Motion in Cardiovascular Radiography

By Charles T. Dotter, M.D.

The minute has given way to the second as an expression of radiographic exposure duration. It is predicted that the millisecond will be the term of the future. Arterial blood velocity exceeds 50 cm. per second. In cardiovascular radiography, especially angiocardiography, maximum detail cannot be achieved unless the x-ray exposure is short enough to "stop" rapid movement. Practical experience indicates that exposures of 3 milliseconds' duration offer an economic alternative to high speed, serial angiocardiography. A method of achieving such exposures consists of a grid-controlled, high-tension, switch tube operated in series with the diagnostic x-ray tube.

Motion affects the study of all living patients and, since 1896, has been of special concern to those dealing with x-rays. Economically, its importance is obvious. Undesired patient-movement during radiographic exposures impairs detail and, thereby, necessitates repeat examinations if mistakes are to be avoided and maximum diagnostic yield obtained.* More fundamental ways in which motion plays a role are illustrated by three overlapping, radiologic approaches to the study of the heart. The chest film by a single exposure minimizes (but does not "stop") motion. Angiocardiography, through serial radiographs, though not directly studying motion, makes use of its effects. Cinefluorographic angiocardiography constitutes a primarily dynamic approach, the study of motion itself being dominant.

In the ensuing discussion, various direct radiographic techniques for angiocardiography will be contrasted as to their usefulness and limitations. Following this, an attempt will be made to define a practical basis for clinical angiocardiography in terms of frequency and duration of x-ray exposures. It is believed that considerable confusion exists in this matter and that a logical approach is desirable. A relevant technical development will be described which allows radiographic exposures of unusually short duration.

Exposure Rates for Conventional Serial Angiocardiography

Clinical angiocardiography is usually accomplished by direct serial radiography following the injection and many different devices exist which provide the necessary rapid film-shifting. Controversy exists, concerning the number of exposures per second desirable for angiocardiography. The optimal rate can be assumed to be some place between advocated extremes of 1 and 12 per second. If new and better equipment is to become available, more precise specifications are needed. Advice given to the manufacturers should be carefully considered. The enthusiastic desire, to incorporate many extra, nonessential features in a new piece of equipment, can result in failure from the point of view of design, manufacture, sales, operation, maintenance and cost. Money and engineering spent in development and fabrication of useless refinements could far better be directed elsewhere. Thus it is advisable to explore in a logical manner certain factors bearing upon exposure rates for angiocardiography. These factors are:

1. The period of study should be that of the transit period of the bolus of contrast agent. For practical purposes, in the absence of heart failure, this amounts to the 10 seconds following the injection. Films made thereafter will be worthless.

2. The exposure rate determines to a variable extent the amount of radiation involved. It determines to a great extent the cost of a given examina-

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* Painridden patients, frightened children, and inferiorly-trained technicians all contribute to the costly total of re-examinations necessitated by movement during exposure. At the University of Oregon Medical School, about 0.5 per cent of the film exposed is so wasted. It is estimated that undesired motion costs U. S. radiologists as much as $250,000 a year.
tion and, to an even more serious degree, the magnitude of equipment-design problems and costs. Thus, the optimal rate (and similarly the film size) is the minimum needed to produce the desired clinical result.

(3) Adequate detail should be achieved through short exposures rather than the "hit or miss" technique of making many films in hope that one of these will be made during a period of immobility and will, therefore, be adequate. This point will be more fully discussed subsequently. To repeat, the search for detail should not influence the exposure rate.

