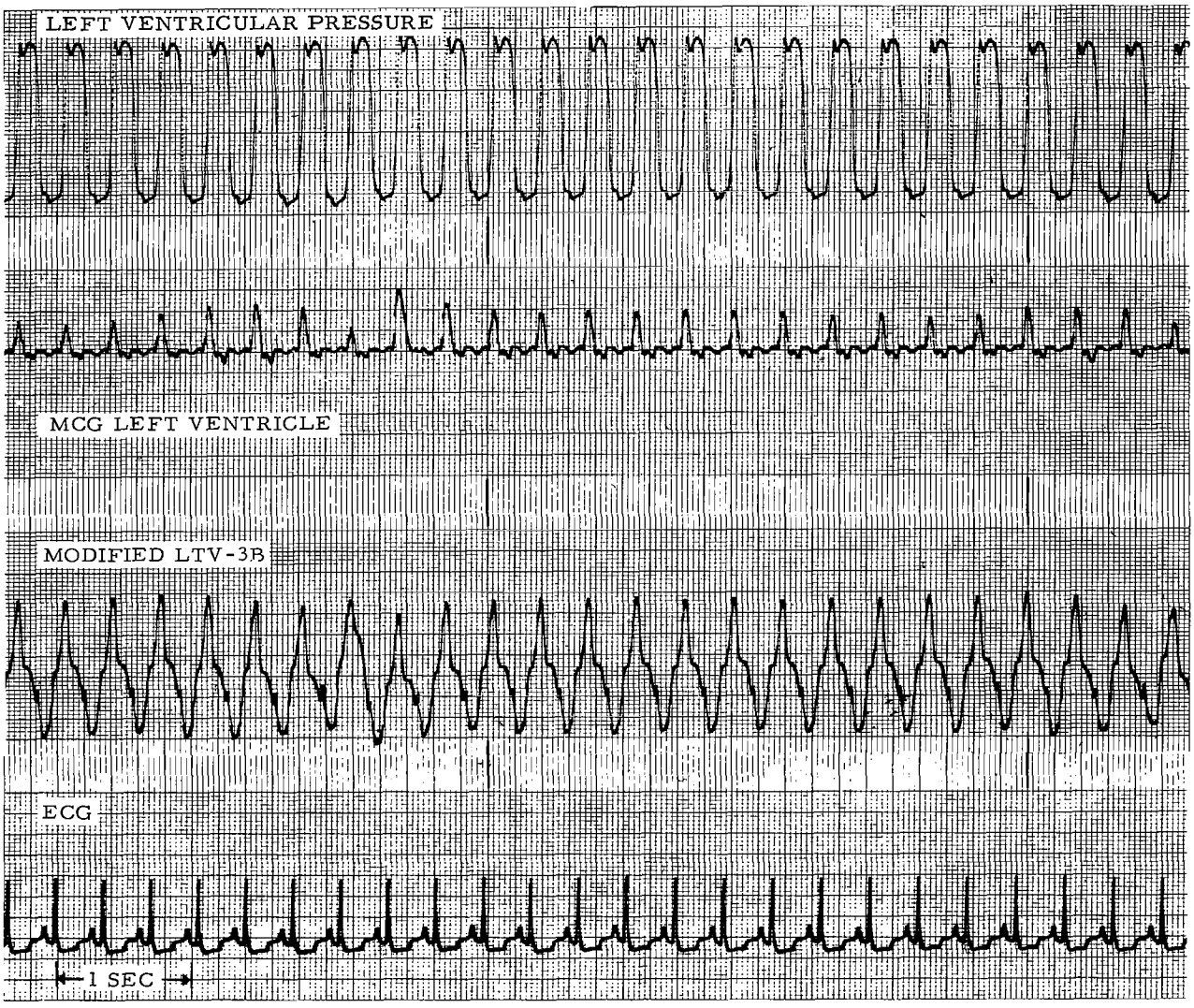


Figure A-34. Animal 11 (Anesthetized), Catheterization, 15 Days Postimplant. At this recording session, electromechanical delay was 0.07 seconds, and the MCG response appears to be time phased with left ventricular pressure. This is the only animal so far described where there is a variation in electromechanical timing. This variation does not appear to be related to heart rate.

CARDIOVASCULAR EVENTS

A-	Atrial Contraction	4-P	1st Max. Ventricular Contraction/Max. Ejection
2-I-H	Onset of Isometric Contraction	5-R-L	Closure of Semi-lunar Valves
J_1-	Onset of Maximum Contraction	6-	2nd Maximum Ventricular Contraction
3-N-J_2	Opening of Semi-lunar Valves		

