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A brief history of X-ray control methods is presented, and the instrumentation requirements and physiological considerations pertaining to an automatic X-ray control system are discussed. The latter half of the thesis describes the design and operation of a device which will permit medical radiographs to be taken automatically and at any specified point in the cardiac or respiration cycle.

X-RAY TRIGGERING
BY
AUTOMATIC SENSING

by

Richard James Murtagh

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I. INTRODUCTION

This thesis is the result of a study into medical radiographic control methods begun in 1965. The project was initiated by friends of the author in various fields of electronics and medicine. The author, invited to join the group, discussed with them theoretical aspects of the problems. In 1966 the author became actively involved with the project.

X-Ray Applications and Triggering

Radiographic analysis is a valuable technique used in different fields and used for different purposes. The four most common applications of X-rays are: X-ray diffraction studies, where the atomic and molecular structure of material is analyzed; gamma radiography, wherein the gamma radiation from radium is used to examine the interior state of solid objects; industrial radiography, primarily in the area of quality control to examine welds, castings, etc.; and medical-dental radiography, the area of widest application and the field in which this thesis is concentrated (15, vol. 17, p. 813-814).

For many medical radiographic studies, involving a cooperative patient, the manual method of triggering is entirely satisfactory. The usual sequence of manually triggering an X-ray machine is to place the patient in position between the X-ray head and the film plate, ask his cooperation ("inhale, hold it, you may breathe now"), set exposure/duration, energize the X-ray tube rotor, and fire the X-ray machine.

If the patient is noncooperative (e.g., an infant, an unconscious individual, an animal) or, if exposures taken at various points in a physiological cycle are desired, the problems attendant with making a good exposure increase. The success of the manual triggering technique, with a noncooperative patient, lies almost entirely in the skill of the X-ray technician. A competent X-ray technician can attain a fair measure of success in making respiration radiographs of a noncooperative subject by visually observing the patient's respiration cycle and then triggering the X-ray machine at what she judges to be the proper time.

If the X-ray machine is not triggered at the correct time, additional exposures must be made until the desired, or nearest to the desired, picture is taken. Thus, the patient may be subjected to prolonged X-radiation exposure in an attempt to get a usable picture. There is also the problem of unavoidable delay while each shot is being developed.

When one wishes to take radiographs at various points on the cardiac cycle (e.g., the time of maximum heart size), the number of successes drop drastically. One can't tell just by looking at a radiograph, taken at random, whether or not the heart is in diastole (a phase of the cardiac cycle during which the heart is at its maximum size), or in systole (a corresponding phase of minimum heart size). The uncertainty in knowing at what point of the cardiac cycle a radiograph has been taken has resulted in misdiagnosis of heart disease (5, 18).

The period of a cardiac cycle is only about 700-800 milliseconds. The length of time during which the heart is in the "proper position" to be radiographed will be less than 100 milliseconds, the motor response time of the technician is about 100 milliseconds. The probability of taking an acceptable radiograph by manual triggering would be about 0.07.

Purpose of the Study

In 1965 a request had been made for a device which would permit one radiograph to be taken of an animal's chest at full inspiration and another at full expiration. Attempts at manually triggering the X-ray machine were not very successful. Delay in the motor response system of the X-ray technician and an irregular patient breathing cycle made it difficult to consistently trigger the X-ray machine near the peak of the respiration cycle.

This was the start of a project to develop a device to automatically trigger an X-ray machine on peaks of the respiration cycle. The X-ray triggering mechanism, the main topic of this thesis, has been developed, tested in hospitals, and is now manufactured under the name Monimat. In November of 1965 the Monimat was shown at the International Radiological Society of America conference in Chicago.

Although the Monimat, at that stage in its development, was essentially a respiration-sensitive device, many of the questions asked at the exhibit were about the possibility of the Monimat being used as a trigger which would be sensitive to the cardiac, rather than the respiration cycle. This has led to a broadening of the original goal, the subsequent results of which are incorporated into this thesis.

II. HISTORY

Methods of Automatic X-Ray Triggering

Respiration Studies

One of the earliest devices of which the author has heard, which was used for automatically triggering an X-ray machine during the respiration cycle, was a nasal air actuated switch developed during the 1950's. The switch was comprised of a flutter valve, placed in the nasal air stream; a microswitch, actuated by the flutter valve; and a control relay, energized by operation of the microswitch. When the patient exhaled, the flutter valve was moved outward away from the nose, the microswitch closed, the relay was actuated, and the X-ray machine was triggered. Some adjustment of the switch was necessary to assure that it closed at the peak of respiration. This system is illustrated in Figure 1.

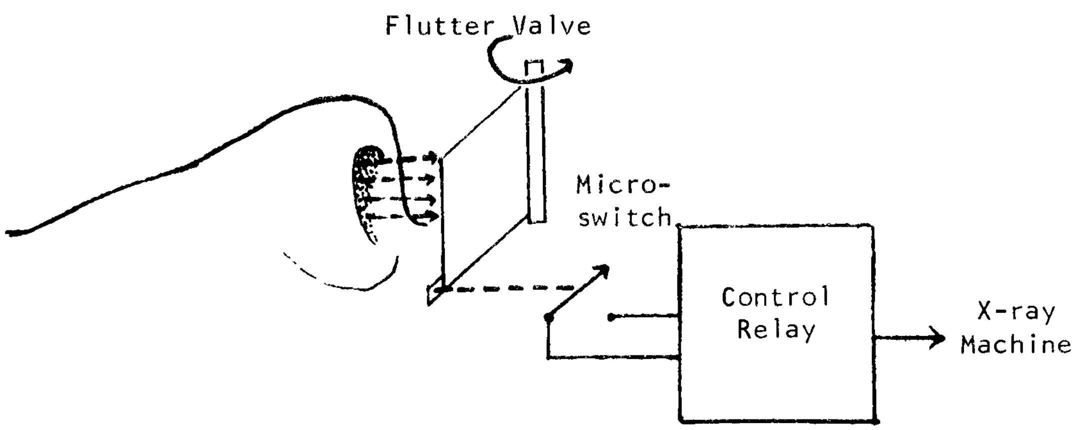

Figure 1. Switch actuated by passage of nasal air.

Another approach, was the nasal thermocouple system (8). In this system a thermocouple was inserted a small distance into the nasal passage, and the output leads were taped to the skin just under the nose. The voltage generated by the warm air, as it was expelled from the body and over the thermocouple junction, was used to control a relay. The actuation of the relay triggered the X-ray machine. A time delay in the relay control circuit afforded a means of triggering the X-ray machine at various parts of the respiration cycle. This system is illustrated in Figure 2.

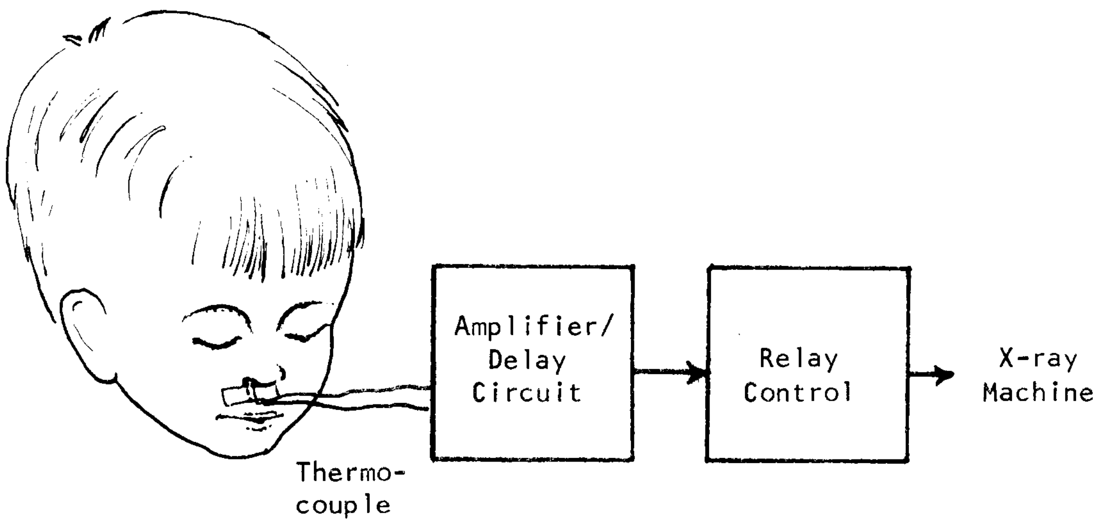

Figure 2. Thermocouple system for triggering of X-ray machine.

A modification of the above system was to incorporate the thermocouple into a mask which covered the lower portion of the face. The mask was used to prevent external air currents from affecting the rhythmical voltage fluctuations generated by the thermocouple.

A new method using doppler effect response for sensing chest motion has been verbally reported, but the author has no knowledge of the location nor of the effectiveness of such a device.

Cardiac Studies

Of necessity, a device used to automatically trigger an X-ray machine during a particular phase of the heart cycle must respond to either an electrical or pressure change related directly to the heart action.

The electrocardiograph (ECG), an apparatus for measuring surface potentials of the body (which are related to surface potentials at the surface of the heart), is the instrument which is most frequently used to obtain the signal voltage by means of which the X-ray machine may be triggered. The largest voltage pulse produced by the heart during the cardiac cycle and measured at the surface of the body is the R-wave. Maximum and minimum voltage peaks occurring during the cardiac cycle are referred to by a system of arbitrary letters: P, Q, R, S, T, U. This is illustrated in Figure 3 (15, p. 28).

The R-wave is the electrical signal indicating the start of electrical systole. Because the electrical R-wave precedes the actual mechanical systolic phase of the heart by about 100 to 140 milliseconds (11, p. 622-623), a time delay feature is usually added between the ECG and the X-ray machine. The ECG may be modified to close a relay at the time of each R-wave (8). Figure 4 (9) illustrates the time lag between electrical systole and mechanical systole (represented by the tracing of left ventricular pressure).