(4) The exposure rate (number of films per second) needed to show all the visualizable cardiovascular structures can readily be calculated. Disregarding "unsharpness" due to movement during exposure, this depends upon the length of time during which there will be diagnostically adequate concentration of the contrast agent at any given point in its route through the heart and great blood vessels. The duration of injection represents the minimal "spot opacification" period since the bolus tends to "string-out" during its passage. Study of the pulmonary valves serves to illustrate this point. Following angiographic injection, there occurs excellent opacification of the pulmonary outflow tract (pulmonary conus and pulmonary artery) for a period of at least two seconds duration. If at any instant during this period, an exposure is made in the correct projection, the rays will pass through the pulmonary valves while the leaflets are in contact with adequate concentrations of contrast agent. Thus an exposure rate of one per second is theoretically adequate to show any structure which might be revealed in studies made at far higher rates. Doubling this rate to two per second and controlling the time of exposure electrocardiographically will theoretically afford visualization of all structures during the extremes of their systolic and diastolic excursions.*

(5) The specific clinical fact sought for often requires that less than two films per second be made. Superior vena caval block (an extreme example) is as well shown by four films during 10 seconds as by 44. Two-per-second exposure rates will suffice for investigative purposes where systolic and diastolic extremes are desired; higher rates would be desirable for studying intervening phases. Since there is good evidence that clinical angiography need not be concerned with cyclic extremes (let alone intermediate phases), manufacturers would be design-wise to relegate such problems to the area of special research devices.

The foregoing discussion leads to the conclusion that adequate diagnostic angiocardiology requires two or at most four exposures per second. Reasoning has been based upon the relatively slow movement of a bolus of radiopaque solution. Thus far, consideration has not been given to movement of the heart itself. The duration, as well as the frequency, of exposures is of great importance.

Exposure Duration in Angiocardiography

Many workers, with wide experience in angiography, have strongly expressed their desire for angiographic exposure rates in excess of two or four per second. Lind and Wegelius and Kjellberg are currently employing exposure rates of up to 12 per second. Justification for this expensive practice (film for a 10-second run in one projection might cost as much as $100) has been their belief that slow, serial studies are inadequate for many clinical states, especially left to right and bi-directional congenital cardiovascular shunts. This report is being written in support of a more efficient, alternative approach.†

A moderately odious analogy may be appropriate: To shoot a rabbit, the wise hunter, by choice, and the impoverished one, by necessity, are prone to accomplish their objective through a single, well-aimed, rifle bullet. An equally lethal alternative might be to fire a submachine gun in the general direction of the rabbit at an explosion rate of 12 per second. The rapid rate involves a greater expenditure of ammunition, a more expensive gun, increased "wear and tear" on hunter, quarry, and countryside as well as much more noise. The essential feature of the more economic method lies in the aim. It is here contended that adequate radiographic detail represents the "aim" of the above analogy.

The unusual success of Swedish workers in

* Systolic-diastolic studies can be achieved without electrocardiographic control by much higher exposure rates and attendant gross inefficiency. Experience indicates that the ends of clinical diagnosis do not justify the means (whether electrocardiographic exposure control or rapid serial exposure rates).

† These remarks do not apply to the elaborate, highly-revealing investigations of cardiac physiology as exemplified by Lind and Wegelius' contributions to the understanding of fetal and neonatal circulation. Such studies, of necessity, take into consideration the various stages of cardiac contraction and represent a highly-informative, investigative approach.
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Fig. 1. Cardiac Movement. A and B are spot films of a cardiac catheter the tip of which lies in the pulmonary outflow tract. Though exposures were made in rapid succession and at technically identical factors (1/20 second), the tip of the catheter is invisible in B due to cardiac motion during this exposure.

showing pulmonary valvular detail is disproportionately greater than can be accounted for by the numerical increase in the number of exposures per second. It follows that a factor, other than the exposure rate itself, is involved. This factor is exposure duration. Workers, employing high-exposure frequency technics, have of necessity utilized high energy generators and short exposures. Kjellberg uses $\frac{1}{250}$ a second during angiocardiography at 12 exposures per second. Most studies performed in our country make use of exposures lasting $\frac{1}{60}$ second or longer (often as long as one-tenth of a second). It is this significantly long exposure (rather than the number of films made) which defines the limits of conventional angiocardiographic technic in the United States.