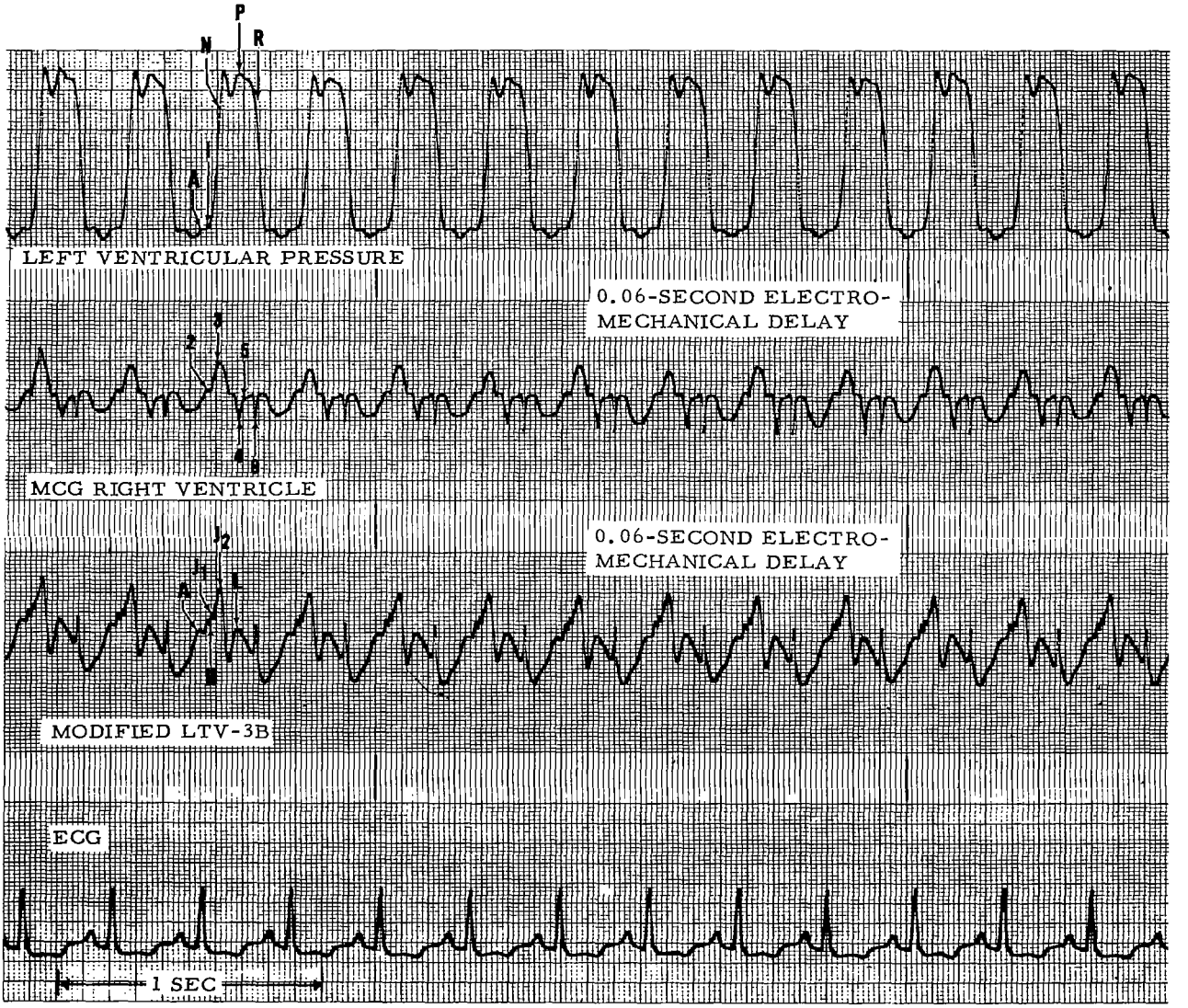


Figure A-35, Animal 11 (Anesthetized), Catheterization and Vibrophonocardiograph Recording, 15 Days Postimplant. This record, similar to the preceding record, was recorded at 50 mm ps, with the modified LTV sensor attached. Time phasing between VCG, MCG, and left ventricular pressure is approximately the same.

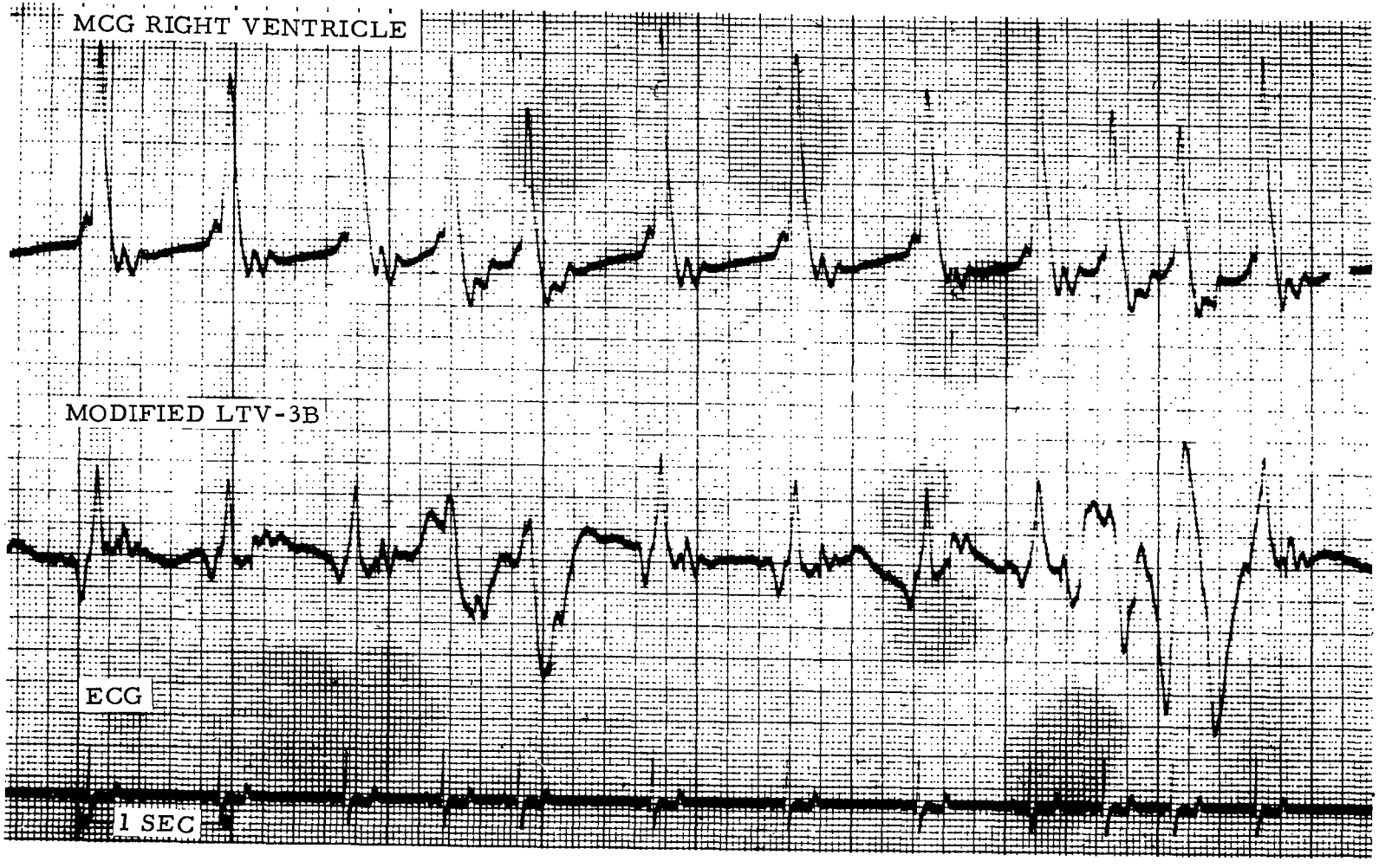
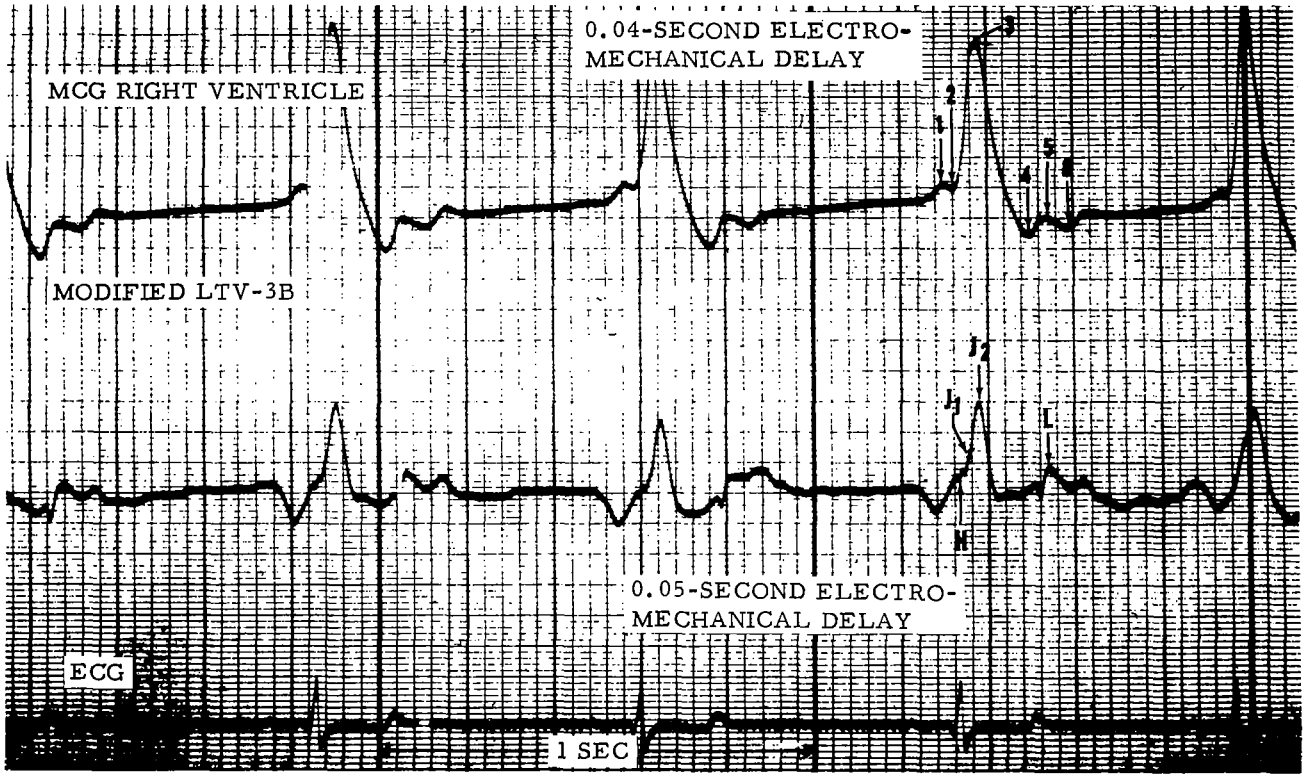


