Cardiac Catheterization and Angiocardiography

An Introductory Manual

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FOREWORD

Dr Verel and Dr Grainger are rendering a valuable service in outlining the place of cardiac catheterization and angiographic methods in the modern study of cardiac problems. Without this vast increase in precision of diagnostic techniques, the miracles of modern cardiac surgery would be impracticable. In commending their book it may be salutary to recall some of the early history of the development of these valuable procedures and the generally conservative attitudes with which they were at first received.

The story goes back to 1929 when Dr Werner Forssmann was a resident in the Augusta Victoria Hospital at Eberswald, near Berlin. In those days, anaesthetic deaths were not uncommon and he had had the experience of seeing intrapericardial haemorrhage result from the heroic intracardiac injections of adrenalin normally used in such emergencies. He conceived the idea that it would be safer to inject adrenalin through a catheter passed via an arm vein into the heart. To prove its safety he asked a fellow resident to undertake this procedure on his own person. The catheter was passed as far as the axilla when Forssmann's associate took fright but Forssmann himself with the catheter in this position walked to the radiological department and, with a radiographer holding a mirror in front of the screen, completed the procedure and took pictures of the catheter in his own right atrium. He felt nothing and no harm resulted. Naturally excited by the possibilities, he later made several further efforts including the injection of concentrated sodium iodide to obtain rather faint angiograms of the right heart and pulmonary vessels. He catheterized his own heart nine times in all and after this was unable to do any more as he had used up all his available superficial veins. He contacted Professor Sauerbruch, then the leading surgeon in Berlin, to see whether any use could be made of the catherization procedure in diagnosis or management in a cardiac surgical clinic. Sauerbruch's reaction was that 'he ran a clinic not a circus'! Orthodoxy banished Forssmann from the university world. In 1949 when I visited Germany on behalf of the British Council I asked 'Where was Forssmann?' His name had been forgotten but Professor Spang of Heidelberg located him in practice in a small town in the Rhine valley. I was able two years later to enlist Forssmann's help in recording the story of catheterization in a teaching film made by I.C.I. and a few years later Forssmann justifiably shared a Nobel Prize with Cournand and Richards.

Forssmann's work, however, was not neglected in other countries. Jimenez-Diaz in Spain realised the possibility of using this technique to get right heart samples for the measurement of cardiac output. He recorded one such attempt but did not follow the matter up. In Portugal, De Carvalho and colleagues used the technique to obtain angiograms of the root vessels of the lung, clarifying much confusion in the interpretation of the branching shadows in the lung roots. Ameuille and others in Paris made similar pictures but all these procedures involved 'quick in and quick out' intracardiac injections. By the time of the outbreak of war in 1939, however, there were on record no less than about 110 occasions on which intracardiac catheterization had been done without trouble to the patient or any recognizable harm.

The war then demanded effort by investigators on the nature of wound shock and a great deal of the investigative endeavour would naturally fall on civilian hospital teams. At the Bellevue Hospital, New York, civilian accident cases came under the investigative supervision of Dr D. W. Richards and Dr André Cournand. They asked their hospital board's permission to study such gravely injured patients by intracardiac catheterization and permission was given. In 1941 Cournand and Ranges published their paper in the Proceedings of the Society for Experimental Biology and Medicine.

I had been intrigued by the possibility of measuring the cardiac output which started with my student contact with Meakins and Whitteridge Davies in Edinburgh. They had made many efforts to obtain the gaseous composition of right heart blood by various indirect rebreathing techniques and the results sometimes seemed surprising, such as a fairly normal cardiac output in the presence of cardiac valvular disease. Such findings led to widespread doubts about the validity of these methods! I had been working (1930–33) on portal congestion and the regulation of portal venous pressure in Aberdeen and in University College Hospital Medical School, London. My interest in the regulation of venous pressure led me to consider making a study of the general congestive phenomena of cardiac failure. In 1932 Grollman had published his book on cardiac output based on the use of the acetylene method for its estimation. I talked to Samson Wright about this and he invited me to come to his department at the Middlesex, a short walk from University College, where he put Grollman's apparatus at my disposal. There were considerable technical difficulties in getting good results with the acetylene method owing to analytical inaccuracies from the high solubility of acetylene in the carbon dioxide absorbent. Realising the difficulty Samson Wright suggested that we eliminate this by using a very small volume of caustic soda in a manometric Van Slyke apparatus which would at least reduce and standardize the amount of acetylene which disappeared in solution. This involved the construction of a special Van Slyke gas chamber with a trap at the bottom for ejection of the gas absorbent mixtures. A small glass blower near Queen Square made it for me very cheaply and I took it with me when I returned to the Physiology Department in Edinburgh. The method worked out splendidly. My first paper on cardiac output was rejected for Clinical Science as Thomas Lewis at that time thought that 'the readers of Clinical Science had little interest in the cardiac output'!