While the optimal angiocardiographic exposure frequency is determined by rate of progress of the bolus itself, the duration of exposure is dependent upon the rate of movement of parts of the bolus and by the movement of any anatomical structure coming into contact with it. In the venous system, mean blood

Fig. 2. Blood velocity. The movement of blood which occurred during this angiocardiographic exposure (made during ventricular systole at $\frac{1}{60}$ second exposure duration) is represented by the superimposed arrow drawn to scale. Such a technic cannot be expected to reveal heart valves or trabecular detail unless made at a certain (elusive) moment during diastole.
velocity is approximately 4 to 10 cm. per second; in both the aorta and pulmonary artery, physiologists indicate that resting mean arterial blood velocity ranges between 50 and 100 cm. per second! During systole, movement of the pulmonary and aortic valves will reflect this high velocity (see figs. 1 and 2). If adequate definition of these valve leaflets requires that they be "stopped" radiographically during an excursion equal to \(\frac{1}{10}\) their assumed thickness of 1 mm., it follows that the exposure of the film must be approximately \(\frac{1}{5000}\) of a second. Fortunately, for clinical cardiovascular radiology, such ultrashort exposures are unnecessary. Exposures \(\frac{1}{500}\) of a second (two milliseconds) should suffice for practical purposes.* In providing detail sufficient to the need, such short exposures offer a highly economical alternative to rapid exposure studies in angioangiography. Judged on the basis of preliminary studies, ultrashort exposures give anatomical information hitherto not available regardless of the exposure frequency employed. Analogously, ultrashort exposure "strobe" photography often provides information not discernable in ordinary photographs, through movies, or on direct observation (fig. 3).

* Probably because semilunar valve movement occurs at much lower speeds than published arterial flow velocities.

**Half-Wave Rectification**

Most modern heavy-duty diagnostic radiographic equipment affords exposures as short as \(\frac{1}{60}\) of a second, i.e. two rectified impulses. Occasionally, it may be possible, by temporarially decommissioning two valve tube, to achieve half-cycle exposures. This deliberate sabotage reduces by substantially more than half the duration of film exposure. The useful exposure period in the conventional \(\frac{1}{60}\) second (two impulses) exposure is actually about \(\frac{1}{80}\) second, while a single impulse will produce a (measured) effective exposure of only \(\frac{1}{240}\) second! The three-fold gain is readily understandable since, as a result of filtration, x-rays generated during the initial and terminal phases of a given impulse fail to reach the film at all. This accounts for the fact that \(\frac{1}{60}\) second on the control panel may mean \(\frac{1}{80}\) second at the film. Through elimination of the "silent" period between the effective portion of succeeding impulses, the three-fold shortening of exposure length is explained. This technique offers a proved, worthwhile improvement in the quality of angioangiograms which can be achieved without great expense. Advice concerning the feasibility of such a change should be obtained from the manufacturer's technical service division.

High-kilovoltage radiology is becoming commonplace and still further shortening of exposures is therefore possible. This cannot be done by filtering the beam without inordinate loading of diagnostic tubes.

**High Tension Switch-Tubes for Diagnostic Roentgenology**

A striking demonstration of short exposures in radiography is offered by techniques employing surge generators and electron arc cathodes. Utilizing condenser discharges, Slack and co-workers produced extremely brief x-ray exposures of tremendous energy (fig. 4). Unfortunately, such a technique cannot make use of commonly available diagnostic equipment.

In an effort to secure greater angioangiographic detail through short exposures, assistance was sought from the Machlett Laboratories. Consultations with Mr. H. S. Cooke and
Mr. W. E. Stevenson and Mr. T. H. Rogers led to the conclusion that, of the possibilities considered, a grid-controlled, electron tube operated in series with the diagnostic x-ray tube offered the most profitable approach. An experimental tube, constructed by Machlett, proved capable of providing three millisecond exposures at diagnostic energy levels. The description of the tube follows.

The tube, a triode, consists of filament (cathode), plate (anode), and intervening grid, the elements being contained within an evacuated glass envelope (fig. 5). The energized switch-tube filament serves as a source of electrons. The tube has a “cut off” point at -250 volts on the grid with +125 kilovolts on the anode. Thus, even though the primary circuit of the high tension transformer is completed, electrons are unable to reach the anode since except during exposures they are repelled by a negative charge (-300 volts) on the grid. Current therefore does not flow in the high tension circuit. The exposure is made by electronically altering the grid voltage or bias from -300 to +300 volts. At this positive grid charge, the tube will pass approximately 700 milliampere peak with less than 500 volts drop to the anode. As long as the grid is held at its positive charge, current flows through the tube completing the high tension circuit.