Figure A-36. Animal 11 (Unanesthetized), Vibrophonocardiograph Recording, 23 Days Postimplant. A record is shown to indicate the change in VCG response with respiration.



CARDIOVASCULAR EVENTS

1-	Atrial Contraction
2-H	Onset of Isometric Contraction
J-	Onset of Maximum Contraction
3-J_2	Opening of Semi-lunar Valves
4-	1st Maximum Right Ventricular Contraction
5-L	Closure of Semi-lunar Valves
6-	2nd Maximum Ventricular Contraction

Figure A-37. Animal 11 (Unanesthetized), Vibrophonocardiograph Recording, 23 Days Postimplant. A segment run at rapid speed; significant points are identified. Electromechanical delay is 0.04 seconds for the MCG.

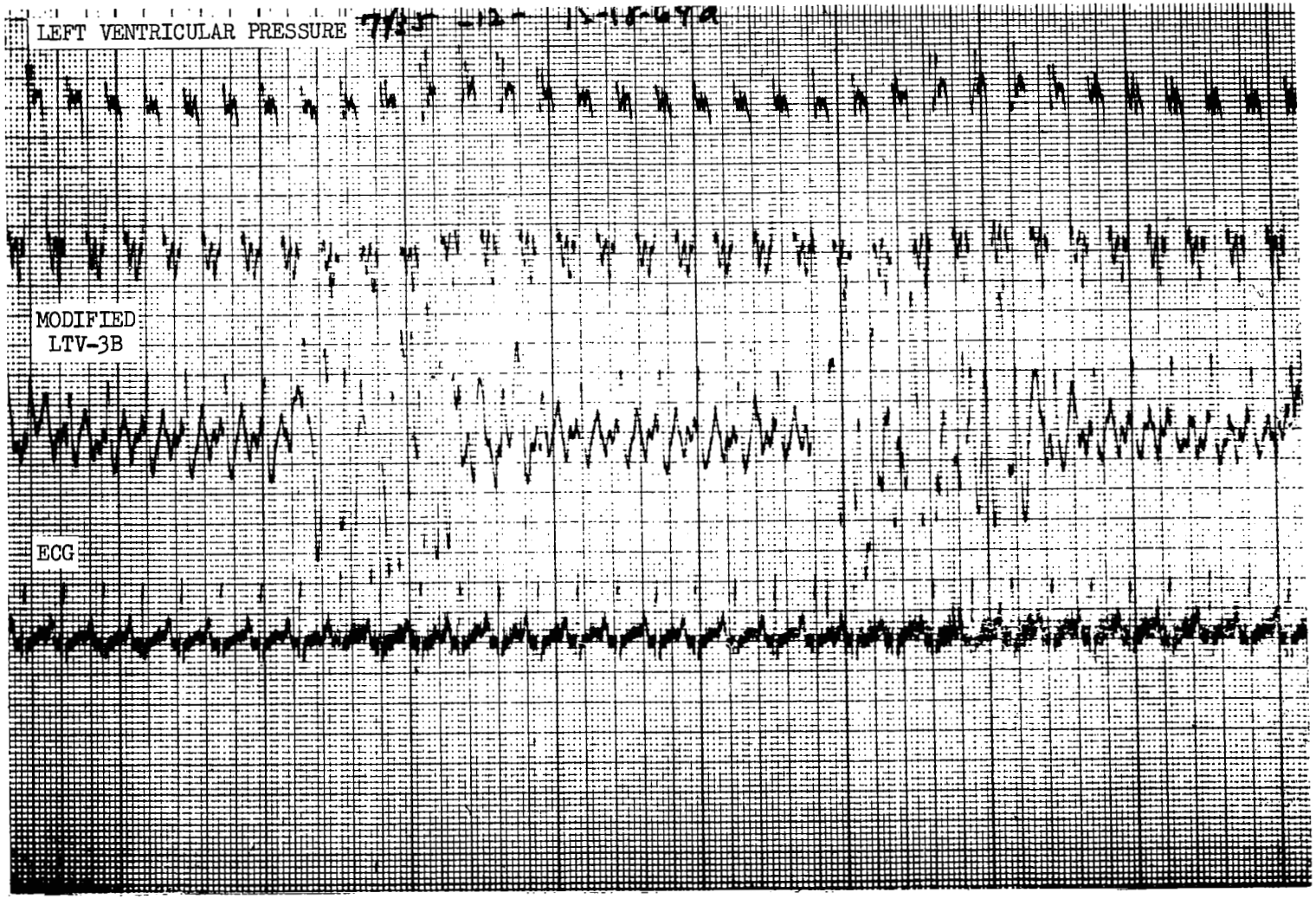


Figure A-38. Animal 12 (Anesthetized), Rib Resection. As described in the text, with the animal on its right side, a resection of a segment of the left fifth rib was made to study the change in response from the external chest wall to the pleura in the region of the apical beat using both an MCG explant and a modified VCG sensor. The animal was catheterized so that simultaneous ECG left ventricular pressure and VCG or MCG could be obtained. In this instance a 110-gram weight was placed on the VCG sensor, located at the point of apical beat on the chest wall. As shown on the recording, run at 25 mm a second, respiration caused a marked increase in amplitude of the VCG; therefore, wherever possible in this whole series, only records are shown where this effect does not interfere.