In 1935 Professor T. R. Harrison published his book on *Failure of the Circulation*. In this book he took into account all published reports of the measurement of cardiac output in heart disease and, accepting the finding that the cardiac output might not be unduly depressed even in heart failure, he evolved the concept that heart failure was a 'dyskinetic syndrome', output being maintained at the expense of venous congestion. I found this an exciting and challenging concept and as I was now given charge of beds in Professor Ritchie's wards in the Edinburgh Royal Infirmary I extended my cardiac output studies in heart failure with resulting confirmation of the validity of many of Harrison's views.

When I returned to London in 1939 I was able to continue with the acetylene technique. Although the method was practicable and indeed sufficiently accurate to give results of great interest, it was cumbersome and took the better part of a day to work out and cross-check a single estimation. With my colleague Sharpey-Schafer at Hammersmith we were indeed trying to make use of the acetylene method for the estimation of cardiac output changes following venesection in blood donors, but the results were too difficult to obtain to give any adequate sequence of cardiac output changes following blood loss.

When we read Cournand and Ranges' paper in 1941, new possibilities suddenly appeared. We realised that Cournand had shown that it was possible to put the catheter into the right atrium and *leave it in situ* for periods of an hour or so, during which sequential observations could be made. It took a little while to persuade our radiological colleagues to cooperate in cardiac catheterization but we began work in the autumn of 1942. The first patient studied was a young man with asthma who became extremely cyanotic in the attacks and whose cyanosis was far in excess of what might be expected from our lung function tests at that time. He proved to have an atrial septal defect through which he was developing a right to left shunt during his attacks. We also began to study patients in heart failure, and to document the consequences of digitalis administration. The improvements in circulatory states which followed our efforts led some of the patients in subsequent hospital admissions to complain of the delay in putting the 'tubes' into their arms!

Our growing experience was convincing us of the wide range of applicability of the new technique. We wished to extend our experience with normal subjects acting as blood donors and I went to see Sir Edward Mellanby, then Secretary of the Medical Research Council. We wanted to get the blessing of the Wound Shock Committee on a request for volunteers. Mellanby's reaction was that no Committee could give its approval of such an unorthodox procedure and that the responsibility must lie with ourselves. He would have no objection, however, to a personal approach from ourselves to the Friends Ambulance Unit and this was made. The first volunteer for cardiac output determination during a venesection indeed bore the name of Cadbury. In order to get the maximum information from these volunteers, we had now obtained the co-operation of Professor Henry Barcroft and Dr. O. G. Edholm, who were in a position to make peripheral blood flow studies simultaneously with measurement of the total circulation. I well remember the excitement of observing for the first time the intense vasodilatation of the forearm vessels during a post haemorrhagic faint. While the war continued with its inevitable increase in the hazards to life, volunteers were not difficult to persuade as they had the feeling that they were contributing to the war effort by helping in these researches.

In December 1943 Sharpey-Schafer and I made our communication to the Physiological Society at University College Hospital Medical School. Sir Thomas Lewis was in the chair. He described our opening paper as 'startling' and at the lunch-table he shook his head hinting that we should abandon the procedure. Sir Henry Dale also at the table, however, took a different view and said that the total record of experience which we had assembled (394 cases) seemed to establish the practicability and safety of the technique and that it was too valuable to be dropped. His powerful and influential support was indeed a great encouragement.

It was already becoming clear that the diagnostic possibilities of the method were enormous as well as the value of the technique in the study of pharmacological and therapeutic effects. We were at that time timidly limiting ourselves to right atrial catheterization and simple saline manometry. The results obtained were precise as far as they went but we went wrong in our interpretation of digitalis action as we failed to realise that a reduction of right atrial pressure could result from improved ventricular function *irrespective* of cardiac output change. Our early approach was, perhaps understandably, too conservative and we did not get round to making optical records of changes in intraventricular pressure through the cardiac cycle until 1948. By this time Cournand and his colleagues in New York had gone well beyond what we had achieved with our simpler and more limited techniques. The development of surgery for congenital heart disease by Blalock and Taussig in Johns Hopkins had also opened a new chapter. The method of catheterization made modern cardiac surgery possible and the subsequent development of cardio-angiography soon arrived. The achievements of the subsequent 20 years are adequately presented in this book, which I can heartily commend.

John McMichael.

1969.

PREFACE

CARDIAC catheterization has been used for the diagnosis of disease of the heart for nearly a quarter of a century. During this time the techniques have remained basically three: the visualization of the heart chambers, the identification of shunts and the measurement of pressure in the heart chambers and blood vessels. Advances in technique have included an increasing refinement of apparatus and a multiplication of the methods available for the demonstration of the three parameters measured. Cardiac surgery has been established as a result of the diagnostic precision achieved by cardiac catheterization: the results of cardiac surgery have, *pari passu*, justified the development of cardiac catheterization.

The increasingly complex instrumentation available for cardiac catheterization has been accompanied by a corresponding increase in the complexity of the investigations themselves. Most noteworthy in this respect has been the development of selective angiocardiography and its incorporation as part of the catheterization along with oximetry, pressure measurement, and other techniques. This has brought together what were, as recently as ten years ago, separate investigations. The post-graduate entering the field of cardiac catheterization is therefore faced by a complex discipline which makes use of a wide range of different techniques.