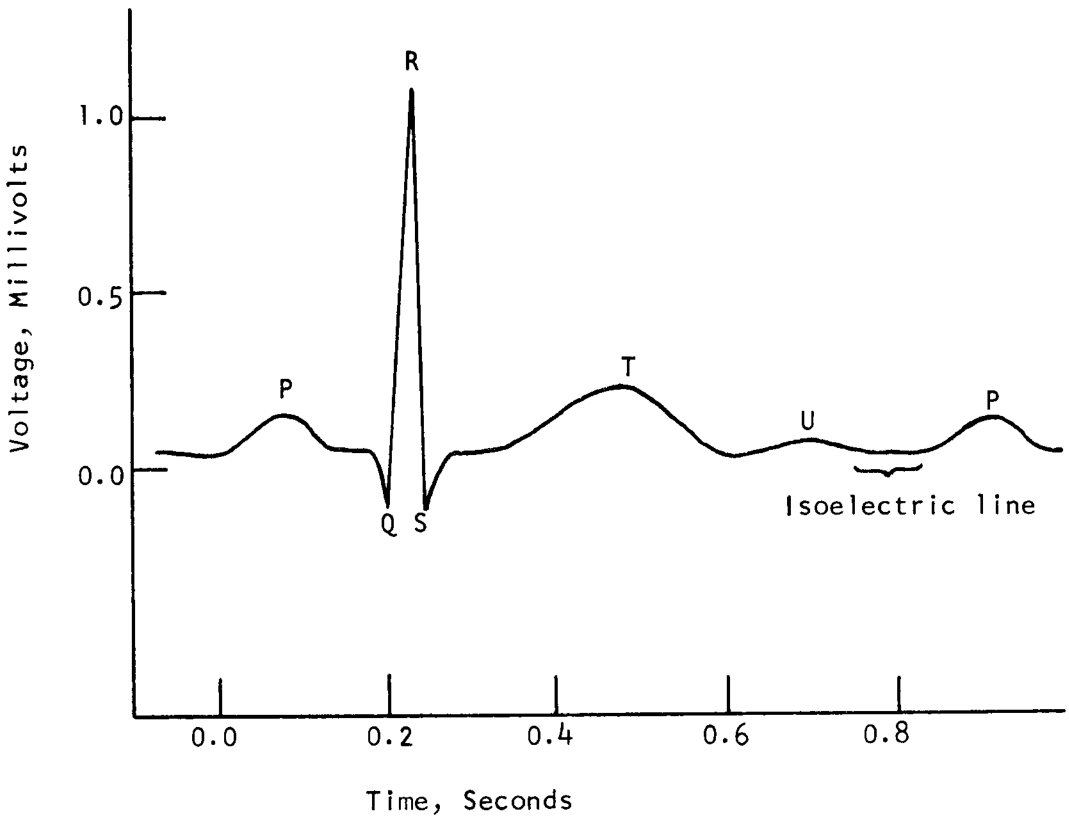

Figure 3. Cardiac cycle waveform

R wave: Onset of systole

Isoelectric line: Region of diastole

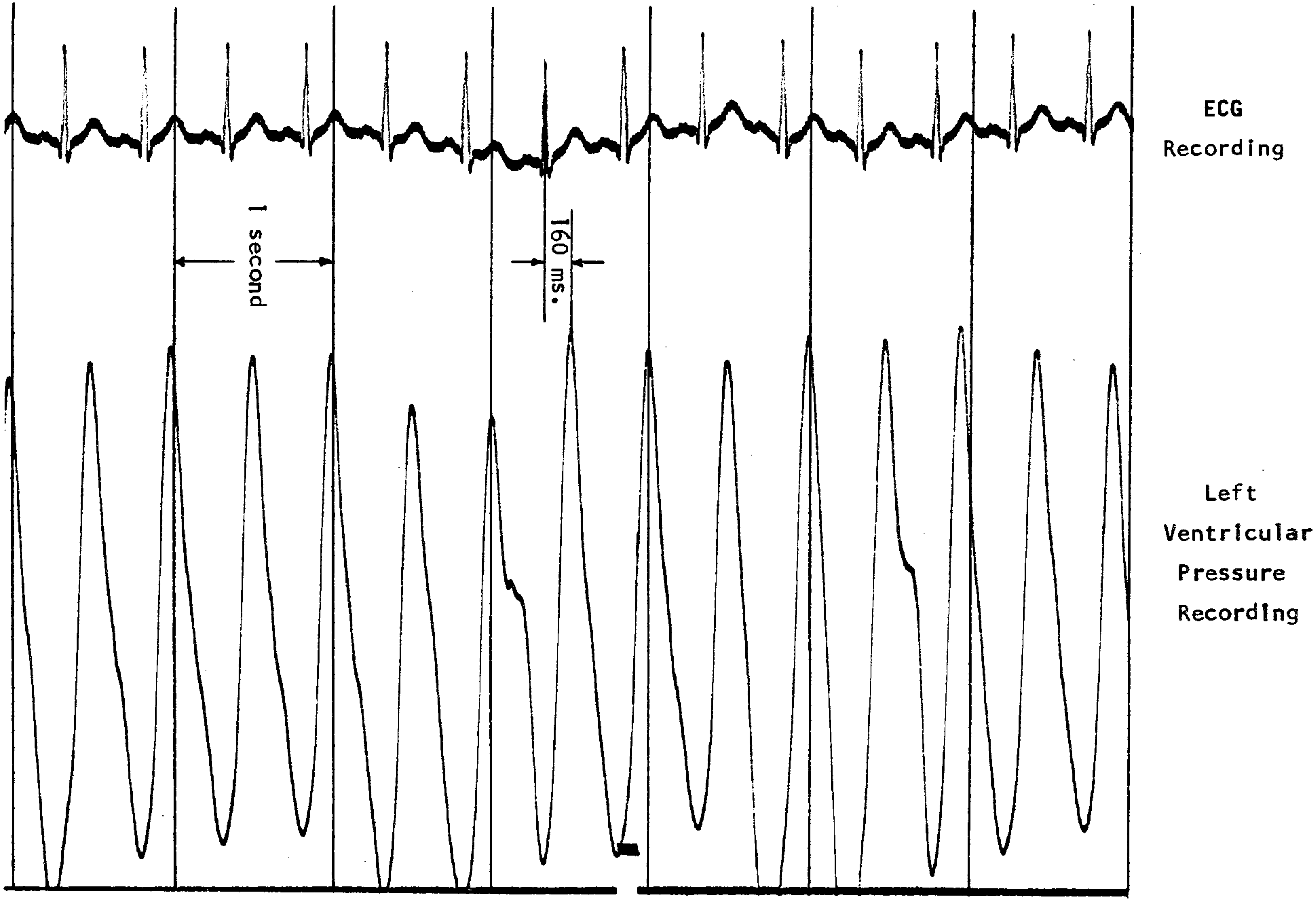

Figure 4. Delay between electrical and mechanical systole

A second means of causing the X-ray machine to be triggered during the cardiac cycle is with the use of a defibrillator, modified to trigger an X-ray machine rather than to deliver counter-shock impulse (6). The defibrillator is a device which is used to deliver a short controlled electrical shock to the heart. It is used in the treatment of "ventrical flicker", a condition wherein both ventricles of the heart no longer contract but show only ineffective rapid and random (flicker) movements (16).

Limitations

The techniques (nasal air switch, nasal thermocouple, thermocouple mask) used in connection with automatic X-ray triggering during respiration studies have two basic disadvantages:

1. Normal respiration cycling can be affected by the psychological reaction to the attachment of the sensing device on or about the face.
2. Response time of the device is slow. Fast response time is not a prerequisite for all modes of triggering, but lack of fast response time in the triggering device will limit one's ability to achieve precise control over the exact point of triggering.

In addition, the use of the nasal switch is further limited by the necessity (for best operation of the switch) of the patient being in the supine position. This limits the type of studies which can be made.

The cardiac waveform, available at the output jack of some ECG machines, is, many times, of limited value in initiating an X-ray trigger, due to noise pickup and distortion of the output signal. However, some models of ECG machines have output waveforms acceptable for triggering purposes, if the proper control circuitry is available.

The use of a defibrillator for triggering purposes appears to have much merit. However, at present, its use is limited mainly to specific clinical studies and is not widely used.

Indeed, none of the above-mentioned methods are widely used.

One cannot be positive of the reasons why automatic X-ray triggering has seen so little application. However, the author, after talking with radiologists, can venture some opinions:

1. Most apparatus used for automatic X-ray triggering, is equipment which has been modified to serve that purpose. Therefore, personnel who understand the electrical-physiological aspects of the problem will be needed to make the modifications. There are too few qualified individuals readily available to all who would desire to make radiographic studies using the techniques of automatic triggering.
2. The result of much of the modification efforts has been too many knobs to turn and adjust for proper operation of the equipment. While this would not be a hindrance to the medical engineering team, it would often put the X-ray technician, who routinely takes most of the pictures, at a disadvantage.
3. There are no standardized techniques, other than those which the doctor, engineer, or technician develops for himself to aid in the setting up and taking of automatically triggered radiographs.

III. REQUIREMENTS OF AN AUTOMATIC X-RAY TRIGGER

Instrumentation Requirements

Safety and Reliability

Patient safety is of primary concern when using any diagnostic apparatus. This is especially true if the apparatus is electrically operated. The patient must be protected against any possibility of electrical shock. And, for sanitary reasons, sense elements, if used in contact with the body, should be disposable or autoclavable.

A device which is designed to fire an X-ray machine automatically must have sufficient safeguards so that accidental pretriggering is not possible.

To be of maximum utility an automatic trigger should be fully operational with a minimum of knob and switch manipulation. Once it has been calibrated, the automatic trigger should remain operational regardless of line voltage variation, temporary overload, and effects of aging (for a period of at least six months). Maintenance, when required, should be well within the abilities of any competent electronics technician.

Triggering at Selected Cycle Points

Since relatively little has been done using the technique of automatic X-ray triggering, many of the uses to which such a device may be put will remain in the realm of conjecture. The design of such apparatus should, therefore, provide for various modes of operation. One should be able to trigger an X-ray machine at any preselected spot on any of the body cycles that, with the proper transducer or sense element, could generate an electrical signal or be transformed into an electrical signal. The cycles of primary interest would be expected to be the respiration and the cardiac cycles.

Without the means to selectively trigger an X-ray machine at various points in the cardiac cycle, all heart radiographs would necessarily be taken at random times during the cycle. This causes a problem in using the cardiac radiograph for many diagnostic studies because of the uncertainty as to "when" the picture was taken. As early as 1919 it was recognized as a problem (2).

Experimental studies have been made with large groups of patients, classified by age, and heart size variations were estimated by computation of means and standard deviations (1, 4, 5, 10). Physicians were cautioned against placing too much faith in the interpretation of cardiac radiographs (6, p. 387). In 1962, Dr. Robert F. Ziegler[1], reported (18, p. 440):

> Our present and continuing efforts are directed toward several ends, among which are the provision of certain diagnostic /radiographic/ criteria not yet currently available. . . to the end of making results more nearly reproducible, and thereby minimizing the role of subjective opinion. The need for these studies is great.

Clinical investigations (8, 14) have indicated that it would be of diagnostic value to be able to take coincident radiographs; specifically, to take a radiograph of the chest when the heart is at a specific point in the cardiac cycle coincident with the time that the

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[1]Physician-in-Charge, Division of Pediatric Cardiology, Henry Ford Hospital

chest and lungs are at a specific point of the respiration cycle.

A radiograph of particular interest to the radiologist would be one which would permit him to compute the ratio between maximum chest diameter and maximum transverse heart diameter, an index which would be used in comparing future radiographs of the same patient in a check for heart disease or malfunction. With a cooperative patient consciously holding his breath at the peak of inspiration, the X-ray machine could be set to fire automatically at a point corresponding to heart diastole (maximum heart size). However, with a noncooperative patient the desired radiograph would be difficult to take. The adult human heart has a transverse diameter of about 13 cm and undergoes a change in size between systole and diastole of about 1.5 to 2 cm (12, p. 579). Since a radiologist normally measures the size of the heart and chest to the nearest 2 mm, the coincident interval would have to be very short if useful results were to be obtained.

An approximate, but reasonable, criterion for coincident X-ray triggering would be to take the radiograph when the heart was within 25 milliseconds of diastole and the chest within about 50 to 100 milliseconds of maximum inspiration. This would result in a point of coincidence occurring approximately every 20 seconds. A format for computing periods of coincidence is given in Appendix I.

Since there is no standardization of sensors or transducers which could be expected to be used with an automatic trigger, provisions must be made in the input circuits to receive and work with different input voltages and different input impedances.

If the patient were to move or cough just before the occurrence of the automatic trigger, the radiograph would probably be ruined. Therefore, it would be desirable to have the trigger automatically over-ridden in the event of an unexpected motion on the part of the patient.

Peripheral Equipment

If the automatic trigger were to be able to sense heart action for the purpose of taking radiographs of the heart at specific points in the cardiac cycle, it would be, in effect, functioning as an ECG device. To obtain a permanent electrical record of heart action, where desired, it would be necessary to provide a means for driving a recorder. Therefore, a recorder output connection would be desirable.

It would be desirable to be able to use existing transducers or sensors whenever possible. Therefore, the automatic trigger should be able to use conventional ECG electrodes when being used for cardiac studies. Conventional ECG leads may be used in any one of 12 different configurations (3, p. 36, 13, p. 59). The output impedance of the ECG leads will depend on the particular configuration used. Provision must be made to match the output impedance of the ECG leads to the input impedance of the automatic trigger, otherwise, 60-cycle pickup could adversely affect the operation of the system.

Personnel Constraints

Patient Cooperation

To be a truly automatic triggering device, the X-ray trigger should be functional with no conscious, cooperative help from the patient. There are two basic reasons why this would be a necessary rather than a "nice" feature:

1. Often times a patient is not able to cooperate in the taking of a radiograph. An infant or an adult who is in pain or unconscious cannot be expected to cooperate with the X-ray technician. Many radiographs are taken of animals during experimental and clinical studies and an animal does not know how to cooperate during radiography.
2. When a patient holds his breath, waiting for a radiograph to be taken, his chest muscles are invariably tensed to some degree. Thus, the resultant radiograph would not depict the normal condition of the chest at inspiration. In some studies (e.g., examination of bone fracture or foreign objects), the "normal" state would not be of primary concern. In other types of studies, it would be (e.g., comparative radiograph series).

The author knows of one instance involving a noncooperative patient where selective radiographs had to be taken. A small child had swallowed a peanut. Because of the circumstances under which this happened, there was some question as to whether the peanut had become lodged in the lungs or had passed into the stomach. A peanut, radiographically transparent, does not appear on film as a foreign object. The usual investigative procedure is to take one radiograph at inspiration, another at expiration, and check for otherwise unexplained displacement of the lung tissue caused by the peanut. In this case, the child was not able to cooperate with the X-ray technician. Before satisfactory film results were obtained, 12 X-ray exposures were made. Two exposures should have been sufficient.

Psychological Reactions

The device used as a sensor with the automatic X-ray trigger should not cause any change in the patient's normal breathing or respiration cycle. This would require the sensor to be as unobtrusive as possible to the patient. Ideally, the sensor should not contact the patient at all.

The author was the subject of a cardiac-respiration coincidence study during the development of the Monimat. At the beginning of this study a respiration sensor was not available. This required that the breath be held at the peak of inspiration, and the X-ray machine was to be triggered from the ECG sensors. When the X-ray tube rotor had gained sufficient speed to permit the taking of a radiograph, the X-ray technician, through force of habit, called out, "Ready!" The author should have been an ideal subject, but, at the sound of the word "ready", the heartbeat rate, as recorded by the monitor, increased by 25 percent.

The X-ray machine was properly triggered but the resulting radiograph showed a slightly different picture than would have been the case if the author had not been alerted to the fact that the X-ray machine was in the ready state. Studies have shown that the heart size decreases slightly as a result of cardiac speed-up (14).

Operational Simplicity

To be of maximum utility, diagnostic apparatus should be of such a nature that it could be routinely operated by technicians. Certain diagnostic procedures must, by law, be performed by a physician (e.g., the placement of a transducer into the bloodstream of the patient).

If a physician had to be present to apply the automatic X-ray trigger sensors to the patient, the utility of the trigger would be limited. Therefore, the complete test setup and subsequent triggering of the X-ray machine should be able to be accomplished entirely by a technician.

A desirable feature of an automatic trigger would be to incorporate an X-ray tube rotor switch into the trigger unit. This would mean that the entire operation of the system, except for the initial exposure/duration adjustment on the X-ray machine, could be executed at one location and with one instrument, the trigger unit.

IV. APPROACH TO PROBLEM

The automatic X-ray trigger, described in detail in Chapter V., was not designed after the fashion of one who, with a blank sheet of paper before him, starts designing a circuit block by block, stopping only when the project is complete. The design progress of the Monimat from conception to reality has been a series of steps--forward, backward, and forward again.

The first effort was to design an automatic trigger that would respond only to changes in the respiration cycle. Design refinement possibilities became apparent, and additional features were requested by medical personnel who aided in the early testing. However, an attempt to incorporate various changes into the circuitry often made evident certain limitations which, while not affecting the earlier design, had an adverse affect on the circuit additions. Results? Back to the drawing board for a redesign of basic circuitry.

As sensitivity was increased, for example, the power supply, which had originally been designed with line regulation only, now had to be load regulated as well. Eventually, even the size of the chassis and cabinet had to be changed to accommodate all the circuit additions.

Effect of Project Constraint on Instrumentation

Sensor

First priority was given to the problem of devising a sensor which would respond to the respiration cycle. Existing methods (e.g., nasal air switch and thermocouple) were discarded as being too ineffectual and not yielding repeatable results. There did not appear to be any readily attainable method of developing a sensor that could be used without making patient contact.

The method that seemed the best compromise was a soft, conductive, stretchable plastic belt that was radiographically transparent. This, with modifications, is being used at the present time. In operation the belt is placed about the patient's chest. The sensor output is a resistance which changes in value as a function of the respiration cycle.

Amplifier

One requirement of the amplifier is that it respond to changes in resistance and convert the time-varying resistance input to a corresponding time-varying voltage signal. Because the signal level was expected to be low, provision was made to amplify the signal and ultimately use it to control the trigger circuit.

When used with ECG sensors, the input signal is electromotive, rather than resistive. Therefore, the amplifier must work with either type of input. In addition, because other sensors might be adapted for use with the Monimat, incorporated in the amplifier was a gain- and impedance-matching input selector circuit.

In order to minimize the effect of component aging, all critical circuits were to have metal film resistors and computer grade capacitors. Protection diodes were used to prevent circuit damage in the event of voltage surges during warmup.

A compromise was reached between the disadvantages of providing a large power supply to operate vacuum tubes (with an attendant heat generation problem) and using expensive (at the time) Field Effect Transistors. The Monimat, in its present form, utilizes vacuum tubes where necessary and transistors throughout the rest of the circuit. A newer version of the Monimat, with the advent of less expensive Field Effect Transistors, will be completely solid state.

Trigger

The basic function of the trigger circuit is, of course, to fire the X-ray machine. The simplest and most effective method is to use a relay to switch the 117 volts alternating current required to fire the X-ray machine.

A second function, almost as important as the first, is to have control over the precise moment when the X-ray machine will be triggered in reference to the time of the cardiac R-wave or the point of maximum inspiration. The cardiac R-wave or the point of maximum inspiration is the source of the largest input signal and would be the logical point from which to reference any trigger delay.