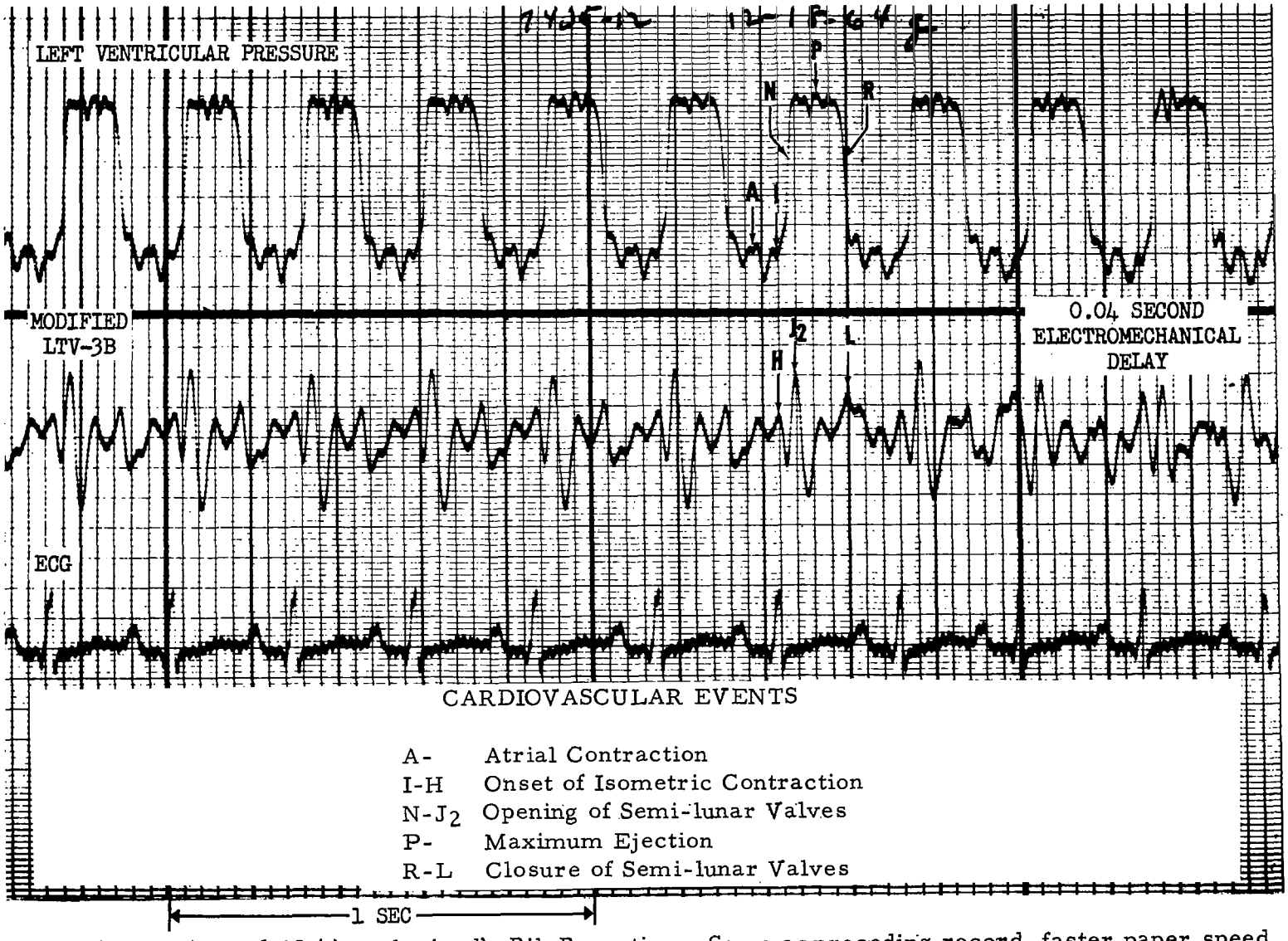


Figure A-39. Animal 12 (Anesthetized), Rib Resection. Same as preceding record, faster paper speed. As the procedure progressed to deeper tissues, the typical VCG was modified and made identification of some events difficult, especially the H and J_1 peaks.

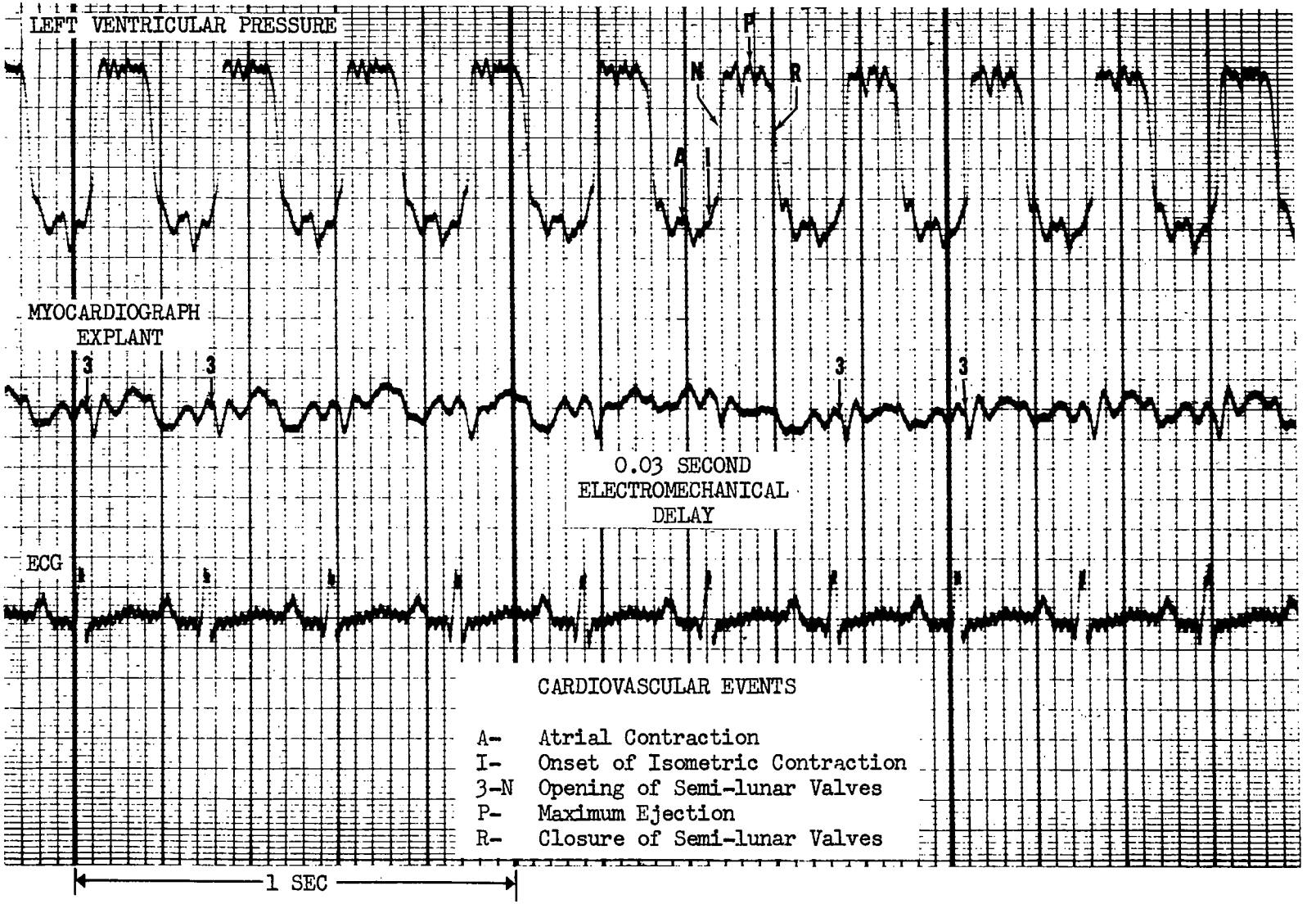


Figure A-40. Animal 12 (Anesthetized), Rib Resection. A MCG sensor was sutured to the skin at point of apical beat for this record. This MCG sensor assembly is the same as that used for the internal implants and, as such, response externally is very small; however, the plan was to note the relation of external to succeedingly deeper placements during the rib resection procedure.