We have found that, despite wide reading, post-graduate students have difficulty in making an appropriate choice of method during cardiac catheterization. There appears to be no simple manual which presents the available techniques as parts of a single integrated investigation. In general, cardiologists have more experience of venous catheterization, whilst radiologists have developed a considerable experience of arterial puncture and catheterization. Because of this, a tendency has developed in many departments for cardiologists to undertake right heart catheterization and angiography, while radiologists practise retrograde left heart catheterization and angiography. Our department has tended to adopt a similar pattern of work, but there is no sharp division. Indeed, it is our belief that both the cardiologist and the radiologist who undertake cardiac catheterization should be competent in both catheter approaches to the heart. In writing this book we have tried to present an introductory account of a single craft which makes use of many widely different techniques. We hope that it will provide the trainee cardiologist with a sufficient background knowledge of the radiological aspects of angiocardiography, and inform the radiologist of the basic concepts of hæmodynamics and modern investigation techniques so that both may become competent and versatile in adopting an integrated appraoch to cardiac catheterization and angiocardiography. We have included a few references: a full bibliography will be found in Zimmerman's series of monographs.

Inevitably, an account of this kind is coloured by our own experience and practice. We have both, however, watched catheterizations performed in many other centres at home and overseas. Our own practice has therefore been modified by that of others, and in writing this book we have tried to take some account of preferences other than our own.

The techniques of cardiological diagnosis discussed in this handbook are entirely dependent on the co-ordinated efforts of many people. In particular, we wish to record our thanks to Dr R. E. Nagle, Dr N. H. Stentiford and other registrars who have undertaken many catheterizations, to our cardiological technicians, our radiographers and our nursing staff. We owe a debt to the many patients whom we have investigated. Without their fortitude and confidence we would have accomplished little.

The illustrations of the text and of the atlas are the work of the Photographic Departments of the Sheffield Regional Hospital Board and of United Sheffield Hospitals. We are particularly grateful for the excellent service which they have so willingly provided, and for the admirable blocks made from them by our publishers.

Several secretaries have typed our indifferently written manuscripts, and to these also, our thanks are proffered.

We are honoured to include a foreword by Professor Sir John McMichael, F.R.S.

D. V.
R. G. G.

Sheffield, 1969.

CONTENTS

CHAPTER 1

METHODS OF RECORDING

RECORDING CHARACTERISTICS

In the course of investigating the cardiovascular system it may be necessary to record a wide variety of phenomena. Events as different as the respiratory cycle and the heart sounds may have to appear upon the same record. Satisfactory work is only possible if there is some understanding both of the characteristics of the phenomena being recorded and of the apparatus in use. Since all observations depend ultimately upon some recording system for their expression, it is desirable to begin a work of this type with a general consideration of the available recording techniques. Certain properties are common to all recording systems and must be understood by those working with them. We shall consider (1) frequency and frequency response; (2) amplitude of response; (3) linearity of response and (4) damping and overswing.

Frequency is a term usually applied to a phenomenon that is repeated in a regular cycle. Thus, one may speak of respiration having a frequency of 16 or 50 cycles per minute, depending on its rate. Similarly the heart rate may have a frequency of 70 or 250 per minute depending on circumstances, while the heart sounds may have frequencies of several thousand cycles per second. A 'cycle' implies that the phenomenon repeats itself. One complete wave form from start to finish constitutes a cycle (Fig. 1.1). When the event is non-repetitive, for example the rise in skin temperature that follows peripheral nerve block, the term 'cycle' is not appropriate, but the recurrent rise and fall in finger tip temperature that follows immersion in ice water (what Lewis termed 'hunting') can fairly be called a cycle although its 'period' (the time for a complete cycle) is several minutes.

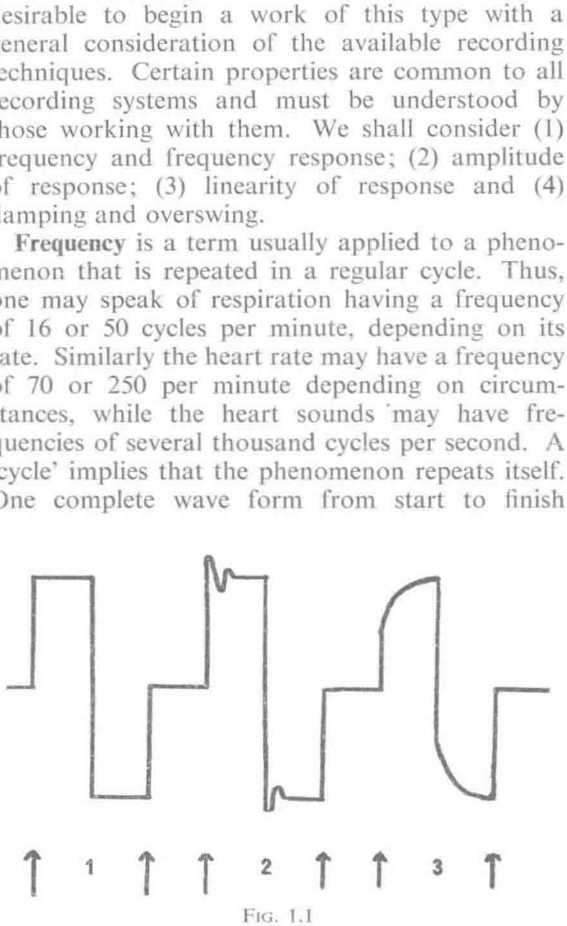

Fig. 1.1

Diagrammatic representation of a square wave oscillation. 1. Critically damped. 2. Underdamped showing overswing. 3. Overdamped showing loss of the square wave form. In each case a complete cycle has been represented as a positive deflection followed by an equal negative one. An example of a square wave with a wholly positive deflection is shown in Fig. 1.4.