An R-C time-delay circuit was used to provide the delay and is adjustable from the front panel. A delay range of 0 to 2.2 seconds, in steps of 0.02 seconds, was chosen based on the assumption that longer delay would be unnecessary.

Signal lights were used on the front panel to indicate to the X-ray technician the status of the operation sequence. Lights were thought to be a more noticeable indication of readiness conditions than meter readings. Aural indicators were not used because of the possibility of the sound being a distraction to either the operating personnel or to the patient.

A meter movement was used to monitor the input response cycle. To simplify the setting of the trigger circuit, limit switches were used on the meter movement (in conjunction with a photo diode and light source) to set the starting point of the trigger delay sequence. The meter movement is a modification of a contactless meter relay (17).

Recorder and monitor output jacks were provided in the event that a continuous permanent record of the cardiac or respiration cycle might be desired.

Power Supply

The power supply had to provide both vacuum tube and transistor operating voltages. Five separate regulated supply voltages are used to supply the various circuit functions: -25V, -50V, +150V, +250V, +300V.

Power supply regulation was the biggest problem to overcome. In the most sensitive position of the input sensor switch, a change of 15 mv in the +250V supply will cause the meter needle to deflect full scale (referencing from center scale on the meter face). A voltage drift of one part in 20,000 would pin the meter. Therefore, it was decided to try to make the short-term voltage stability about 50 times better than one part in 20,000. A short-term voltage stability of one part in 10^6 would mean that voltage drift would cause a meter needle deflection of no more than 2 percent of full scale.

Alternate Solutions

A new problem arose during the later stages of development of the Monimat. It wasn't one of the type, "How can this device be made to function more effectively?" but was rather, "At what point should a stop be put to the incorporation of new features in the Monimat?" One of the original constraints, simplicity of operation, was being threatened.

Rather than try to make one automatic X-ray trigger do everything, a decision was made to have two basic models and a coincidence unit. In this way, increasingly complex studies could be made by "stacking" the triggering units, yet routine examinations and studies could be made by using the individual unit. The present units are:

1. Model 200 - This model is intended to be used primarily for studies where the input signal has a relatively long period. The more common studies would be: respiration, with triggering at any point in the breathing cycle; esophageal, where stop motion studies are often made; fetograms, with the prevention or interruption of exposure in the event of fetal movement. The Model 200 is illustrated in Figure 5.
2. Model 350 - This model incorporates all the features of the Model 200 plus additional features to permit the taking of selectively timed cardiovascular radiographs, when used with an ECG adapter. This system is illustrated in Figure 6.
3. Model 400 - This coincidence triggering accessory, when connected to the two above instruments, will trigger an X-ray

machine when two selected body functions occur coincidently. The Model 400 is illustrated in Figure 7. The coincident system is illustrated in Figure 8.

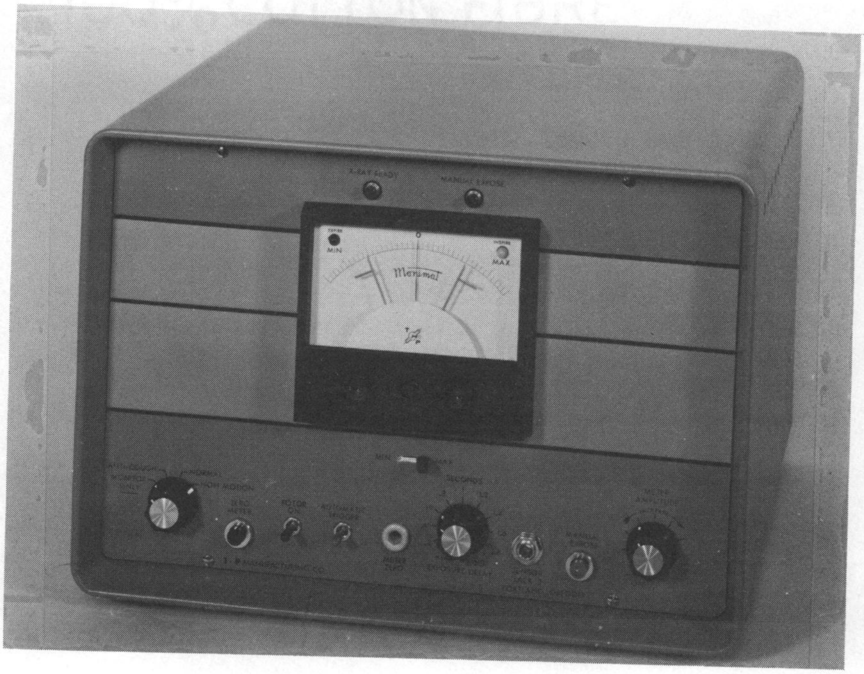

Figure 5. Model 200 Monimat

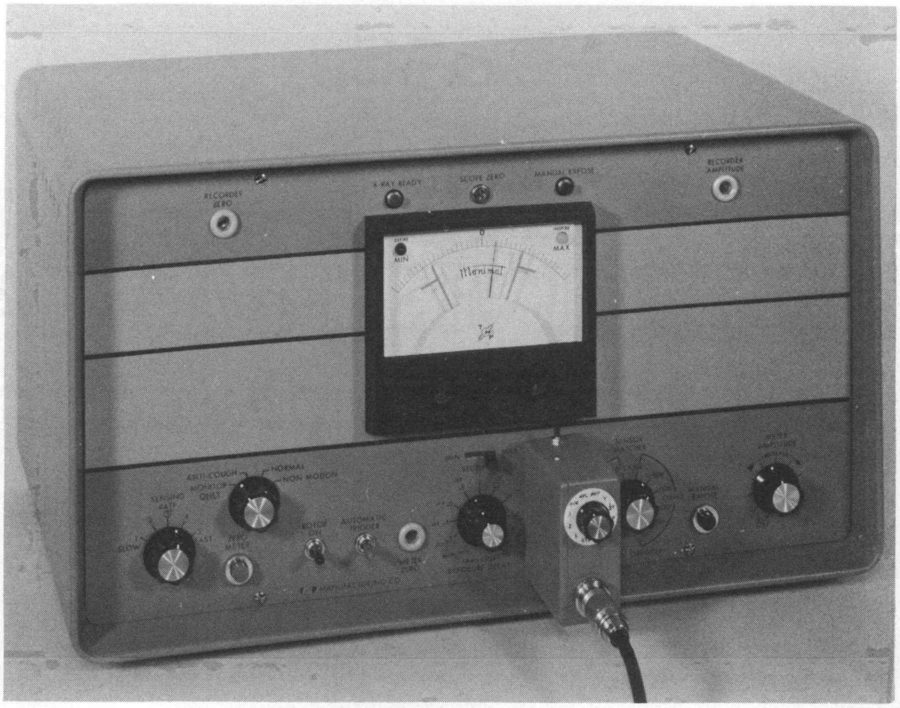

Figure 6. Model 350 Monimat

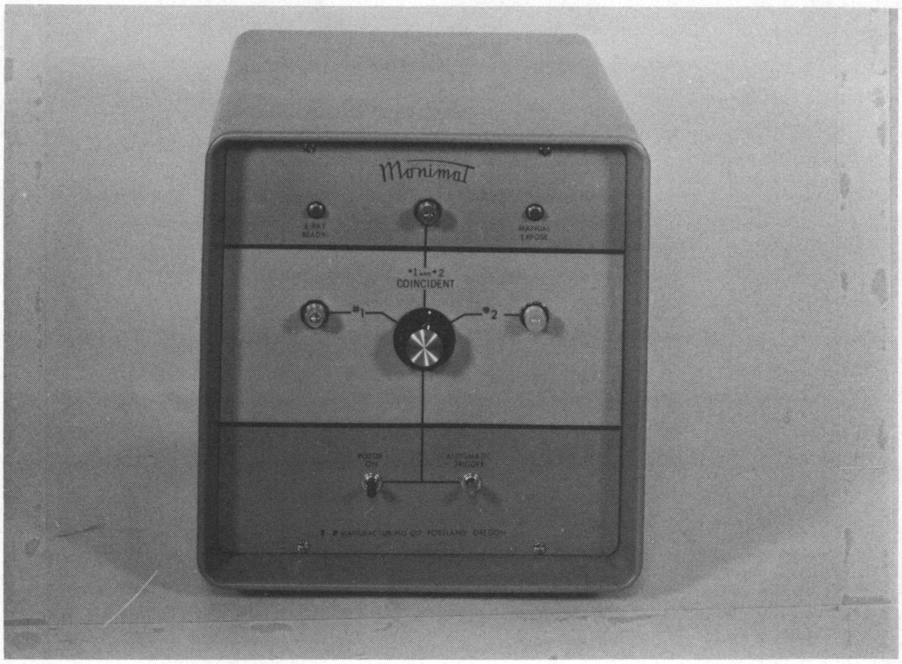

Figure 7. Model 400 Monimat

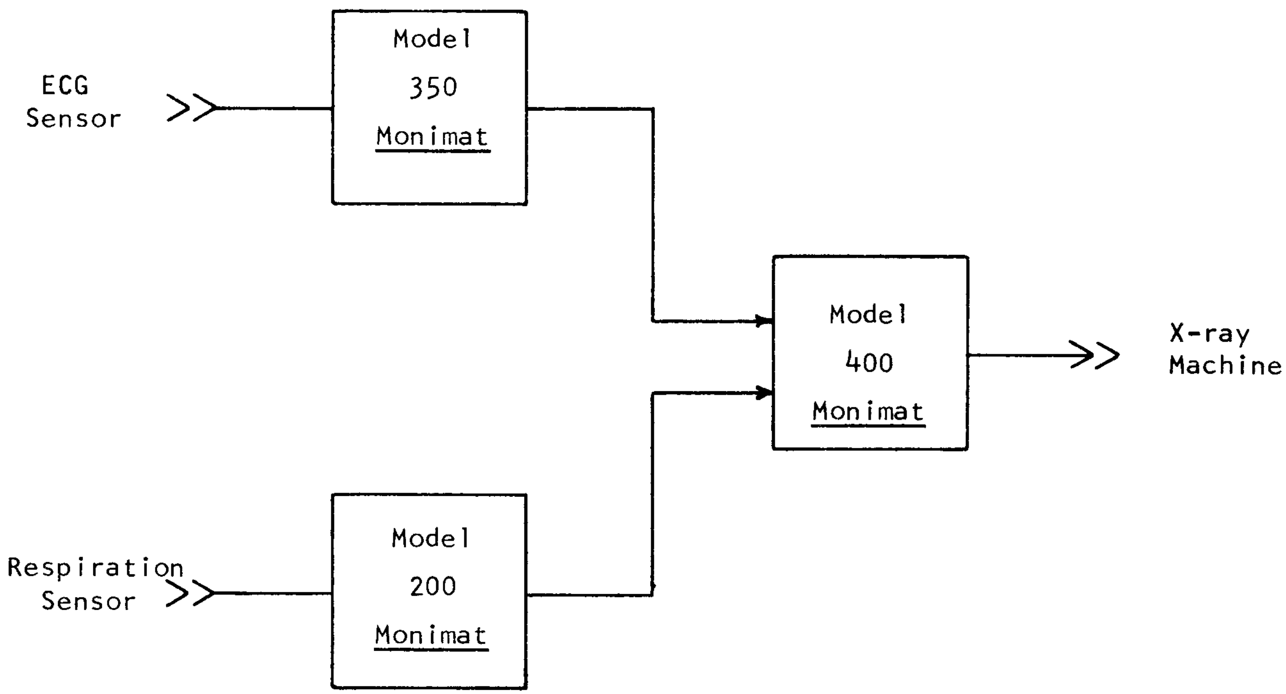

Figure 8. Coincidence triggering system block diagram

V. INSTRUMENTATION

General Theory of Operation

The Monimat consists basically of an input sensor, an amplifier (utilizing resistance-capacitance coupled and direct-current coupled amplifier stages), a meter circuit, and a trigger circuit. Figure 9 is a block diagram of the Model 350 Monimat.

Two identical sensor input jacks are provided. One is located on the front panel and the other on the rear panel. The two input jacks are mutually exclusive so that, if sensors are connected to both jacks at the same time, both jacks are disabled. For permanent connections, the rear panel jack would be used. For temporary, or intermittent connections, the front panel input jack would normally be used.

A front panel sensor-matcher switch is used to select between various sensors which may be used with the Monimat: differential voltage input sensors, single-ended voltage input sensors, changing-resistance input sensors. A range selector feature is incorporated into the sensor-matcher switch so an input range, appropriate to the particular type of sensor being used, may be selected.

Differential and single-ended voltage inputs are amplified in the preamplifier stage. The output of the preamplifier is connected, through a buffer cathode follower, to the main amplifier. The changing-resistance input is not amplified, in the preamplifier stage but is instead transformed into a voltage signal. This signal is connected, through a buffer cathode follower, to the main amplifier.