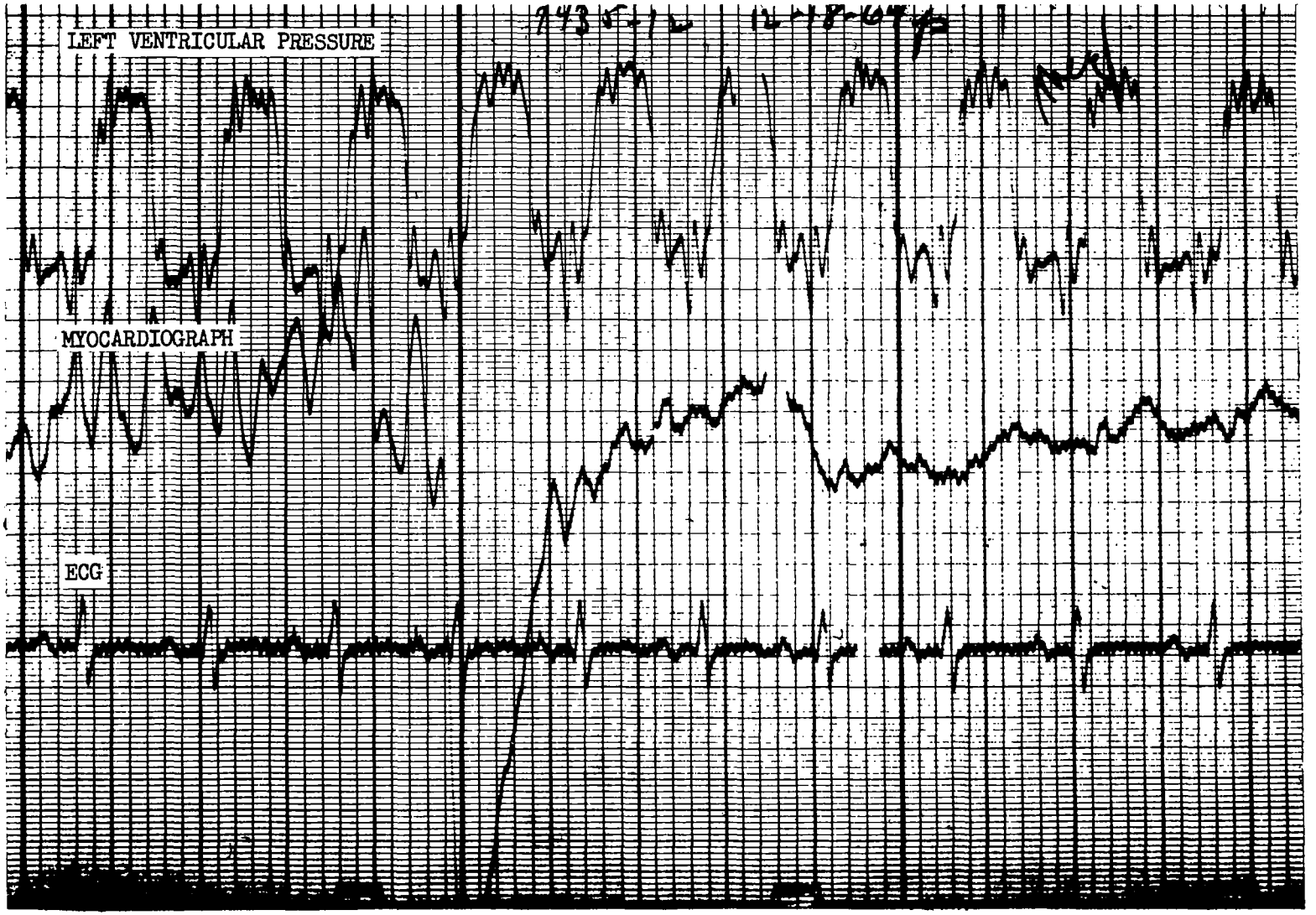


Figure A-41. Animal 12 (Anesthetized), Rib Resection. After an incision along the fifth interspace was made, the MCG sensor was sutured subcutaneously in the fifth interspace. It was apparent from the data collected during this segment that considerable signal was lost when the intact skin was opened leaving a much looser tissue site. Respiration and shivering frequently caused marked baseline shifts and amplitude changes during the whole procedure.