The **frequency response** of a recorder is the maximum frequency that can be recorded faithfully. This may be low, as in the float recorders used in limb phethysmography or spirometry, which may become inaccurate at rates over about 25 cycles per minute (cpm.), particularly if the excursion made by the instrument is large. Alternatively the frequency response may be high, as in the cathode ray oscilloscope, which can follow precisely anything likely to be encountered in cardiovascular work. In considering the purchase of equipment, the nature of the work to be recorded must be carefully related to the frequency response of the apparatus (Fig. 1.2).

The **amplitude** of the response is a fundamental property in any recorder. It ranges in complexity from the length of the wooden spill attached to a float recorder to make the excursion on a smoke drum equal approximately (say) 1 cm. rise for each 5 ml. increase in volume, to the electronics needed to provide a range of responses in an oscilloscope enabling any voltage from 1,000 V. to 1 V. to give a deflection of precisely the same degree in the electron beam. In considering equipment, the cost and amplitude of response are usually closely linked, high sensitivity and high cost going together. Here the likely use of apparatus is again of prime importance. There is no point in spending large sums of money on sensitive equipment if it is only to monitor the electrocardiogram in post-operative cases. Equally, if a direct writing recorder is in use, it is not going to produce the high sensitivity necessary for a precise analysis of the wave form of an intracardiac pressure tracing. The pros and cons of various recording systems are considered later.

Linearity of response is now found in most recording systems available commercially. By 'linearity' is implied a constant excursion for a given change over the whole range of the recorder

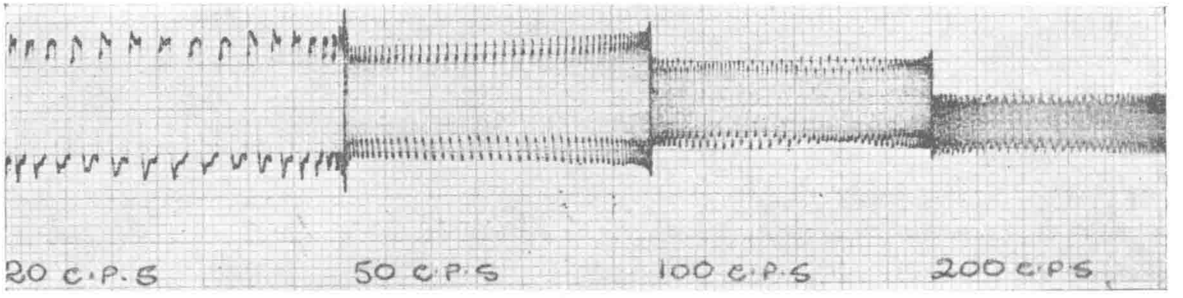

FIG. 1.2

The effect of increasing the frequency beyond the capacity of a recorder. The instrument was a standard direct writing electrocardiograph of Continental make. A square wave is recorded at 20, 50, 100 and 200 cycles per second, the voltage being constant. Even at 50 cps. the recorder shows a falling off in the amplitude of the response, with a progressively poorer performance as the frequency is increased. Clearly the phonocardiograph attachment sold with this instrument can give only a crude indication of the sounds occurring in the cardiac cycle.

movement. The usual fault in recording systems is a progressive lessening in the movement produced by a given change as the recording rises above the base line. For example, in a recorder which is tracing blood pressure, it may be that a change from 0 to 10 mm. Hg causes a rise of 1 cm. while a change from 100 to 110 mm. Hg causes a rise of only 0·6 cm. Clearly a recording system of this kind presents great difficulties if it is used for anything more than a qualitative record.

Damping is a term which is applied to any reduction in the frequency or amplitude of a phenomenon caused by the characteristics of the recording system. Such a reduction may be deliberate or accidental, and it is necessary to distinguish clearly between them. Undesirable damping may occur in a simple float recorder if the needle bearings, about which the float rotates, are too tightly screwed up. Similarly, in the recording of intracardiac pressures by electronic transducer, damping will occur if the