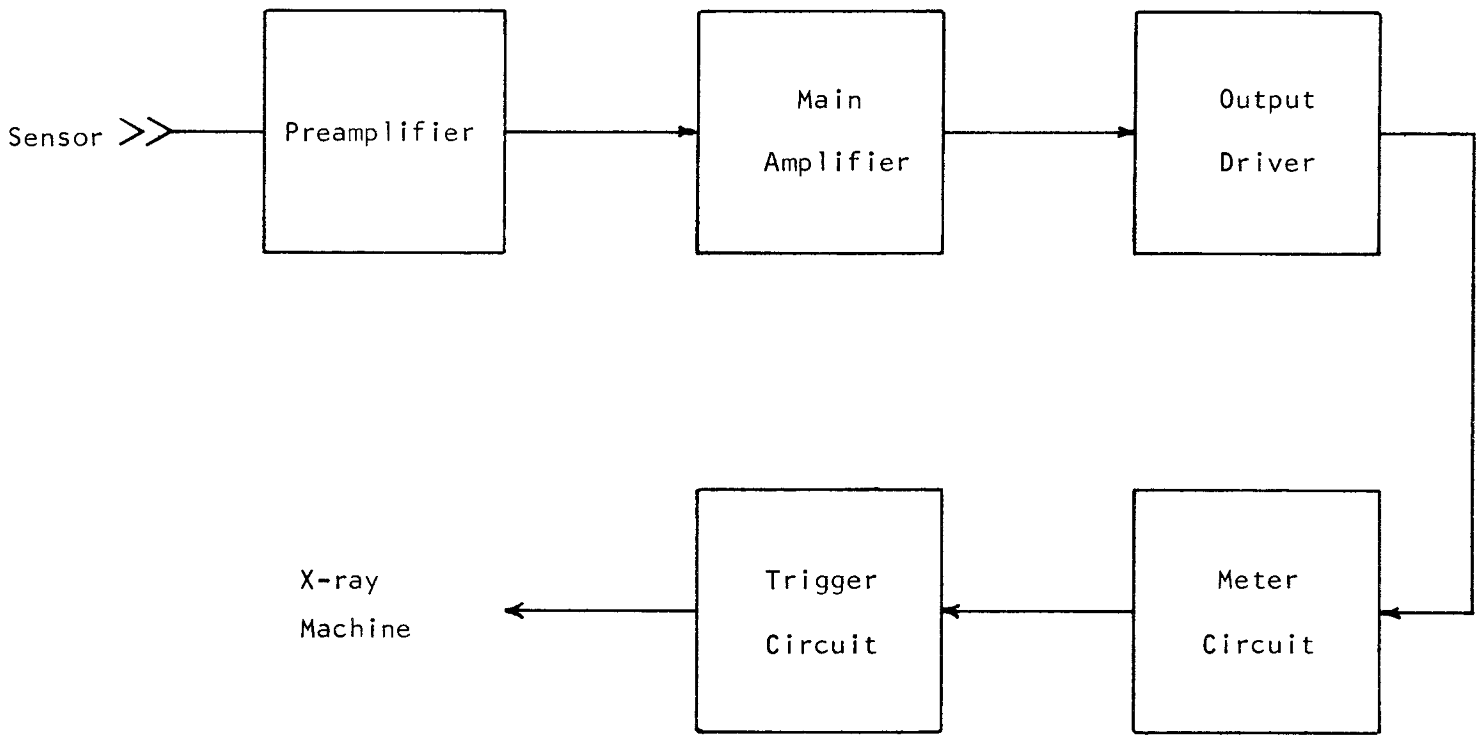

Figure 9. Model 350 Monimat block diagram

Input to the main amplifier is through a variable rate sensing circuit. Specific time constants of the rate sensing circuit may be selected by a front panel sensing-rate switch. The purpose of the rate sensing circuit is to permit one to adjust the recovery rate of the Monimat to a value more nearly corresponding with the natural cycling rate of the phenomenon being observed: fast for cardiac studies, slow for respiration studies.

It is possible for an unexpectedly large input signal to pin the monitor needle in the extreme right- or left-hand position. This will not harm the meter movement, but, in the slow response position of the sensing-rate switch, it could be many seconds before the meter circuit would recover. A quick return circuit (operable from a front panel, spring-loaded zero meter switch) will return both the input and output of the main amplifier to a zero voltage reference. This permits immediate recovery of the meter circuit.

All input signals are amplified in the main amplifier stage and the output of the main amplifier is push-pull. The (+) phase output and the (-) phase output are connected to the output driver stage through (+) and (-) phase buffer output cathode followers.

The (+) phase and the (-) phase output of the main amplifier cathode followers are a-c coupled into a (+) phase and a (-) phase output driver amplifier. The outputs of both output driver amplifiers are fed to the meter driver circuit and to the recorder driver cathode followers.

The meter driver circuit contains a multivibrator stage which is connected directly to the meter movement. The multivibrator circuit is designed to produce a large overshoot on the rise position of the cycle. The overshoot at the beginning of the meter drive cycle is to get the meter needle moving rapidly. Otherwise, the risetime and inertia of the meter movement would be too slow to permit accurate tracking of the rapid input signal variations inherent in the cardiac cycle.

The recorder driver cathode follower outputs are fed to jacks on the rear panel of the Monimat. The output voltage, the amplitude of which may be controlled by a front panel screwdriver adjustment on the Monimat, is about 1.5 volts which is sufficient to drive most recorders.

The (+) phase output driver amplifier is also used to feed an oscilloscope driver cathode follower. The output of the oscilloscope driver cathode follower is single-ended and is connected to an oscilloscope output jack on the rear panel of the Monimat. Markers, generated in the trigger circuit of the Monimat, may be fed, through a rear panel selector switch, to the oscilloscope driver cathode follower so that time marker signals may be available at the oscilloscope output jack. The purpose of the markers is to permit more accurate trigger timing during individual studies when the Monimat may be used with an oscilloscope.

A photo diode and light source are mounted on a high-limit switch and on a low-limit switch. The two limit switches are easily set by means of knobs projecting through the front of the meter movement panel. A light beam interrupting plate is attached to the meter needle. The amplified input signal causes the needle to move in either a right- or left-hand direction. When the plate attached to the meter needle interrupts the light beam, the triggering sequence is started.

The trigger circuit can be set to respond to an impulse from either the high-limit photo diode or the low-limit photo diode. Selection is made by a front panel max-min switch.

The mode of operation of the trigger circuit is dependant on the setting of the front panel function switch. The function switch has four positions:

1. Monitor Only - In this position the trigger circuit is disabled and the Monimat functions only as a monitor. The cycling rate, relative amplitude, and variations in the input signal may be observed on the meter face, on an oscilloscope (connected to the Monimat through the oscilloscope output jack), or recorded on a strip line recorder. An output pulse is generated whenever the position of the monitor needle is in line with the position of the meter limit switch. This output pulse may be used to drive a counter, trigger an external alarm, etc.
2. Respiration/Anti-cough - In this position the trigger circuit will prevent the automatic firing of the X-ray machine if the patient coughs or in any way creates a sharp, spasmodic motion. A cough or other spasmodic motion would, of course, result in a blurred radiograph. Tubercular patients, or infants subject to coughing or crying spasms, for example, are difficult subjects to radiograph, because many times radiographs are ruined by uncontrollable patient movement.

3. Normal - This position is used for the normal operation sequence of the Monimat. In this position the delay circuit is active. By means of a front panel exposure-delay switch, the firing of the X-ray machine can be delayed, from 0 to 2.2 seconds in steps of 0.02 seconds, from the time the meter circuit initiated the triggering input pulse.
4. Non-motion - This position is used for those instances where manual triggering of the X-ray machine is desired, and it is unimportant to reference the instant of exposure with respect to a specific point on the cardiac or respiration cycle. The X-ray machine is fired by means of a spring-loaded front panel manual-expose switch. A lockout feature of the Monimat will override the manual-expose switch and prevent the triggering of the X-ray machine, or will interrupt an exposure, if the patient moves before or during an exposure. If fetal radiographs were being taken, for example, movement of the fetus would result in a blurred radiograph. In the Non-motion position this movement would result in a lockout or termination of exposure, preventing unnecessary exposure to radiation for both the patient and the fetus.

The power supply is load- and line-regulated. Five individual supply voltages are provided (in addition to a d-c filament supply): -25V, -50V, +150V, +250V, +300V. The -25V line is used to supply the power for ovens in the output driver and preamplifier stage. These ovens are used to assure a constant temperature environment for matched reference diodes in the above circuits. The -50V line is used to supply operating voltages for the transistors and is also used as the main voltage reference line. The +150V line is used primarily as a plate supply for the resistance-capacitance coupled cathode followers. The +250V line is the plate supply voltage for the preamplifier. The +300V line is used as the plate supply for the amplifiers in the main amplifier and output driver circuits, and for the direct-current coupled cathode followers.

Voltage stability of the +250V line is better than one part in 10^6 over 30 seconds. Direct-coupled voltage feedback transistor amplifiers are temperature compensated to minimize the effect of drift due to temperature changes. The +150V, +250V, and +300V supplies are mounted on individual heat sinks. This is done to provide a uniform temperature environment for temperature sensitive semiconductors in the positive power supply circuits and to provide better heat transfer, through ventilation ducts, to the outside of the chassis.

Circuit Detail

Preamplifier

The basic components of the preamplifier are the sensor matching circuit, preamplifier, and output cathode followers. Figure 10 is a block diagram of the preamplifier. Three basic modes of operation, depending on the setting of the sensor-matcher switch, are possible:

1. Differential Voltage Input - When a sensor with a differential voltage output (e.g., ECG leads) is used, both grids of the differential preamplifier are connected to the two sides of the input jack. A voltage divider on the sensor matcher switch permits the selection of three sensitivity ranges: 0.5 mv, 10 mv, 200 mv. These values represent the input voltage level required for full-scale deflection of the meter circuit.
2. Single-ended Voltage Input - In this position the input circuit to one-half of the differential preamplifier is grounded through the sensor-matcher switch. The remaining grid is connected to the input jack and the amplifier operates as a single-ended amplifier. The same sensitivity ranges are available as in the differential voltage input mode.
3. Variable Resistance Input - In this position both grids of the preamplifier are returned to ground. The input jack is connected, through an impedance matching network, to an output cathode follower. Six input impedance ranges may be

selected: 20KΩ, 50KΩ, 150KΩ, 500KΩ, 1.5MΩ, 5.0MΩ. As the input resistance varies, it results in a voltage change across the impedance matching network. The changing voltage then corresponds to the input signal.

The direct-current coupled differential preamplifier uses two halves of a 12AX7, the cathodes of which are tied together through a balance control and are returned to a constant-current source. "Long-tailing" the cathode in this fashion increases the stability but at the cost of gain. The preamplifier stage has a gain of ten. Preamplifier gain is set by adjusting a variable resistor, connected between the two plates.

Because the preamplifier output is direct-current coupled to the preamplifier output cathode follower, the plates of the latter are returned to +300V. Protection diodes in the grid circuit protect the cathode follower from developing excessive plate current during the initial warmup. The cathode of the cathode follower is returned to -50V and a zener diode, enclosed in a temperature stabilizing oven in the cathode line, is used to reference the output voltage.

The resistance input sensor forms the first side of a parallel voltage divider in the grid circuit of the resistance input cathode follower. A condition of maximum sensitivity results when the resistance of the second side of the parallel voltage divider equals the nominal resistance of the input sensor. The resistance of the second side of the voltage divider can be varied from 20KΩ to 5.0MΩ with the sensor-matcher switch.

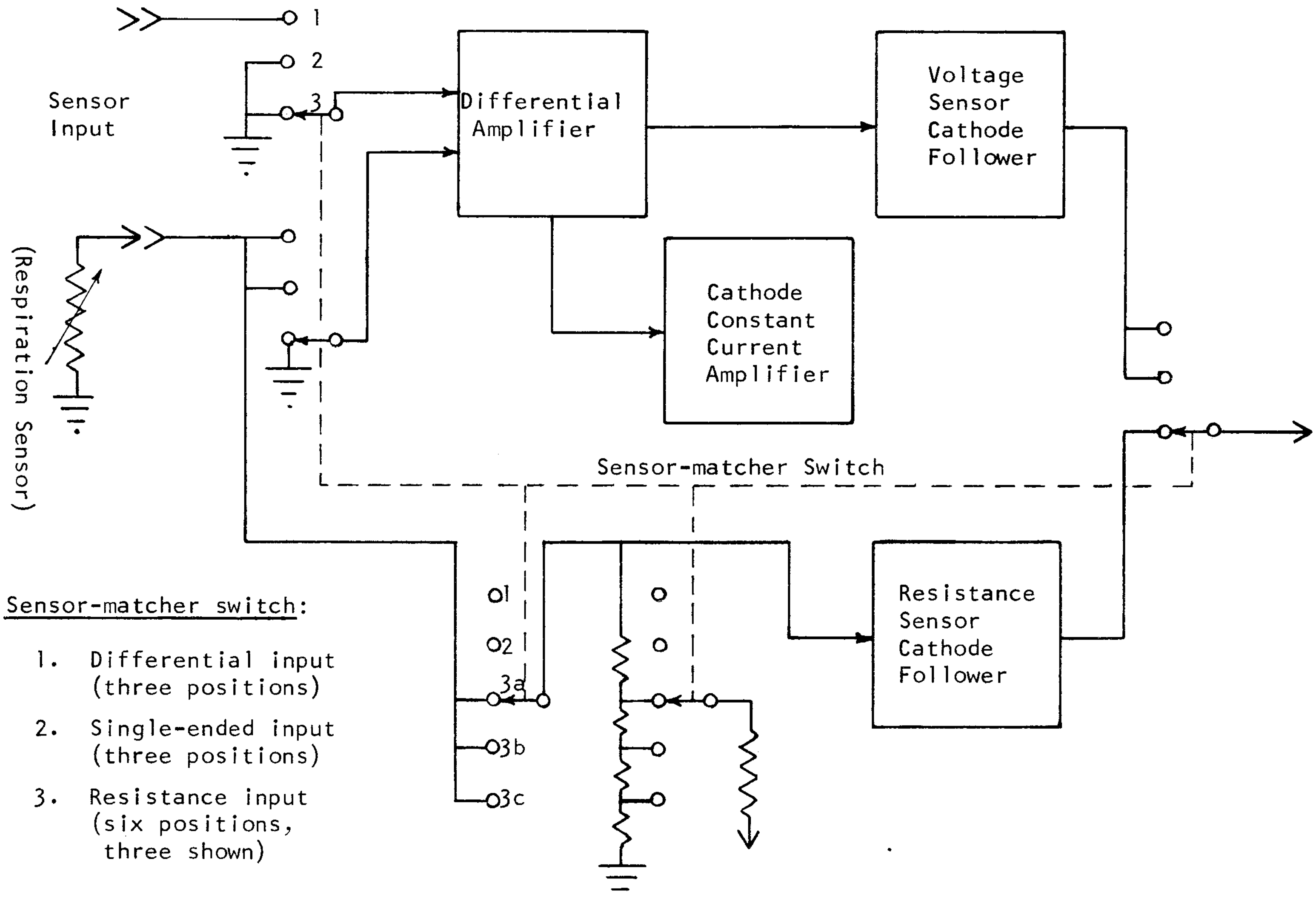

Figure 10. Preamplifier block diagram

Main Amplifier

The input to the main amplifier section is alternating-current coupled from either the preamplifier-output cathode follower or the resistance input cathode follower, depending on the setting of the sensor-matcher switch. Figure 11 is a block diagram of the main amplifier section.

A 2.0 µf high quality capacitor is used to couple the preamplifier output to the grid of the (+) phase main amplifier stage, the input grid resistance of which is adjustable in five steps. The sensing-rate switch is used to select the value of the input grid resistance, and, thus, the coupling R-C time constant. A long R-C time constant is used with slow-response input signals and a short R-C time constant with fast responses.

The cathode of the (+) phase main amplifier is "long-tailed" through a constant cathode current amplifier in a manner similar to that of the preamplifier cathode circuit. The (-) phase signal is obtained by cathode coupling the (+) phase main amplifier to the (-) phase amplifier. The amplifier gain is variable from a gain of zero to a gain of 25 per section and is controlled by an adjustment of the cathode coupling resistor, a front panel control.