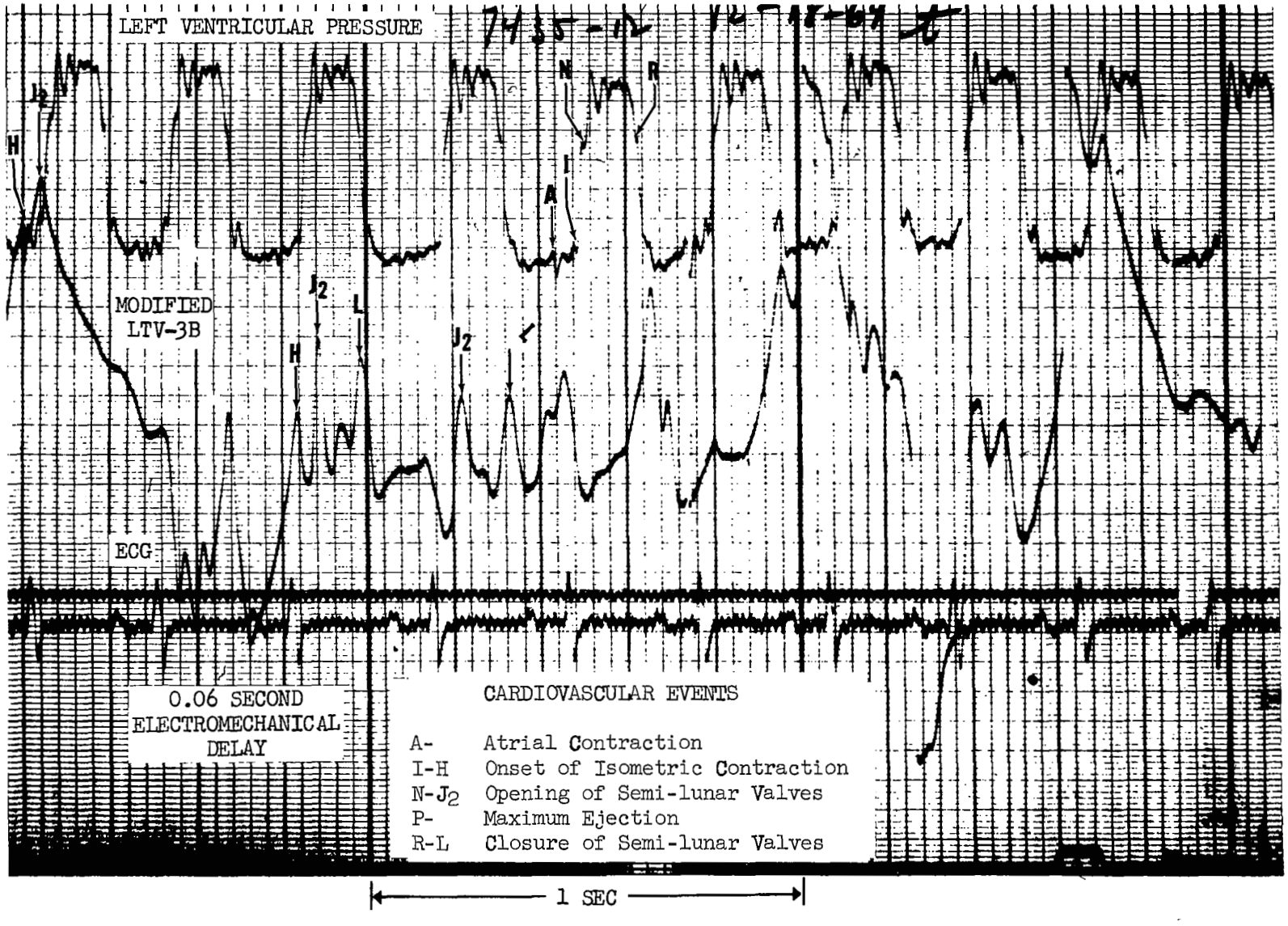


Figure A-42. Animal 12 (Anesthetized), Rib Resection. When the VCG was placed subcutaneously, a marked increase in amplitude was noted; in fact, as can be seen, the sensor was frequently driven beyond its limit, giving a poorly interpretable record.

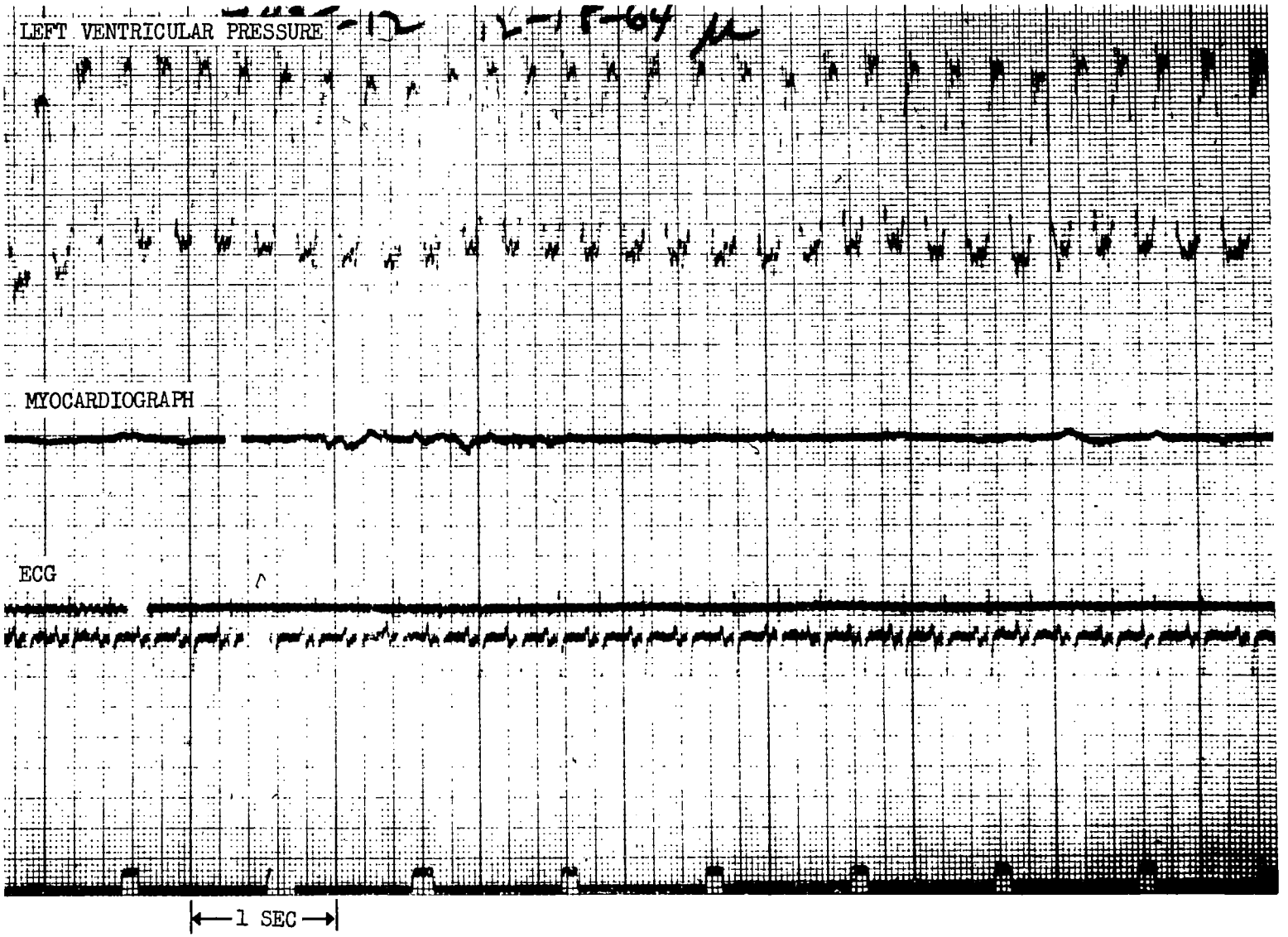


Figure A-43. Animal 12 (Anesthetized), Rib Resection. After further spreading of subcutaneous tissues, the MCG was sutured to the intercostal muscle in the fifth interspace. No response was apparent, again evidently due to the looseness of the surrounding tissues.