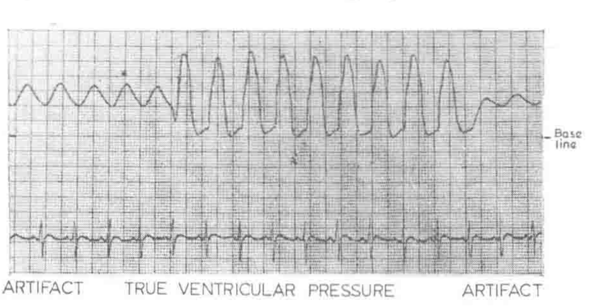

FIG. 1.3

A pressure tracing showing the artifact which may be produced by damping. Throughout this tracing the catheter tip lay within the ventricle. Initially, a small air bubble was present in the catheter. The removal of this produced a normal ventricular tracing and at the end of a period of recording, the tap between the pressure head and the catheter was turned off. The pressure head was sufficiently sensitive to record a pressure tracing despite the rather loose tap obstructing the fluid column. Similar damping might be due to blood clot in the catheter or contrast medium of high viscosity.

recording system contains an air bubble, or if blood or X-ray contrast medium fills the catheter instead of the less viscous saline or dextrose solution, or if the hot stylus is adjusted to press too hard on the heat sensitive paper of a direct writing recorder (Fig. 1.3). Whatever the cause, the effect is a reduction in the amplitude of the recording and of the frequency response of the system.

Damping is deliberately introduced into recording systems for a variety of reasons. That most commonly found is concerned with 'over-swing' (Figs. 1.1 and 1.4). This use of damping is similar to that employed in the springing of a motor car. Here the frequency of the springs of the car is such that if no damping were applied the passengers would soon be bounced into travel sickness. The car dampers apply a graduated friction which smooths the natural oscillations imparted to the springs by the irregularities in the road surface. Examples of this type of damping are built into recording systems to prevent the inertia of the system causing oscillations—for example, most galvanometers are just sufficiently damped by some mechanical device to make them swing steadily to an indicated reading and then stop. Such damping is precisely calculated to reduce the overswing to a desired degree without affecting the amplitude of the response, and is termed '*critical damping*'. Without it the recorder swings beyond the end point and then reaches its final deflection after a series of diminishing oscillations. Too much damping reduces the frequency response, obliterating fine detail, and reduces the amplitude of the response progressively as the damping increases until an oscillation such as the electrocardiogram is converted to a straight line. Damping of this degree is used in pressure recorders for obtaining mean pressure recordings. The degree of damping

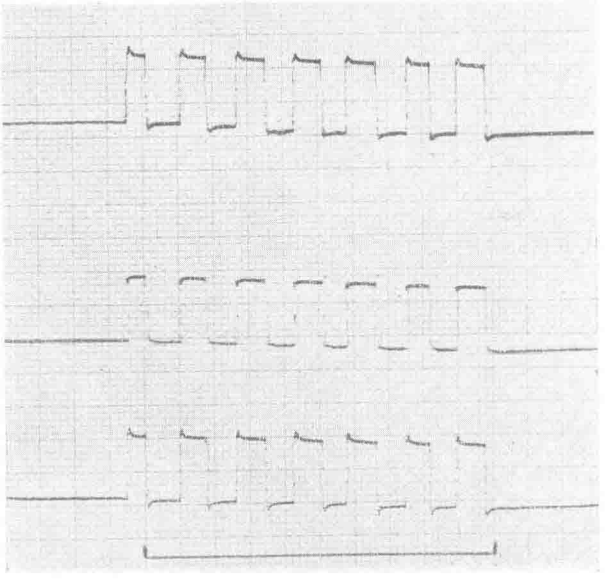

FIG. 1.4
Square waves generated by calibrating a three channel electrocardiograph. The centre channel is slightly over damped, the other two slightly under damped. Recorded at 50 mm. per sec.

is usually ascertained by recording a so-called 'square wave'. This may be a change in pressure, volume, electrical potential or voltage, depending on the recorder, but whatever the quantity changed, it has the characteristics shown in Figure 1.1, i.e. the transition from one value to another is achieved as nearly instantaneously as possible.

Deliberate damping may be employed for a rather different reason in the recording of pressure during cardiac catheterization. The pressure transducers used in this work are necessarily extremely sensitive with a high frequency response. They will, therefore, record not only the pressure waves occurring in the heart and vessels, but also pressure changes of higher frequency originating in the liquid filled catheters which connect the pressure sensitive device to the site from which the record is being made. These high frequency pressure oscillations are similar to the vibrations in an organ pipe

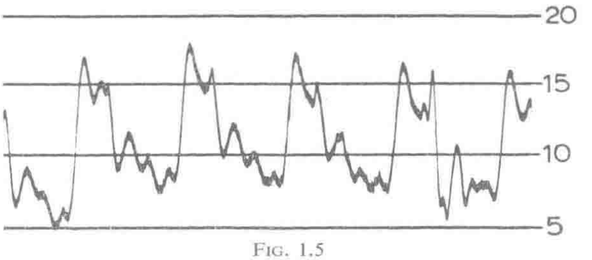

FIG. 1.5
A very badly distorted pulmonary artery tracing. This normal pulmonary artery pressure (15/5) is grossly distorted by harmonic pressure waves in the catheter tubing. The basic pressure change due to the heart action is overlayed by a coarse oscillation having a frequency of about 0·2 seconds.