The push-pull output of the (+) phase and (-) phase main amplifiers are direct-current coupled to their respective output cathode followers. The output of the (+) phase and (-) phase cathode followers are alternating-current coupled, through a variable response circuit identical to that of the input, to the output driver section. Protective diodes in the cathode follower circuit assure that circuit

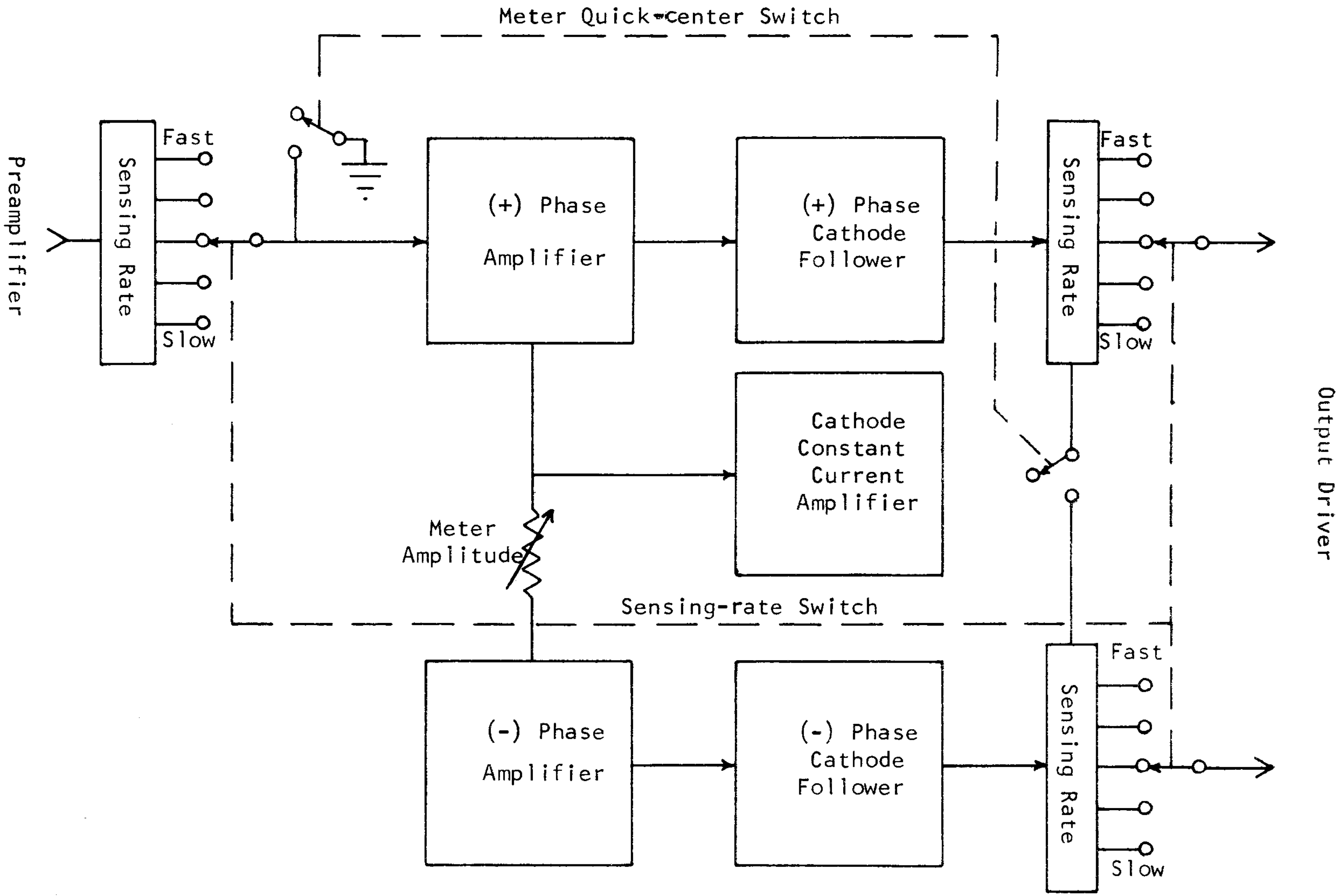

Figure 11. Main amplifier block diagram

overheating does not occur during initial warmup of the Monimat or in the event that the main amplifiers fail.

If, while the Monimat were in the slow response mode, a large input signal caused the needle to be pinned against the stop, there would be a delay of many seconds before the charge could bleed off and the needle return to zero. A front panel, spring-loaded switch is used to momentarily return the main amplifier input to zero volts and cause the push-pull output voltage to drop to zero volts. Such action will enable one to quickly return the meter needle to zero.

Output Driver

The output driver section is of straightforward design. The block diagram is illustrated in Figure 12. The output driver amplifiers are low gain and are intended primarily as current driving devices. The output is direct-current coupled push-pull and is used to control the meter circuit.

A second output, also push-pull and taken from the cathode circuit in both output driver amplifier stages, is direct-current coupled to the grids of two recorder cathode followers. A ganged two section variable resistor, with one section common to each recorder cathode circuit, is used to set the recorder output level to zero volts in the absence of an input signal. This recorder zero control is a front panel screwdriver adjustment. A second ganged two section variable resistor is in parallel with the recorder zero control. This second variable resistor is also a front panel screwdriver adjustment and is the recorder amplitude control. Figure 13 is an illustration of the recorder cathode follower output level control.

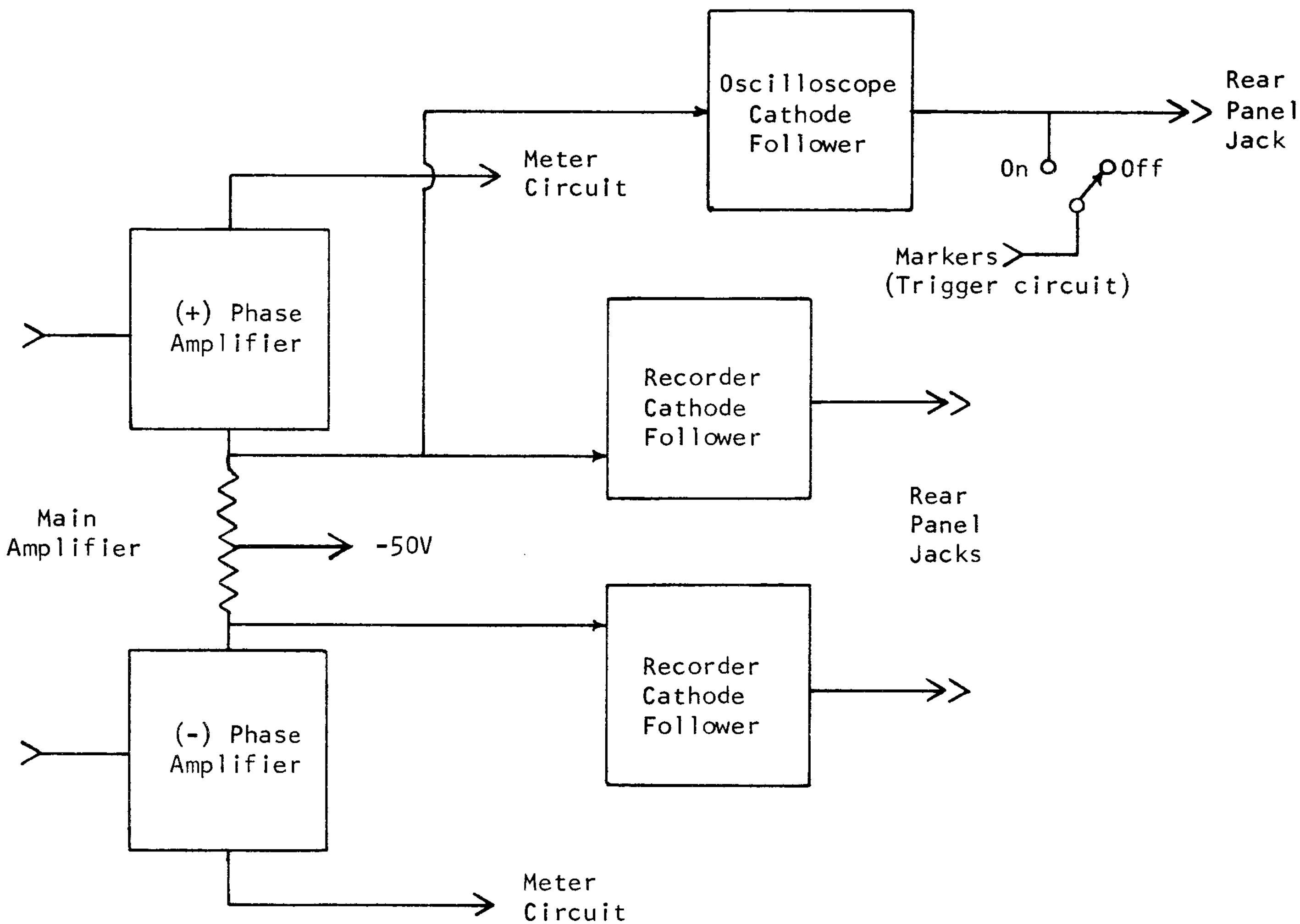

Figure 12. Output driver block diagram

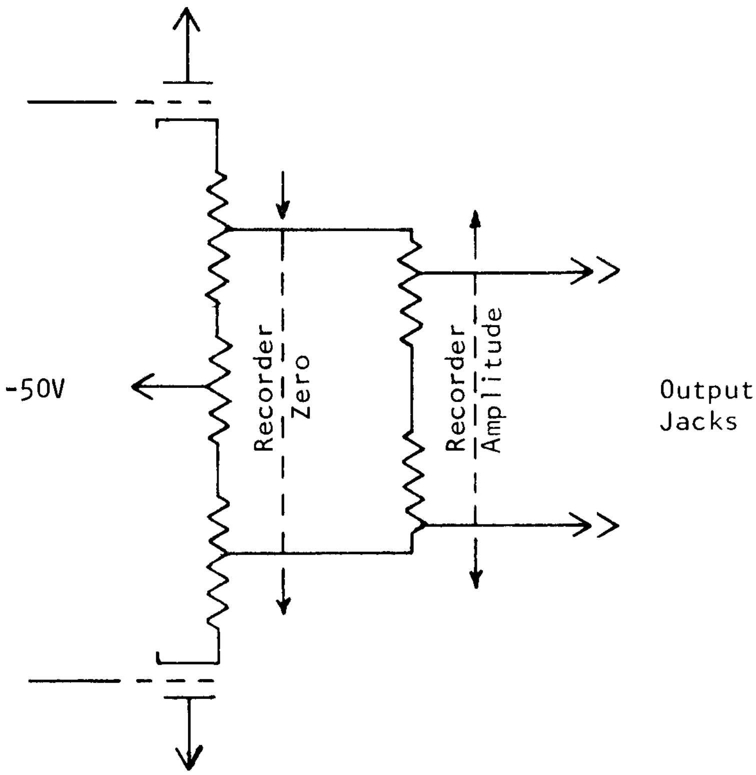

Figure 13. Recorder output level controls

A third output is taken from the (+) phase output driver. This output, which is also common to the recorder cathode follower, is fed to the oscilloscope cathode follower. The output of this cathode follower is connected to a rear panel BNC jack. Markers, generated in the trigger circuit, may be mixed with the output of the oscilloscope cathode follower or may be switched to a rear panel BNC jack.

Meter Circuit

The meter circuit consists basically of a meter driver amplifier and the control meter movement. The main purpose of the feedback amplifier is to enable the meter movement to respond rapidly to input signals with a fast risetime. The extra "boost" applied to the meter movement acts to offset the effect of meter movement risetime and inertia. During a time of slow rise input signals, the meter movement will respond normally, without the need for a "boost". For the following explanation, see Figure 14.

Assume a rise pulse of one volt at the grids of the output driver amplifier. The sharply rising plate voltage of V1B will be alternating-current coupled to point A' and will be added to the positive pulse which is direct-current coupled from the cathode of V1A. The resultant signal at point A' will be a differentiated pulse, rising to +2.5 volts and decaying, with an R-C time constant of 25 milliseconds, to a level of +0.5 volts, as determined by the cathode circuit of V1A. The +0.5 volt level will ultimately decay to zero at a rate determined by the setting of the sensing-rate switch.

The network between points A' and A'' is an impedance isolation network with a gain of one-half. Therefore, the level of the signal appearing at point A'' is one-half the level at point A'. The signal level at points B' and B'' are obtained in a similar manner.

With no input signal, V2 will have a steady-state plate current of 3 milliamperes per section. As soon as the grid of V2A starts to rise, the resultant plate voltage drop of about 2 volts is coupled to the grid of V2B driving it almost to the point of cutoff. Because of the low impedance of the meter movement, the plates of V2 remain relatively unchanged. However, the 3 milliamperes of plate current, which were originally conducted by V2B, are now conducted through V2A, resulting in a current through V2A of 6 milliamperes.

There is now a peak current of 6 milliamperes through the meter, instead of the initial 0 milliampere. The meter movement will deflect full scale with 0.25 milliampere through it. Since there are 24 times that amount of current through the meter, it will deflect rapidly. The meter movement is designed to withstand repeated overloads of 50 times rated current for 25 milliseconds.

As soon as V2B is driven to cut off, it will start to recover. Recovery time is determined by the series R-C time constant of the V2 coupling capacitor, V2A plate impedance and V2B grid impedance. In 20 milliseconds, recovery is almost complete and the current through the meter movement will drop to 0.25 milliampere.

If the input signal has a very slow risetime (e.g., a respiration signal), the cross coupling capacitors of V1 and V2 are effectively an open circuit due to the low frequency cutoff of the amplifiers. Then the amplifiers will function as direct coupled amplifiers and the meter movement will receive no signal "boost" during the risetime of the input signal.