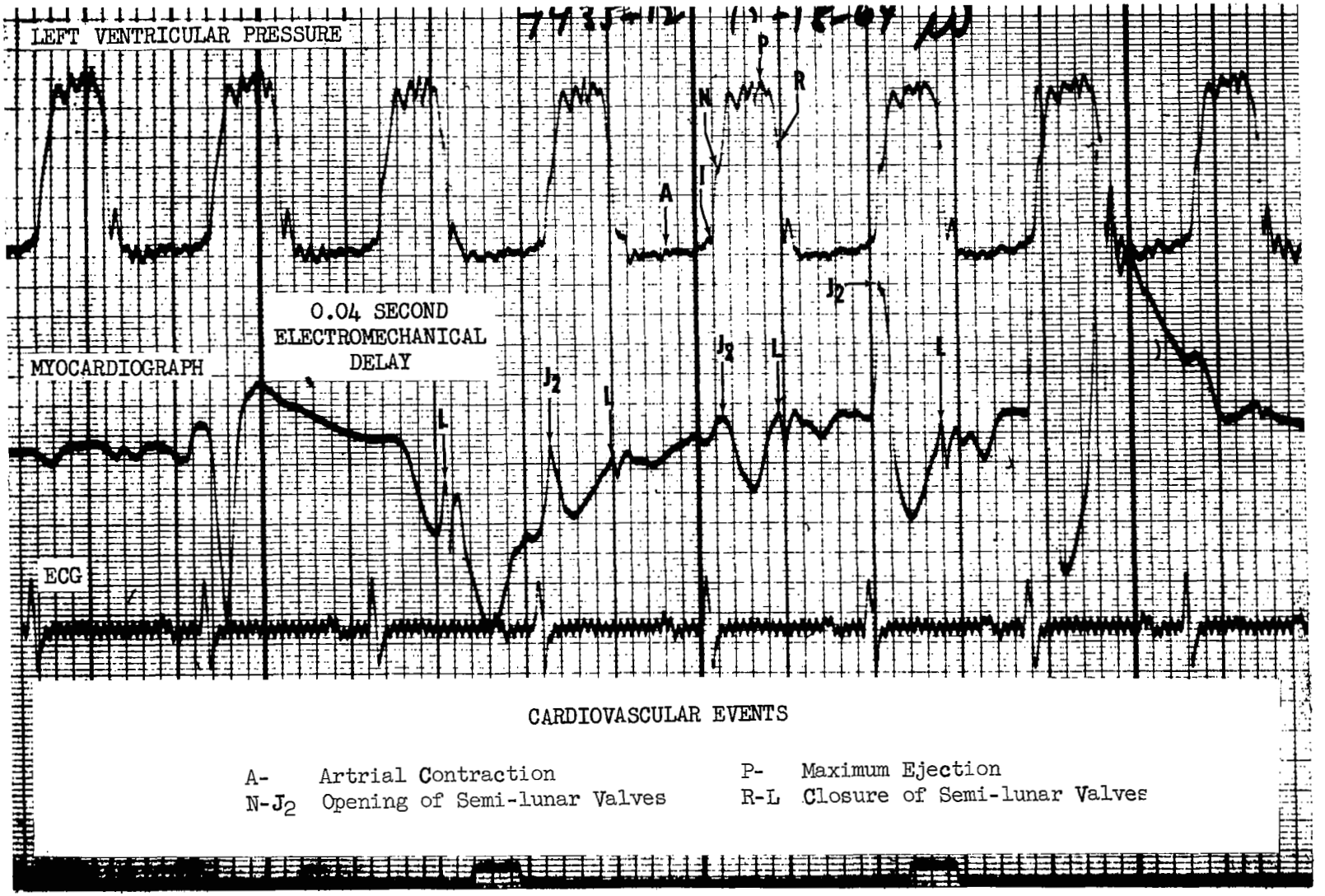


Figure A-44. Animal 12 (Anesthetized), Rib Resection. The VCG sensor was placed over the apical beat on the intercostal muscle site. Again the sensor is frequently overdriven; however, events can be identified and the increase in amplitude can be compared to the previous external location.

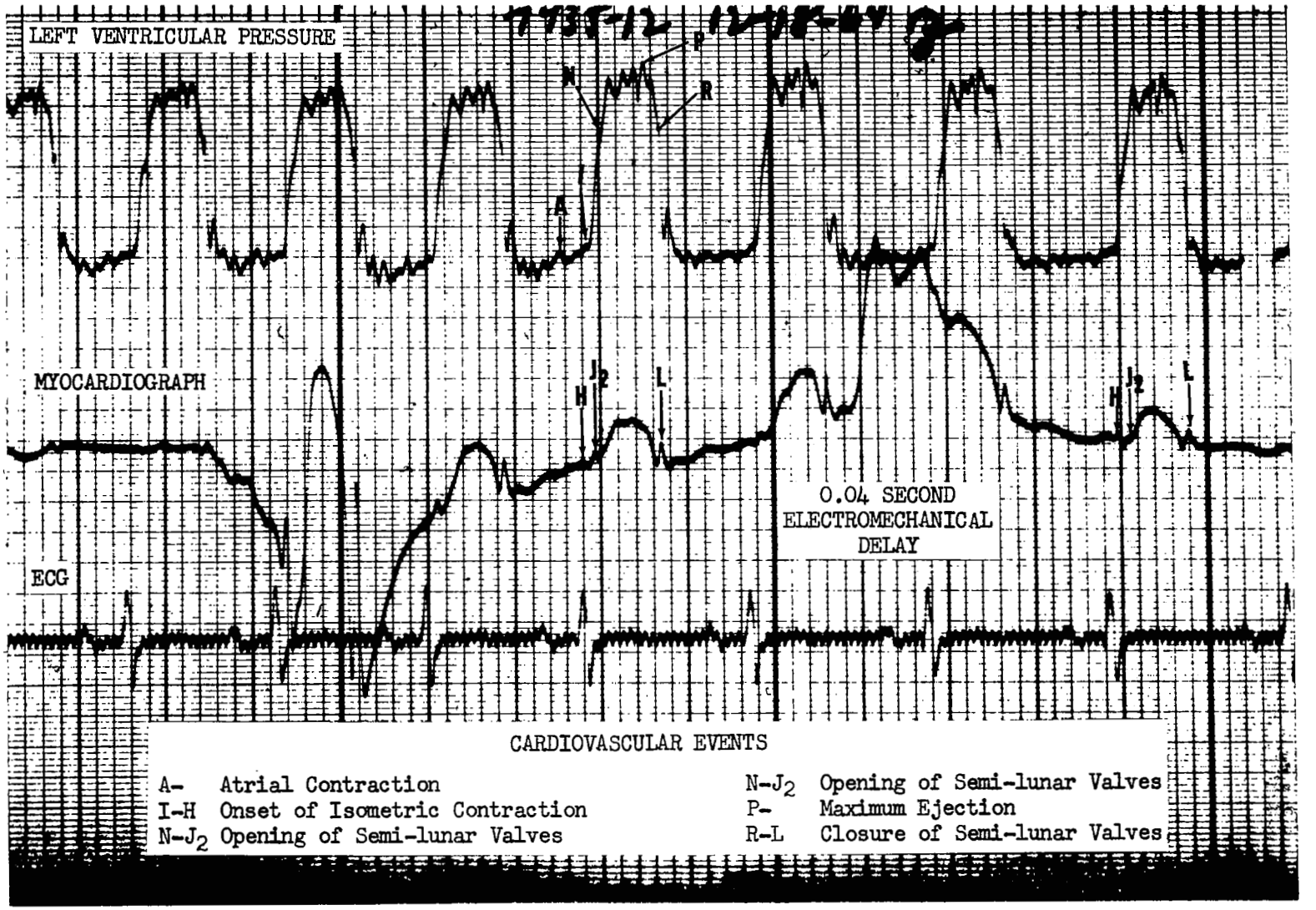


Figure A-45. Animal 12 (Anesthetized), Rib Resection. A two-inch section of the rib was resected to the sternum. The VCG sensor was placed on the pleura over the apical beat with a 110 gram weight added. Apical movement was so great that it was difficult to maintain the sensor on this site so that response comparison is not appropriate. However, timing of events can be noted and compared to preceding segments.