which is resonating, or in a length of central heating pipe which is struck by a hammer. They are generated by the movement imparted to the catheter by the beating heart and their frequency is a function of the bore of the catheter, having lower frequencies in wider bore catheters. They may occur throughout the pressure cycle or be generated only at certain times in the cycle, as, for instance, at the onset of systole when the movement of the heart is particularly likely to tap the side or end of the catheter (Fig. 1.5). Undesirable oscillations of this kind may be removed by suitable damping. The mechanism for achieving this is built into the amplifiers in most apparatus and acts by reducing the frequency response. In some centres critical damping is applied to each catheter by introducing a suitable length of capillary tubing between the catheter and the pressure transducer. This latter technique is not easy and carries the hazard that any oscillation occurring in the tracing which has the frequency that is being damped out will be eliminated—in other words the damping process cannot distinguish between pressure changes generated in the heart and those generated in the catheter if they are of the same frequency. In general it is safest to record a length of undamped tracing followed by a tracing with as much damping as is needed to clarify the record. When the artefact is large, it may be impossible to eliminate it without applying so much damping that the amplitude of the recording is reduced and the tracing thereby falsified.

TYPES OF RECORDER

Recorders used in cardiovascular work are, with very few exceptions, designed to measure changes in voltage, or by a mechanical system to appreciate displacement or volume change. It can be surprisingly difficult to record a large mechanical movement with a small electrical one as anyone who has tried to get the output from a venous occlusion plethysmograph on the same record as an electrocardiogram and a pressure tracing can testify. In most recording systems some compromise also has to be reached between the frequency response of the recording (this is usually limited by the mass of the recording stylus), the frequencies of the parameters being measured, and the cost of the apparatus. Other considerations may also play a part—for example the amount of processing needed to render a recording available, or the need for having records in a permanent, durable form suitable for incorporation in hospital notes. In deciding on methods, delineating the scope of an investigation, and assessing the value of results, a thorough knowledge of the potentials and limitations of the various recording systems available is essential.

Brodie bellows. In its original form the Brodie bellows consisted of a small bladder which lay between a fixed lower platform and a hinged upper plate to which a stylus was attached. The stylus inscribed a smoke drum. Volume changes were

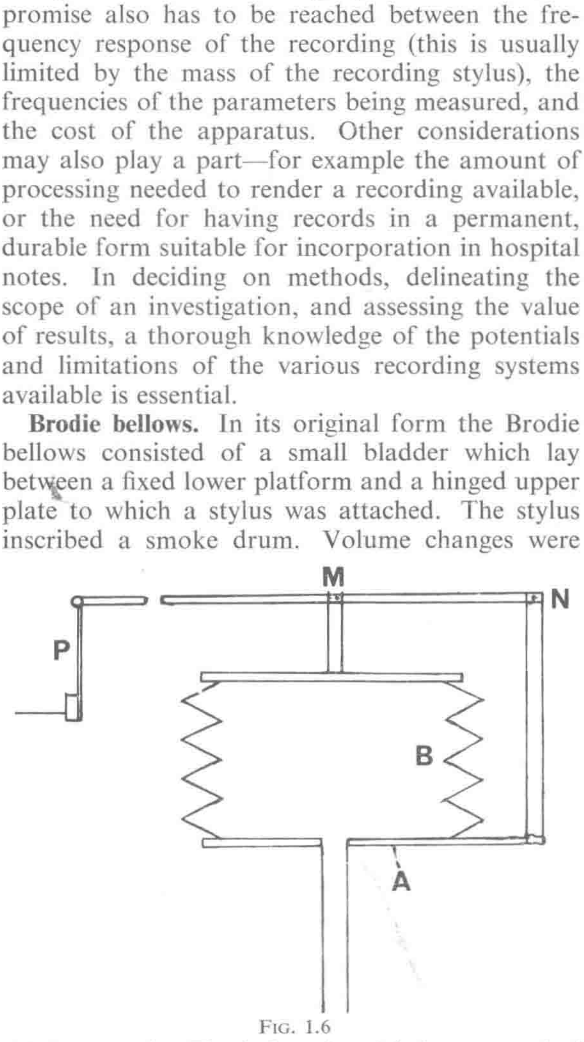

FIG. 1.6

A bellows recorder. The platform, A, and the levers are made of perspex or celluloid. M & N are light joints made with hypodermic needle tubing pinned through the plastic. The pen P is made from celluloid tube and sheet with a stainless steel tubing stylus. The bucket reservoir of the pen holds a drop or two of ink. In this type of recorder the linearity of the record depends in the relations between P, M and N, and the sensitivity on the length of M to P (as well as the area of the Bellows B). Increasing the distance M–P makes the recording more sensitive as well as more nearly linear. The light weight of the moving parts makes this a relatively sensitive recorder.