The desired grid bias voltages are readily obtained and applied to the switch-tube electronically (in this case by using an electronically timed “flip-flop” circuit isolated from ground by a transformer insulated for 60 kilovolts). It is thus possible to determine precisely the duration of the positive bias, and therefore the length of the exposure. The change in grid potential which causes the switch-tube to conduct may be likened to a flimsy key unleashing the tremendous force of the exposure current. Due to the relatively low grid current, electronic circuits suffice. Phasing of the exposure pulse with relation to the utilized sine-wave impulse may be varied readily. Thus, control of quality of the beam can be achieved independent of the high tension transformer. This may prove to be of importance in equipment design. At the high kilovoltages and short exposures employed, the beam is composed of fairly uniformly penetrating rays. Thus far, loss of contrast has not proved to be a factor of importance. Diagnostic applications of the fairly homogeneous x-rays beams which can be obtained by this tube are being explored.

On Nov. 23 and 24, 1954, preliminary appraisals of short exposure techniques, utilizing this tube, were conducted by the author and Machlett engineers at the Machlett Laboratories in Springdale, Conn. Studies consisted of radiographic examination of the anesthetized dog’s heart during catheter injection into the superior vena cava of 10 to 15 cc. of Urokon sodium, 70 per cent. Factors which proved satisfactory for one of the animals were 750 milliampere peak (equivalent to conventional 500 milliamperes), 95 kilovolt peak (KVP), 3 msec. (133 second) and a distance of 36 inches between the 2 mm. focal spot and the film. The dog’s chest measured 18 cm. in the projection employed; while Eastman Bluebrand film and Patterson parspeed intensifying screens were used. Numerous radiographs at varying factors were made. The results, believed to be highly encouraging, are exemplified by figure 6.

Detail was greatly improved. As a result, visualization was far superior to that of controls exposed at 1/10 second. Trabeculae carneae within the right auricular appendage and ventricular trabecular muscles were distinctly revealed. Hitherto invisible minimal retrograde reflux of contrast solution entered tributaries of the superior vena cava. When this did not occur, contributory or mixing “jets” were routinely present and revealed the site and relative volume of streams of nonopaque blood-deforming contrast substance within the
Fig. 5. High Tension Switching Triode for Diagnostic Radiography. A. Circuit diagram. Electronically changing the grid voltage in the switch tube, B shows a “low power” operation allowing the high-powered, much higher voltage of the x-ray generator to create a current through the switch tube and the x-ray tube. C shows an oscillographic photograph of a 3 msec, x-ray tube pulse so controlled. With conventional technics, x-ray exposures are longer and less efficient.

superior vena cava and right atrium. Clarification of the border between blood and contrast substance was sharp, allowing a fairly precise definition of the extent of the bolus. Demonstration of the leaflets of the tricuspid valve was unmistakable. Though during these preliminary tests but one exposure could be made following a given injection, more information was gained about the right side of the heart and its tributaries than would probably have been obtained from the first four exposures of a conventional two-films-per-second serial study.

Thus, the added detail achieved through short exposure duration reduces the need for high exposure frequencies and simplifies the problem of equipment design accordingly. It is probable that through short exposures, the volume of angiocardiographic injection can be reduced, thus increasing the safety of angiocardiography (while at the same time its diagnostic potential is enhanced).

A switch-tube has been installed in one of the regular radiographic rooms of the Department of Radiology of the University of Oregon.
Medical School. Installation caused few problems; routine use of the room is still possible since the tube itself is housed in a fairly small box and placed in the diagnostic room while the control box, even smaller in size, is placed as desired. Details of installation will vary according to the design of the equipment being modified. Basically, an important objective is realized in that the switch-tube timer-contactor is readily adapted to ordinary diagnostic apparatus and does not preclude the use of a more conventional timer. Since there is reason to believe that the life expectancy of the tube will be good and the production cost need not be prohibitively high, the switch-tube should not be relegated to the limbo of "for research only."