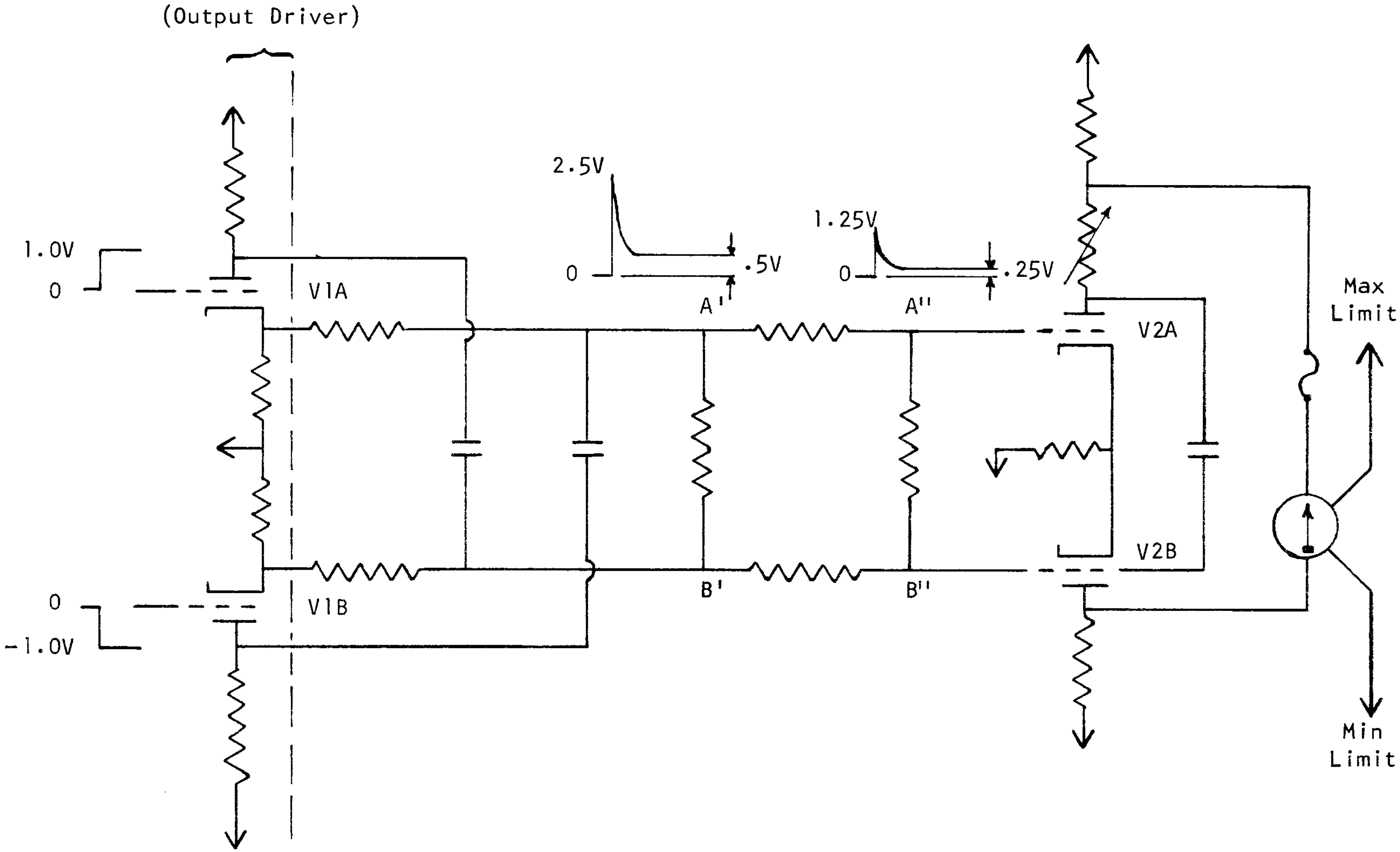

Figure 14. Meter circuit block diagram

Trigger Circuit

The purpose of the trigger circuit is to initiate the triggering sequence upon receiving a signal from the meter circuit, develop the trigger pulse, fire the X-ray machine, and lock out the trigger sequence so that the X-ray machine cannot be refired until the trigger circuit is manually reset. Secondary functions of the trigger circuit are to provide for delay in firing the X-ray machine, develop the output gate pulses and monitor pulses, and control the switching of the operation status indicator lights. The trigger circuit block diagram is illustrated in Figure 15.

The trigger sequence is cyclical and may be examined by starting at any point in the cycle. In the following explanations the "starting point" will be the time at which the front panel rotor "on" switch is actuated. The operation of the trigger circuit is dependent upon the setting of the function switch: Monitor Only, Respiration/Anti-cough, Normal, Non-motion. The basic mode of operation is the Normal mode and will be outlined first.

1. Normal - When the spring-loaded rotor "on" switch is actuated, the X-ray tube rotor begins to build up speed. When the rotor is up to speed, the X-ray machine will feed back a signal to the Monimat. This is accomplished with a simple interconnection between the X-ray machine and the Monimat. The rotor feedback signal energizes the rotor speed lockout relay in the Monimat, partially arming the first and second multivibrator and turning on the X-ray ready panel light.

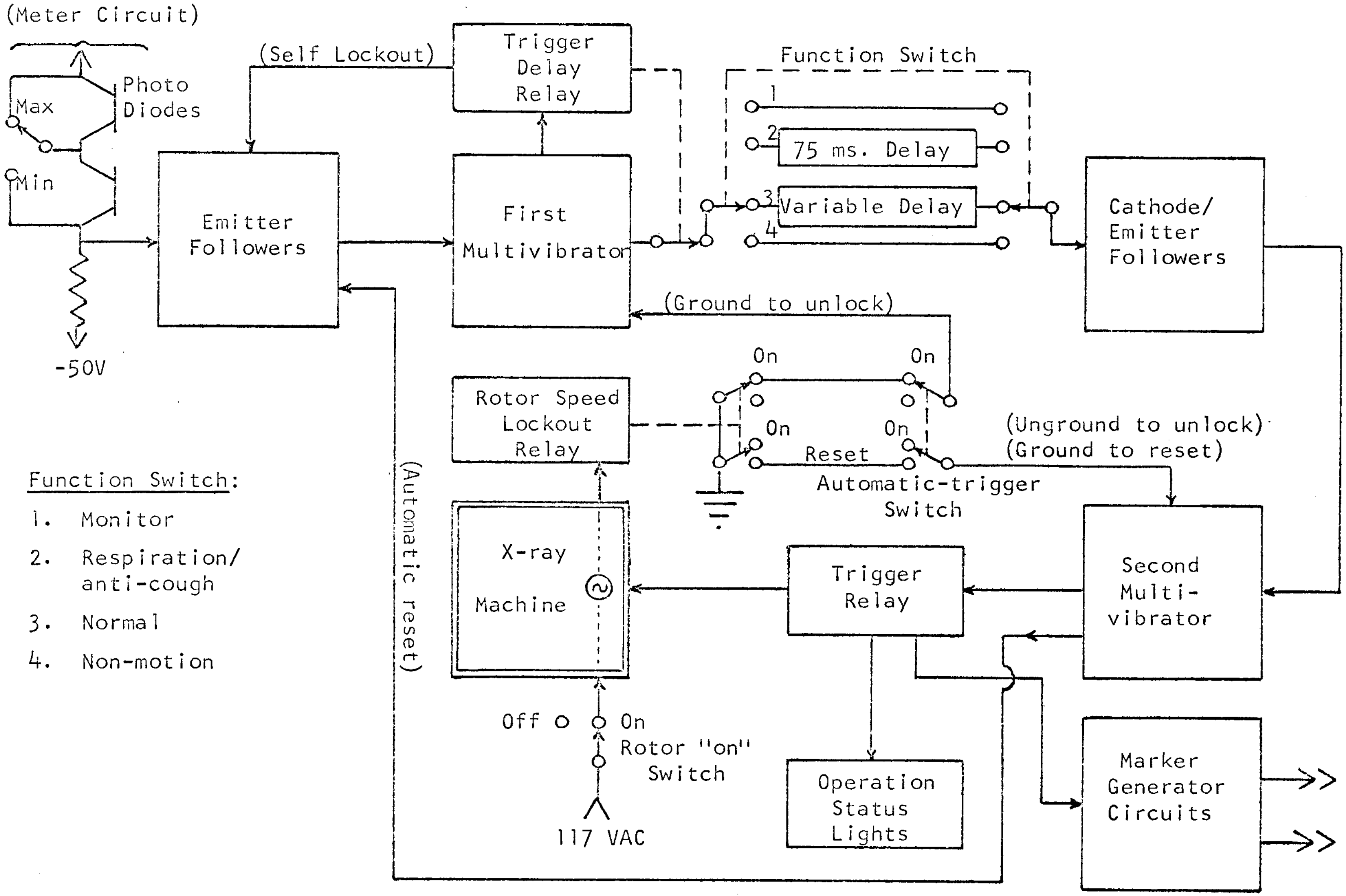

Figure 15. Trigger circuit block diagram

When the spring-loaded automatic-trigger switch is actuated, the first and second multivibrators are fully armed (unlocked) and are ready to function on receipt of a signal from the meter circuit.

When either meter limit switch photo diode is interrupted, the resistance of that diode increases. Both photo diodes are connected in series and are themselves in series with a resistance voltage divider. The increase in photo diode resistance will result in a voltage drop at the base of an emitter follower which is referenced to the voltage divider. The voltage drop at the emitter follower base is coupled through to the first multivibrator.

The negative input to the first multivibrator cuts off the first section and causes the second section to turn on. When the second section conducts, a trigger delay relay, in the collector line of the second section, is energized. When the trigger delay relay is energized, the delay circuit is activated, a monitor pulse is fed to a rear panel jack, and a lockout pulse is fed back to the input emitter follower. The lockout pulse will prevent the first multivibrator from turning back on before the X-ray machine has fired.

When the delay circuit is activated, a capacitor is switched into a negative voltage supply line and begins to charge through a preselected amount of resistance. The amount of resistance, and corresponding R-C time constant, is controlled by the exposure-delay switch. The negative going charge pulse is fed through a cathode follower, through an emitter follower, to the first section of the second multivibrator. The cathode and emitter followers serve as consecutive impedance matchers and to isolate the second multivibrator from the delay circuit.

The first section of the second multivibrator, which is in the "on" state when the multivibrator is unlocked, will be cut off when the negative going pulse from the delay circuit reaches -30V. At -30V the second multivibrator switches (and stays switched until manually reset), and a trigger relay in the collector lead of the second section becomes energized.

The closing of the trigger relay accomplishes several things. The X-ray machine is fired. Front panel exposure indicator lights are switched on. The first multivibrator is unlocked. An oscilloscope marker signal and a recorder marker signal are generated and fed to rear panel jacks.

Some models of X-ray machines will automatically disable the rotor after firing, others will not. However, the trigger circuit second multivibrator is locked out and the X-ray machine cannot be refired until the Monimat is manually reset by releasing both the rotor "on" switch and the automatic-trigger switch. Thus, the cycle is complete.

2. Monitor Only - In this mode of operation, the first multivibrator trigger delay relay is inoperative; however, a monitor output pulse is still available. When the trigger delay relay is inoperative, the line to the second multivibrator, through the delay circuit, is open. Since the second multivibrator cannot switch when the input line is open, the trigger relay will be locked out and the X-ray machine cannot be fired.
3. Respiration/Anti-cough - During a normal respiration cycle the meter needle will interrupt the limit switch photo diode for about 100 milliseconds before moving out of the limit switch zone. As long as the photo diode is interrupted, the base of the first section of the first multivibrator will be held at cutoff. In the Normal mode, the first section was automatically locked in the "off" position as soon as the first multivibrator switched. However, in the Respiration/ Anti-cough mode, there is no automatic lockout. The first multivibrator will remain switched only as long as the photo diode is interrupted.

The trigger delay circuit, in the Respiration/Anti-cough mode, has a fixed trigger delay of 75 milliseconds. Therefore, it will take 75 milliseconds from the time the first multivibrator is switched before the second multivibrator can be switched and the X-ray machine fired. If, for any reason, the first multivibrator switches back to its original state before the second multivibrator has had a chance to switch, the second multivibrator will not operate. The trigger delay circuit will have been disabled by the opening of the trigger delay relay in the first multivibrator circuit, and the second multivibrator will not receive an input switching pulse.

When a patient coughs, or in any way produces a sharp, spasmodic movement, the meter needle will interrupt the limit switch photo diode for only about 25 to 50 milliseconds before moving out of position. The first multivibrator will then be switched back to its original state before the second multivibrator has a chance to switch and fire the X-ray machine.

4. Non-motion - In this mode, the X-ray machine must be manually fired, but the exposure is automatically prevented or interrupted if the patient moves during exposure. The rotor "on" switch, automatic-trigger switch, and manual-expose switch are connected in series with a pair of trigger relay contacts. All three switches must be actuated, and the trigger relay must be in the deenergized position before the X-ray machine can be fired. The rotor "on" switch and the automatic-trigger switch are adjacent to one another and may be operated with one hand. The manual-expose switch must be actuated with the other hand.

In operation, the patient holds his breath, and the maximum and minimum limit switches are positioned on either side of the meter needle. The rotor "on", automatic-trigger, and manual-expose switches are actuated. A manual-expose indicator light turns on when the manual-expose switch is actuated. If the trigger relay is deenergized, the X-ray machine will be fired.

The max-min limit selector switch is bypassed and both limit switches are active. If the patient moves, either limit switch photo diode will be interrupted and the first multivibrator will switch. There is no trigger delay in the Non-motion mode so the second multivibrator will switch immediately, energizing the trigger relay. When the trigger relay is energized, the X-ray machine actuation line is opened and the X-ray machine cannot be fired or, if an exposure was being taken, it is terminated. When the trigger relay is energized, it also extinguishes the manual-expose indicator light.

Power Supply

There are five regulated voltage supplies (-25V, -50V, +150V, +225V, +300V) plus two unregulated filament voltage supplies (+10V, +161V) in the Monimat. All regulated supplies are referenced against the -50V supply. The +161V filament supply is referenced against the top of the +150V supply. This is done to obtain an elevated +11V (+161V - (+)150V = +11V) filament voltage which is used for the direct-current cathode followers, the cathodes of which are at about +150V. The power supply block diagram is illustrated in Figure 16.