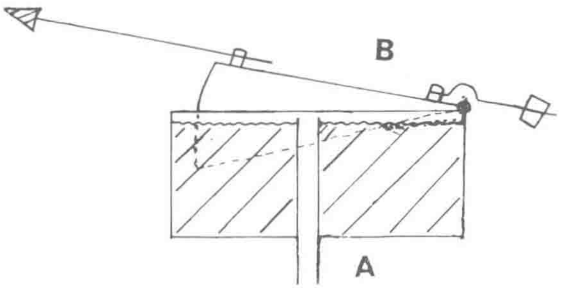

FIG. 1.7

A float recorder. In this instrument a thin brass float with an open lower surface traps air over a water filled tank, A. The pointer is counterbalanced and the inertia of the float considerable. The sensitivity depends on the area of the water surface trapped and on the pointer length. Increasing the length of the pointer makes the instrument more sensitive and the record more nearly linear but also increases the inertia and so increases the tendency for the water in the reservoir to oscillate, thus offsetting by counter-oscillation the gain in sensitivity. Rapid movements are damped out by this water movement.

imparted to the bladder which moved the hinged plate. The record produced by this simple system is not linear, but a more sophisticated version of the same thing does give a linear record over a considerable part of its range, and is easily made from plastic sheet and either celluloid or perspex. It is a sensitive recorder which has little inertia and can be made in any size from about 1·5 cm. diameter up to over 30 cm. diameter (Fig. 1.6). It has many advantages over the float recorder.

Float recorder. This exists in many forms, two being common. In one, a hinged open box traps air in a water bath, and a stylus moves up and down to record changes in volume (Fig. 1.7). The bell recorder (Fig. 1.8) has the advantage of being precisely linear over the whole of its range. It is usually employed for this reason for spirometers. The float recorder is not precisely linear, but the error is negligible over much of its range, and when used at right angles to the recording paper can usually be arranged to stop recording when it reaches a significantly alinear part of its range, by the simple device of having a pen length so short that the point leaves the paper. In arranging this type of recorder there is again a compromise: the longer the stylus, the more nearly linear the record and the greater the inertia of the recording system. The bell recorder is obviously less sensitive than the float.

The main disadvantage of these recorders is their failure to record accurately when the excursion demanded of them is either rapid or large. This comes about because the water which acts in both types as a seal can move up and down in the opposite phase to the recorders themselves. This means that in rapid deep breathing, for example, as the bell of a spirometer is forced up by expiration there is a simultaneous movement of the water in the bell going downwards, with a complementary upwards movement of the water outside the bell. Bernstein and Mendel (1951) have proposed a partial solution to this dilemma: a very light bell of wide diameter, but this is attaining a more accurate record by sacrificing sensitivity, for a wider bell will have a smaller excursion per unit of volume.

Bubble recorder. The inertia of the preceding recorders is considerable, and they are incapable of making faithful records of rapidly changing events. Where considerable changes in volume or displacement are concerned, it is surprisingly difficult to devise a recording system that is of low inertia and that is genuinely recording the change observed, and not some function such as pressure change or rate of change of pressure which is dependent on the phenomenon under observation. For example, the device sold with most multi-channel ECG recorders for arteriometry is a piezo-electric crystal. Placed over an artery or other pulsation, it will produce what appears to be a convincing record of movement. Comparison with a recorder which is truly recording displacement, however, reveals that the record is distorted, and is really a record of the *rate of change* of position. Small displacements can be accurately followed by suitable devices (e.g. those used by Mounsey (1962) and by Nagle (1967) but large volume changes are difficult to record in detail. The bubble recorder is sometimes a convenient answer to this problem. It consist of a suitable length of glass tubing which is wet inside with a detergent solution. A bubble is formed in the tube which is connected by wide bore tubing to the apparatus whose pulsation is to be recorded. The recording tube is arranged along the slit of a photographic recorder and the bubble illuminated so that its shadow falls on the recorder paper.

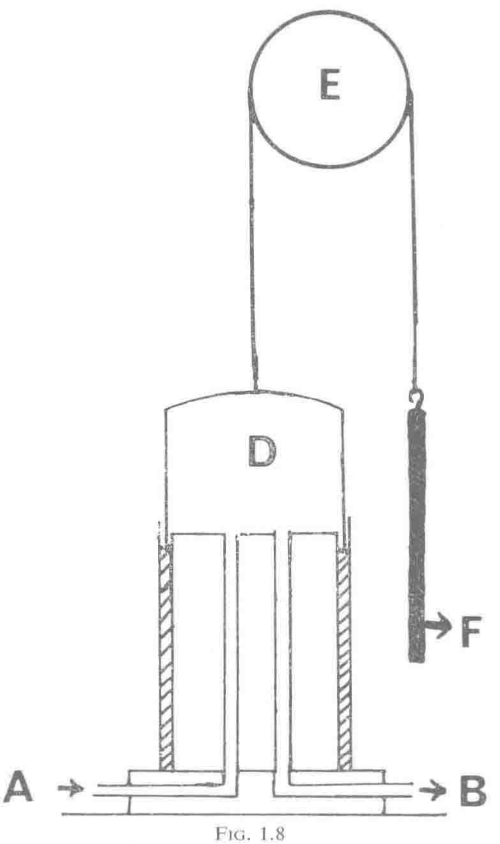

FIG. 1.8

A bell recorder. The tube A leads air into the bell D in which air is trapped over a water seal which is shown hatched. Air leaves the bell by B. A counterweight and pointer, F, balance the bell, by means of a pulley E. This apparatus gives a linear record over its whole range. The sensitivity is a function of the area of the bell and so of its diameter. Large oscillations of low frequency are well recorded but rapid or small movements are damped by movements of the water which is forced down inside the bell and up outside when the bell is blown rapidly up, and vice versa.