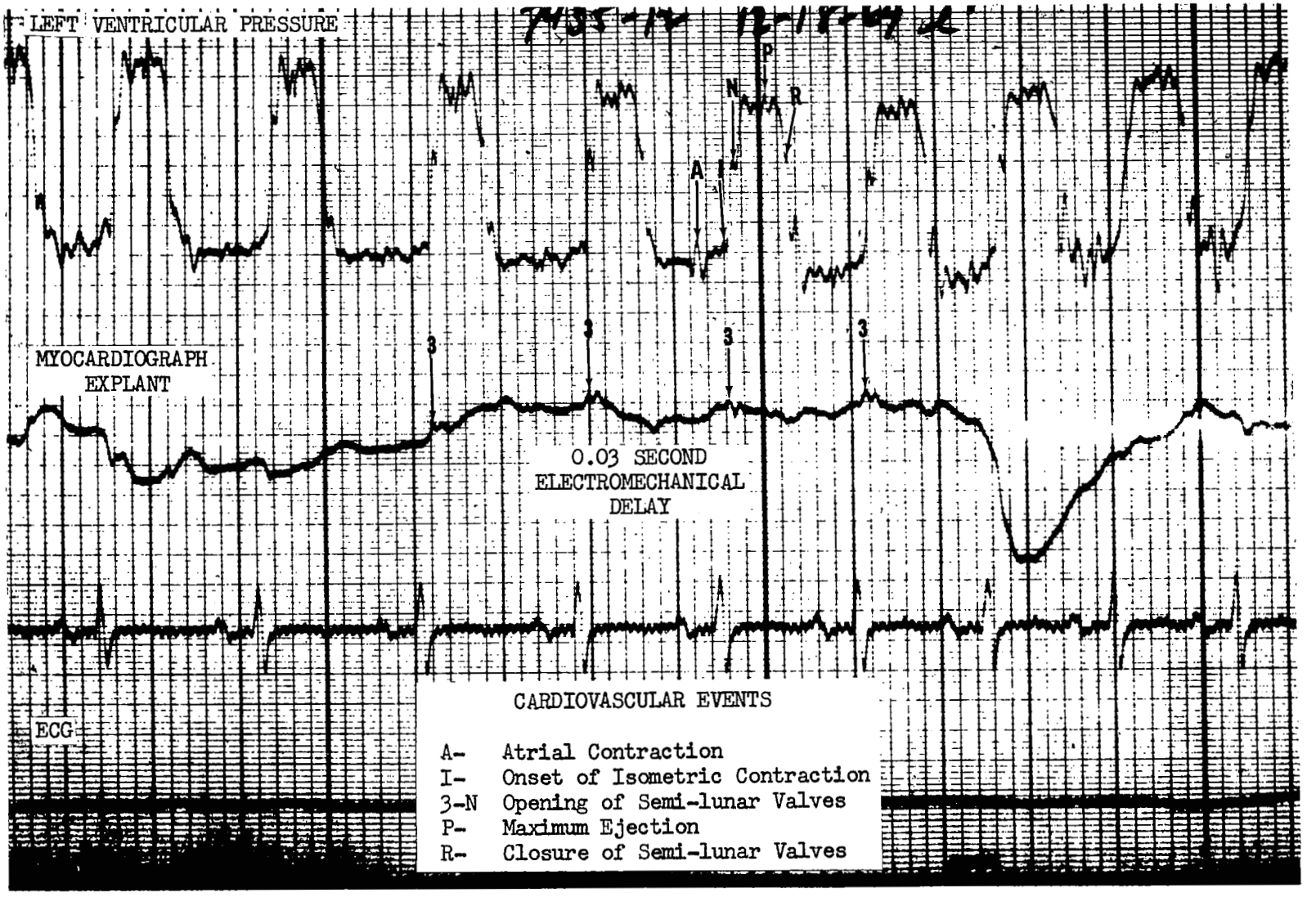


Figure A-46. Animal 12 (Anesthetized), Rib Resection. The MCG sensor was sutured to the periosteal pleural layer at the site of the apical beat, parallel to the excised rib location. Electromechanical delay does not appear to be markedly changed between this record and that obtained with the sensor attached to the skin. Although there are wave shape changes between internal and external chest wall, marked time phase shifts did not occur in this series. In other words, the chest wall is acting as a piston rather than as a viscous or fluid medium.

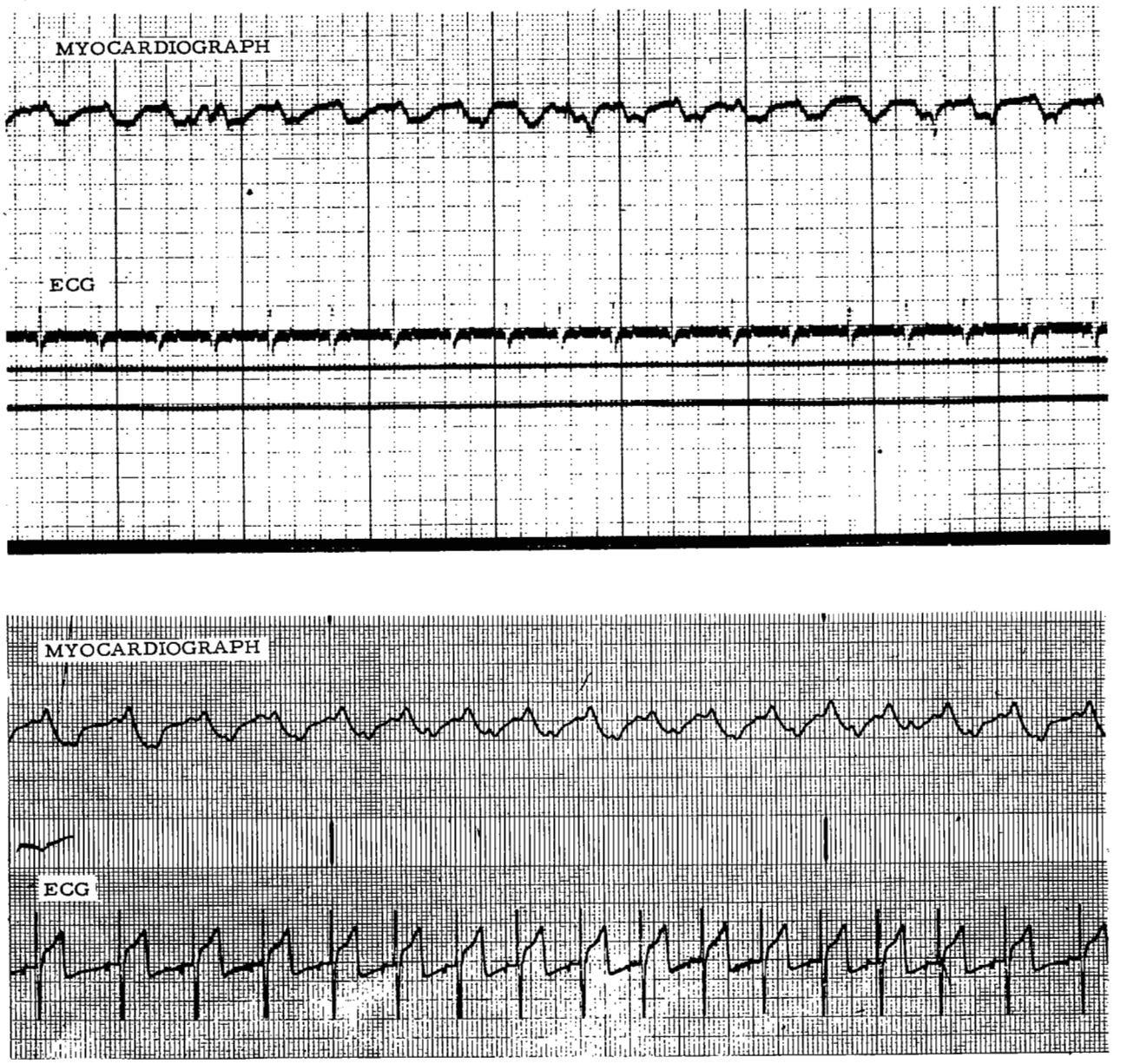


Figure A-47. Animal 5165-4, MCG Recording. This record shows a comparison of MCG data taken 12 days postimplant to information obtained from the same animal 214 days postimplant. Though there is a definite change in waveform, the characteristic timing points are still discernable.