All of the voltage regulators are basically the same. The base

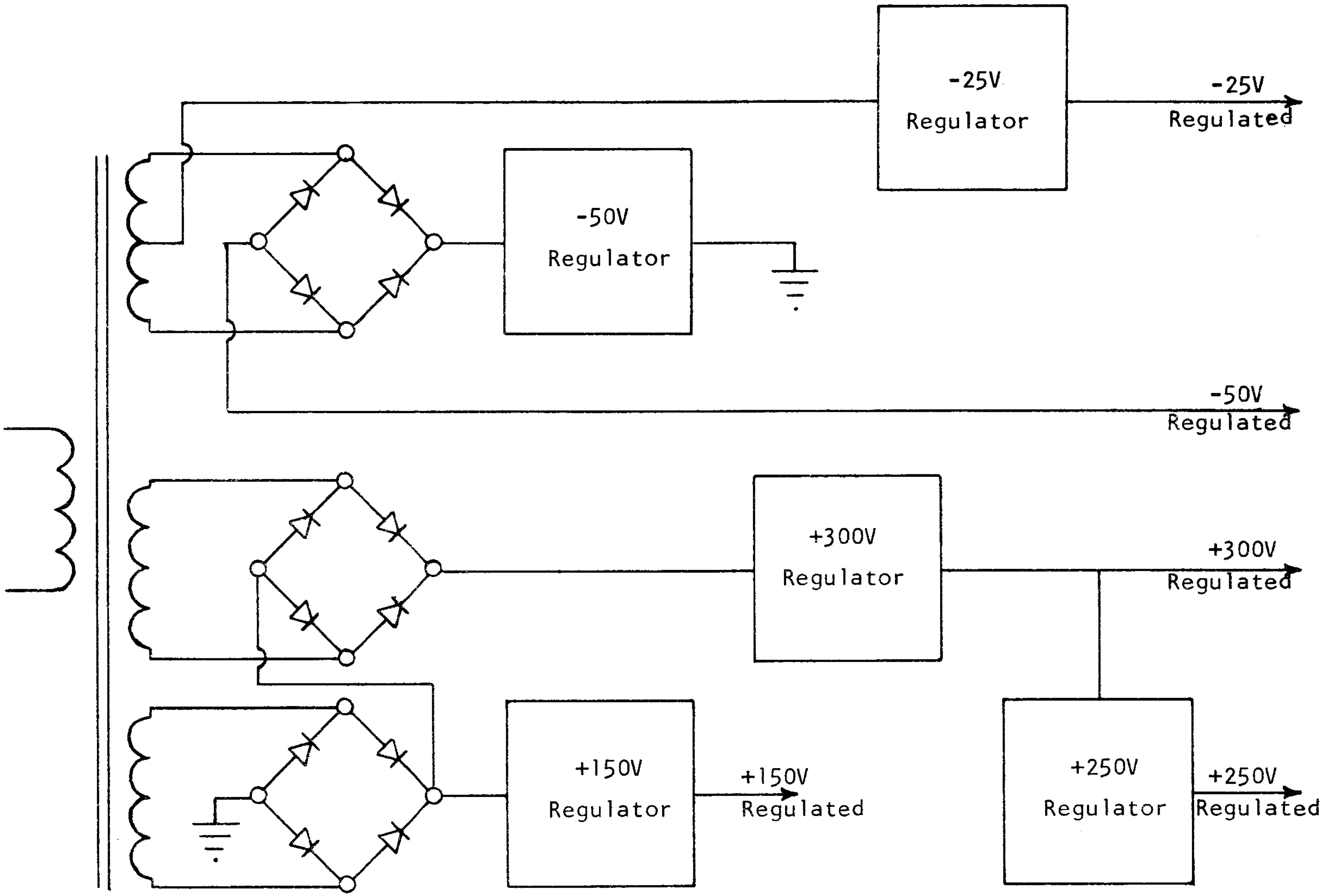

Figure 16. Power supply block diagram

of a direct-current amplifier is connected to a voltage divider on the regulated side of the supply. Changes in the regulated supply voltage are amplified in three direct-current feedback amplifiers. Three feedback amplifiers are used in order to obtain a higher degree of voltage stabilization than that which could be obtained by using only one feedback amplifier. The collector of the third feedback amplifier is used to control the base bias of an emitter follower (series regulator) located in the output voltage line. Short term stability is on the order of one part in 10^6. Refer to Figure 17 for the following explanation of the regulation sequence.

When the regulated voltage output, point A, tries to rise, the base of Q4 also rises. This rise is amplified, inverted, and appears at the base of Q3 as a decrease in voltage. The feedback signal is amplified twice more and appears between resistors R1 and R2 as a decrease in voltage. The base of Q1 is connected to the junction of R1 and R2 and transfers the decrease in voltage, through the emitter, to the regulated voltage output line. The voltage decrease at the emitter of Q1 opposes the original voltage rise at point A. Therefore, the net change in the regulated voltage is essentially zero.

Diode D1 limits the maximum V_{CE} which may appear across Q2. Diode D2 is used as an emitter load resistance, instead of a physical resistor, because the lower zener resistance contributes to a greater voltage gain for the stage. Capacitors C1 and C2 were added to stop the oscillation which resulted from increasing the gain of the voltage feedback circuit.

Resistor R3 is a series limiter which will protect Q1 from

A_i : Unregulated input

A : Regulated output

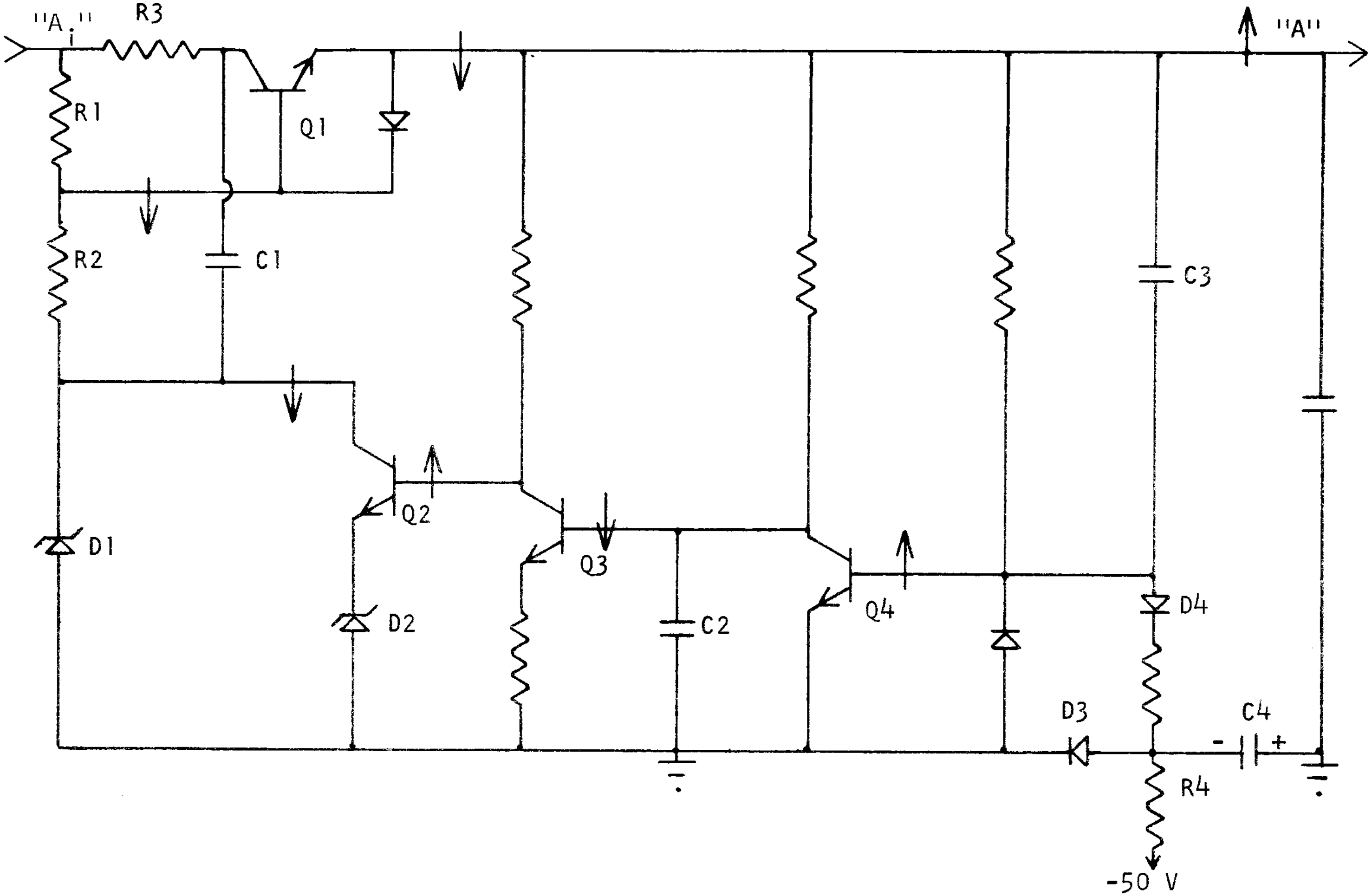

Figure 17. +300V regulator

burning out in case the regulated output were to be shorted to ground.

Capacitor C3 is used to enable Q4 to respond faster to sharp increases or decreases in the regulated voltage line. The rapid voltage fluctuations would be coupled directly to the base of Q4.

Capacitor C4 and resistor R4 are used as a filter to prevent noise, caused by the actuation of the relays, from appearing in the power supply. Capacitor C4 is reverse voltage protected by diode D3.

Temperature variations will cause V_{EB} of Q1 (and other transistors as well) to vary which will result in fluctuation of I_E. Diode D4 tends to compensate for variations in V_{EB}.

VI. OPERATION

Basic Operation

A terminal jack must be installed in the X-ray machine control panel so that a control cable can be run between the Monimat and the X-ray machine. Three separate control lines, all contained in the control cable, are required: an X-ray tube rotor control line, from the Monimat to the X-ray machine; a rotor speed sensing line, from the X-ray machine to the Monimat; an X-ray trigger line, from the Monimat to the X-ray machine.

When the Monimat and the X-ray machine are connected together with the control cable, all control operations may be performed at the Monimat, except for the initial steps of switching on the X-ray machine and setting the exposure/duration and intensity control. A sensor, appropriate to the type of study to be made, is selected, attached to the patient, and plugged into the Monimat. After the X-ray head is positioned and film placed in the film holder, the Monimat may be adjusted to automatically trigger the X-ray machine.

Typical Studies

Respiration

The basic respiration sensor is an autoclavable elastic belt with a stretchable, conductive plastic element bonded to the belt. The respiration sensor belt is illustrated in Figure 18. When the elastic belt stretches, the plastic sensing element stretches with it and undergoes a change in resistance, proportional to the amount of stretching. The belt is placed low on the chest and is adjusted to fit so that a slight belt tension is maintained (see Figure 20). Two belts are presently in use: one for infants and children, one for adults. The belt is "buckled" with a Velcro tape fastener. The patient may be positioned in the supine position or in the standing position. These two positions are shown in Figures 21 and 22, respectively.

The sensor belt is attached to an extension cable and is plugged into the Monimat. The sensing-rate switch is set at either position one (slow), or position two, and the function switch is placed in the Respiration/Anti-cough position. The sensor-matcher switch is set on "ohms", the specific range of which will depend on the type of sensor belt used. The exact ohmic range may have to be determined by trial and error but will probably be about 500 kilohms.

The Monimat power "on" switch is located on the meter amplitude control. The Monimat should be allowed to warm up for a few minutes with the meter amplitude control in the minimum position. During the warmup period, the meter needle may deflect abruptly and be pinned against the limit stops. This will not harm the meter movement. The