Short exposure technics represent a logical step in the progress of diagnostic radiology. As high kilovoltage through "wide latitude" technics can decrease film wastage due to improper quantitation of exposures, so can "short shot" technics minimize the effect of unwanted motion during radiography. Since at 120 kilovolt peak (KVP) an adequate chest film of the average adult requires less than 1 milliampere-second, ordinary high voltage diagnostic tubes and generators will suffice. It is predicted that short-duration exposures will expand the potentialities of angiocardiography to a considerable extent. The definitive diagnosis of septal defects with left-to-right blood-shunting may eventually fall to the radiologist rather than to those employing cardiac catheterization. Its applications in the study of ventricular...
form and function are unexplored. Preliminary radiographic studies employing relatively short exposures in the study of the left ventricular wall in coronary heart disease are already in progress and should be enhanced by millisecond exposure techniques. Calcified valves can be seen more clearly in radiographs made at short exposures than by fluoroscopy. Other applications such as in pediatric radiography are obvious.

A strong impetus toward the development of ultra-short exposure techniques suitable for clinical applications has been a long-term interest in the development of satisfactory and harmless "particulate" contrast agents for use in cardiovascular roentgenology. These are a practical possibility and open up yet another unexplored approach. "Punctate" or particulate radiopaque agents of proper size and viscosity (whether solid, liquid or gas) should provide a radiologic method for studying the characteristics of blood flow (fig. 7). Abnormal turbulence patterns may offer valuable data in many disease states, such as valvular deformities and cardiac arrhythmias. By measuring particle excursion during exposures of sufficiently short, known duration, blood velocity and flow may prove to be simultaneously quantifiable in many parts of the cardiovascular system. For example, simultaneous blood-flows in the pulmonary artery and all its segmental branches could conceivably be calculated from a single radiograph, while the determination could be repeated at much shorter intervals than allowed by technics based upon the Fick principle. Studies with "particulate" contrast agents necessitate the use of short exposures of a precisely known duration based upon the velocity of bloodflow.

**Summary**

(1) The radiologic significance of cardiovascular motion has been the underlying basis for the foregoing report.

(2) The optimal exposure frequency for clinical angiocardiography has been considered in detail in a conscientious effort to guide those concerned with design and manufacture of future apparatus. A combination of economic, clinical, anatomic, and physiologic reasons have been advanced in support of exposure rates of from one to four per second.

(3) The value of short-duration roentgen exposures for angiocardiography has been discussed at length. Diagnostic accuracy is improved while economy is achieved in terms of the number of films needed and the amount of contrast agent to be used. The duration of exposures for angiocardiography should be based upon the velocity of blood-flow in man. The two millisecond exposure appears to represent a reasonable objective. The frequency of angiocardiographic exposures is, on the other hand, best determined in terms of progress rate of the entire bolus of contrast agent.

(4) Through the use of an electronically-controlled, grid-operated, electron tube in series with the diagnostic tube, three millisecond clinical radiographic exposures have been achieved. The tube is described and a number of its potential applications to medicine discussed.

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**Sumario in Interlingua**

Es discutite le problema del frequentia optimal de expositiones angiocardiographie in le practica clinic. Considerationes economic, clinic, anatomic, e physiologic es presentate in supporto del selection de un frequentia de inter 1 e 4 expositiones pro secunda.

Es discutite in detalio le valor de roentgenexpositiones a breve durantia pro ob-
jectivos angiocardiographic. Le duration del exposition debe esser determinate in relation al velocitate del fluxo sanguinee.

Per medio de un tubo electronic in serie con le tubo diagnostic, expositiones radiographic de un duration de non plus que 3 millisecondas ha essite effectuate. Le tubo usate es descritite. Un numero de su applicationes potential in le practica medical es discutite.

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