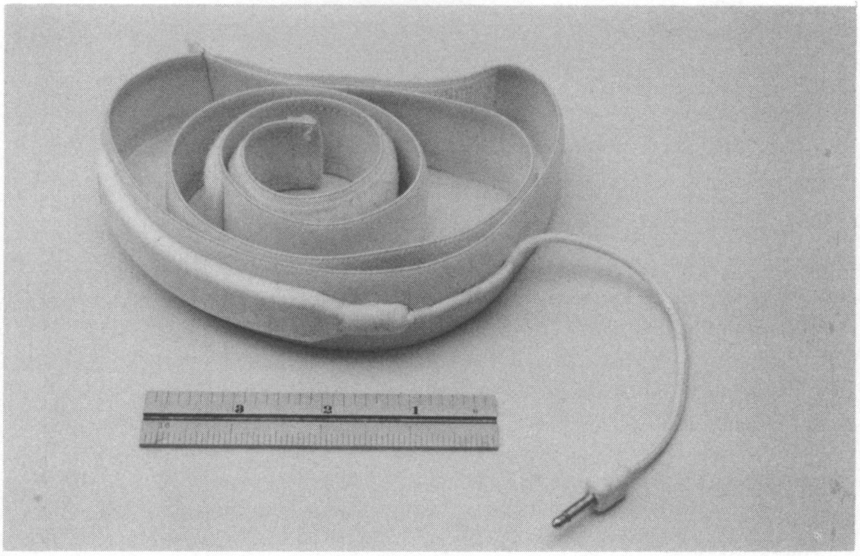

Figure 18. Respiration sensor

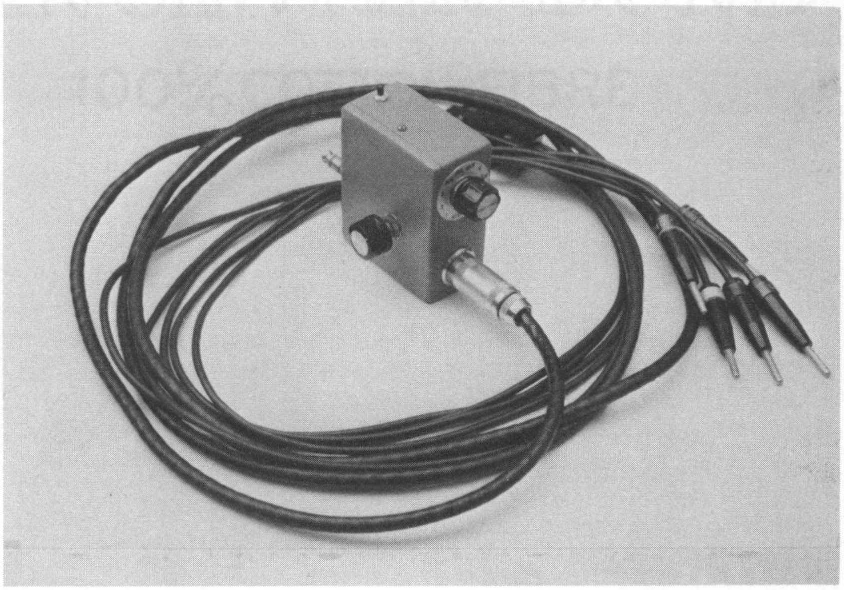

Figure 19. ECG sensor with
ECG adapter

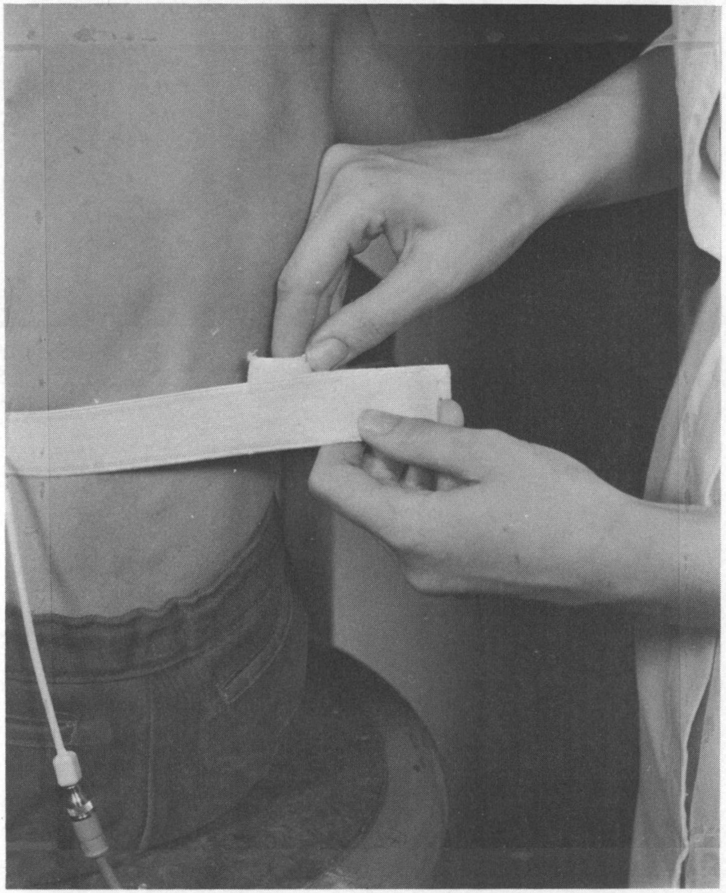

Figure 20. Adjustment of respiration sensor

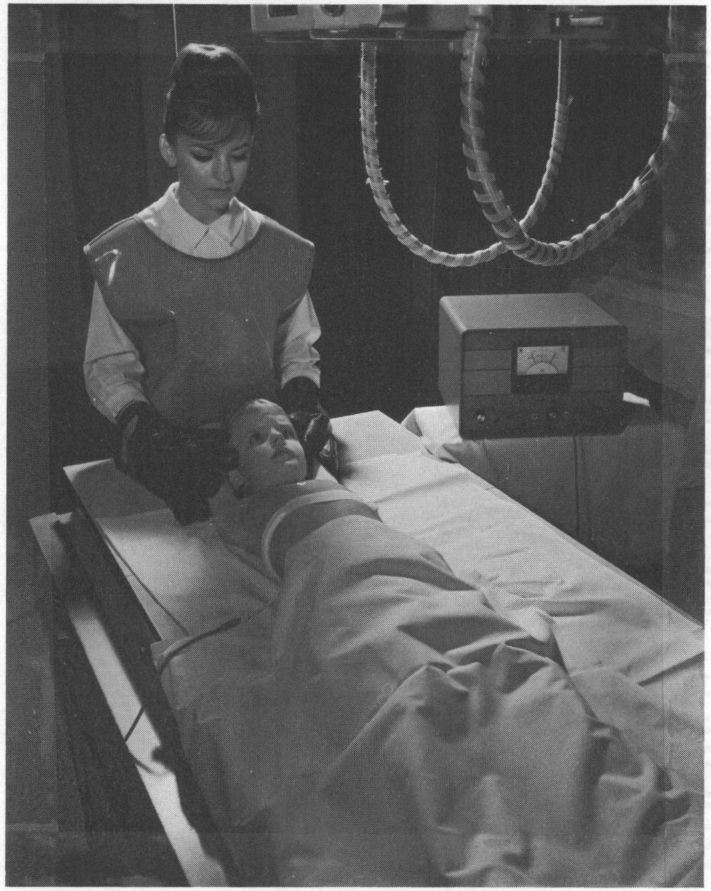

Figure 21. Supine subject with respiration sensor

Figure 22. Standing subject with respiration sensor

Figure 23. Standing subject with ECG sensor

meter needle may be returned to zero by depressing the meter zero switch.

The meter amplitude control should be advanced until the meter needle deflects approximately full scale with the patient breathing normally. If this adjustment cannot be made, it may be necessary to select a different ohmic range with the sensor-matcher switch.

The maximum or minimum meter limit switch is adjusted so that the meter needle will intercept the limit switch at the point at which one wishes to trigger the X-ray machine, usually at the peak of inspiration. The max-min selector switch is then set accordingly.

To make the exposure, the rotor "on" switch is actuated. In about five seconds, the X-ray ready light will turn on, indicating that the X-ray tube rotor is up to speed. The automatic-trigger switch is then actuated. The X-ray machine will fire when the meter needle interrupts the maximum or minimum limit switch photo diode, whichever had been selected. As soon as the exposure is taken, the X-ray ready light extinguishes and the meter face panel lights turn on.

Cardiac

The sensors most commonly used during cardiac studies are ECG electrodes. The ECG leads must be used with an ECG adapter (see Figure 19). A switch on the ECG adapter is set to an index corresponding to the lead configuration of the ECG leads (e.g., I, aV_R, aV_F, etc). The ECG electrodes are taped to the patient who is then positioned for the exposure. A typical arrangement is shown in Figure 23.

The function switch is set in the Normal position, the sensor-matcher switch is set to one of the differential voltage input positions, and the sensing-rate switch is set to position four or five (fast). The meter amplitude control and meter limit switches are adjusted in the same manner as for the respiration studies. However, in cardiac studies the max-min selector switch is usually set in the maximum position.

Timing the firing of the X-ray machine with respect to the cardiac cycle may be accomplished in two ways. First, the exposure delay switch may be set for a delay of about 140 milliseconds if systolic cardioradiographs are desired, or about 640 milliseconds if diastolic cardioradiographs are desired. Second, an oscilloscope can be connected to the rear panel oscilloscope jack and the oscilloscope marker switch actuated. The ECG waveform and a marker, indicating the point in the cardiac cycle at which the X-ray machine will be fired, will appear on the oscilloscope screen. Adjusting the exposure delay switch will cause the marker to move, relative to the ECG waveform, on the screen. In this way, the operator can pick the exact point in the cycle at which the X-ray machine will be fired.

The X-ray machine is fired in the same manner as for the respiration studies.

Coincidence

With the use of a Model 400 Monimat coincidence unit, coincident radiographs are possible. The cardiac and respiration cycles have been the only two cycles used to date in coincidence studies; however, it would also be possible to use other cycles (e.g., ventricular blood pressure) if the sense information can be transformed into a voltage or resistance signal.

Two Monimat automatic trigger units are used with the coincidence unit. The trigger output of each unit is connected to the Model 400, and the Model 400 is connected to the X-ray machine control panel by the control cable. After the two Monimat automatic trigger units are adjusted, the rotor "on" and automatic-trigger switches on the Model 400 are actuated in sequence. When a signal from the two automatic trigger units arrive simultaneously at the Model 400, the X-ray machine is automatically fired. Coincident cardiopulmonary radiographs, taken as described above, are shown in Figure 24 and Figure 25.

Fetal

One of the biggest problems in taking fetal radiographs is that when the fetus moves or kicks the radiograph may be ruined. The chance for a faulty exposure is high because of the low intensity, long exposure conditions under which many fetal radiographs are taken.

A respiration sensor belt is placed about the abdomen of the patient and adjusted as for a respiration study. The function switch is set in the Non-motion position, and the sensor matcher switch is set in the "ohms" position. The patient is asked to hold her breath and the meter limit switches are placed just above and just below the meter needle.

The rotor "on", automatic-trigger, and manual-expose switches

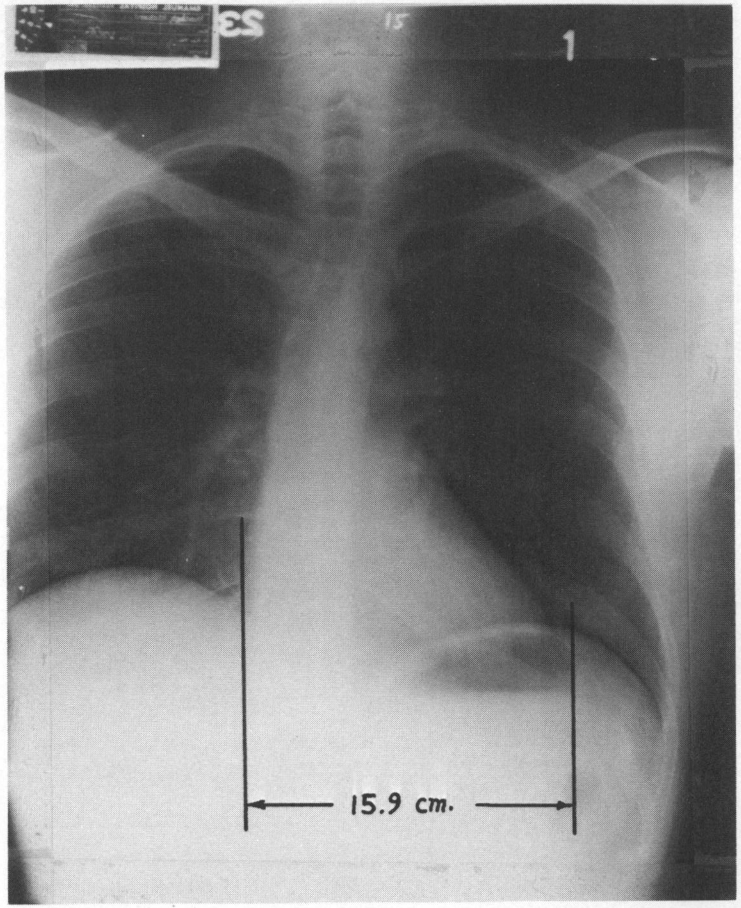

Figure 24. Radiograph of systolic cardiac phase at maximum inspiration

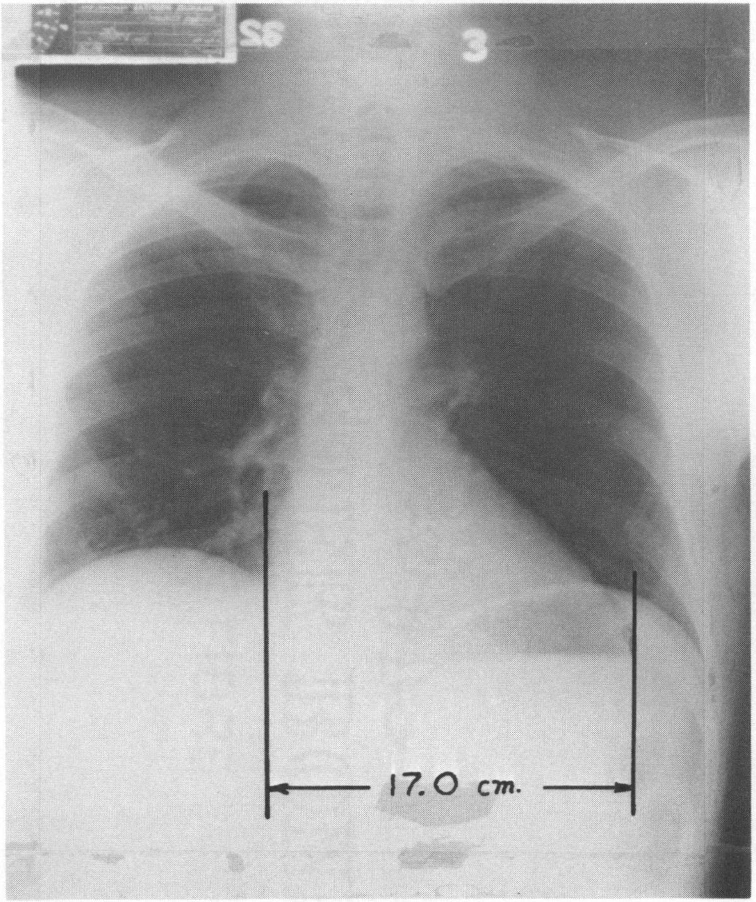

Figure 25. Radiograph of diastolic cardiac phase at maximum inspiration

are actuated in sequence. When the manual-expose switch is actuated, the X-ray machine is fired, and a manual-expose indicator light turns on. The manual-expose indicator light will remain on as long as the manual-expose switch is actuated. If the fetus (or the patient) moves before, or during, the time the manual-expose switch is actuated, the exposure is prevented or interrupted. If the exposure is terminated because of patient movement, the manual-expose light extinguishes, even though the manual-expose switch may still be actuated.

VII. CONCLUSIONS

Automatic X-ray triggering has not been widely used because of the limitations of control devices presently available. A new control system has now been designed, constructed, and operated. This system, the Monimat, meets many of the requirements that the author considers to be necessary for accurate, simple, and reliable operation.

As is true with most physical apparatus, the Monimat is capable of refinement. The knowledge gained thus far in using the Monimat for clinical and experimental studies has suggested several improvements which can, and will, be made. It is the hope of the author and his associates that, with the continuing and increasing use of automatic X-ray triggering systems, new and expanded areas of radiographic investigation may be explored.

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APPENDIX

IX. APPENDIX

Four factors must be determined before the time between cardiac/ respiration coincidence triggers can be computed:

1. The period of the respiration cycle. This will vary according to the respiration rate, but it will typically be about 3500 milliseconds.
2. The length of time that the meter needle interrupts the limit switch photo diode on the respiration sensing Monimat. This will also vary according to the respiration rate but will typically be about 75 milliseconds.
3. The period of the cardiac cycle. This will vary according to the cardiac rate, but it will typically be about 750 milliseconds.
4. The trigger circuit relay actuation time in the cardiac sensing Monimat. This is fixed at about 25 milliseconds.

The four factors listed above were assigned a code: factor 1 = TMSP1, factor 2 = XINC, factor 3 = TMSP2, factor 4 = XINC2. The approach followed in writing the computer program was to perform a continuing series of divisions between respiration intervals and cardiac intervals, stopping only when the remainder was less than, or equal to, the total time (XINC + XINC2) of the two "on" gates.

The computer format, in Table I, was used by the author in computing cardiac/respiration coincidence intervals. The program was run on the IBM Model 1130 computer.

TABLE 1. COINCIDENCE PROGRAM

```
98      READ(2,1) TMSP1,XINC,TMSP2,XINC2
1       FORMAT(4F10.3)
        ICNT=1
2       TMSAV=TMSP1* ICNT
        TMSL=TMSAV-XINC
        TMSP4= TMSP2-XINC2
C       NEXT STATEMENTS DIVIDE TWO VALUES BY LOWER VALUE.
        X= TMSAV/TMSP4
        I= TMSAV/TMSP4
        IF(ABS(X-I)-.0001) 4,4,5
5       Y= TMSL/TMSP4
        J= TMSL/TMSP4
        IF(ABS(Y-J)-.0001) 4,4,6
6       IF(I-J)  4,7,4
C       NOW  REPEAT FOR THE UPPER VALUE
7       X= TMSAV/TMSP2
        I= TMSAV/TMSP2
        IF(ABS(X-I)-.0001) 4,4,9
9       Y=TMSL/TMSP2
        J=TMSL/TMSP2
        IF(ABS(Y-J)-.0001) 4,4,10
10      IF(I-J) 4,11,4
11      ICNT=ICNT+1
        GO TO 2
4       WRITE(3,15)TMSAV,TMSL,ICNT
15      FORMAT('1 HIGHER BOUND IS ',E20.10,/,' LOWER BOUND IS ',E20.10,/,
       1 ' NUMBER OF SEQUENCES IS ',I5)
          GOTO98
999      CALL EXIT
        END
```