Galvanometers. The great majority of data recorded in cardio-vascular work is recorded by galvanometers of some sort or another. For the purposes of this discussion they may conveniently be divided into three groups—direct writing, ink jet and photographic.

Direct writing instruments consist of a stylus attached to a magnet which oscillates in a magnetic field. The changes recorded are made to affect the field and so the position of the magnet. Suitable damping is built in to the apparatus to prevent overswing, and most instruments are linear in their response. The record is inscribed either by a hot wire on heat sensitive paper or by a capillary tube touching the paper which draws an ink line by capillary attraction. The advantages of this type of recording are that it is immediately available for inspection, is reasonably permanent, and is easily copied. The main disadvantages are the poor frequency response and its limited capacity for recording detail at high sensitivity. These recorders cannot exceed a frequency of about 90 cycles per second (cps.) (Fig. 1.2), and attempts to record at high sensitivity are often limited by the limited excursion of the recording arm. It is also impossible to superimpose simultaneous recordings. Despite these limitations they remain the most frequently employed recorders, being used universally for routine electrocardiography and many other purposes. They have the same limitations as the previously described mechanical recorders—a large movement needs a long and heavy lever.

Ink jets are a partial answer to the poor frequency response of the direct writer. In these instruments the stylus tip does not quite touch the paper and the ink either runs out by siphonage or is blown out under pressure. The stylus writes in an arc (as does the ink direct writer) which makes the records difficult to quantitate if the area described by the writer is important. The line traced is rather thick. Some instruments have an exasperating habit of going dry at inconvenient moments, and some have an equally disastrous capacity for making puddles of recording ink on records. Frequency responses as high as 500 cps. are claimed for the more sophisticated instruments, but even the durability and immediacy of the records they produce do not make them a substitute for the more complicated photographic recording, for it is not possible to superimpose recordings.

Photographic recording dispenses with the inertia of the recording stylus and the drag of friction on recording paper. Small mirrors are mounted on the coils of the galvanometers and are used to reflect light which shines through a suitable slit. The light may impinge on bromide paper which provides an excellent black on white record, but which requires development and fixing like any bromide photographic print. Alternatively, immediate recording paper using an ultra-violet light source is available. The records obtained with the latter system are adequate, but have rather poor contrast, making reproduction difficult. This is important as the records may fade if exposed to light. On the whole, the increased complication of bromide paper recording, despite its delays and risks of spoiled records is preferable in the author's view to the present direct photographic recording systems. Frequencies up to 1,000 cps. can be recorded with suitable galvanometers, making this the only system really suited to the production of permanent phonocardiograms of high quality, and the nature of the light beam makes it possible to use the full width of the recording paper for any parameter measured. It is also possible to increase the sensitivity so that only part of a tracing takes up the full width of the record, making detailed analysis of parts of tracings possible. This type of recording is essential for most units undertaking research, but is time consuming in circumstances where much routine work is done. A satisfactory compromise where circumstances allow is achieved by providing both direct writing for routine work and photographic recording for research.

Oscilloscopes provide the most sensitive records available, having practically no limit to their frequency response and being capable of tremendous amplification. Their main limitation is the problem of providing permanent records of the tracings described by the electron beam on the oscilloscope tube. Photography, either with a conventional camera or a polaroid instrument is useful, e.g. for recording vectorcardiograms, but the use of oscilloscopes is largely in *monitoring* changes to avoid the continuous recording of phenomena of little permanent interest. The most up to date instruments can be supplied so that the record seen on the oscilloscope is precisely that to be recorded on photographic paper. On others with independent amplification in the oscilloscopes, the records may differ in a misleading fashion, e.g. an adequate oscilloscope movement may be present when the amplification on the recording paper is far too small. Mention of vectorcardiography is a reminder of the use of the oscilloscope as a tool for integrating data. By applying data to the X axis and Y axis of the oscilloscope simultaneously, it is possible to record the resultant of two factors, e.g. the vectorcardiogram. Similarly a continuous pressure-flow record can be made to show changes in resistance.

Tape recording provides a convenient method of storing large quantities of data. The commonly available types used for sound recording are not suitable for the low frequencies of the ECG and pressure records, but need frequency modulation circuits which at present make them expensive. The main disadvantage is the mass of data that can be collected. Continuous records of the ECG over several days are easily collected, but not easily analysed, even by a very sophisticated computer. In the field of radiology of the heart, however, the storage of image-intensifier records on video-tape is likely to become standard practice, and to create a minor revolution in technique.

Computer recording is used in this context as a somewhat unsatisfactory name for a promising development in this field of technology. Just as the oscilloscope permits the integration of two variables, so it is possible to use electronic circuits to partially process data before recording them. An obvious example is found in the recording of 'mean' pressure where the application of a long time constant to the recorder results in the obliteration of pressure oscillation so that the record is reduced to a straight line at the mean position. A more advanced example is found in the electronic integration of the area under a curve such as is used in the estimation of cardiac output by dye dilution. Great advances are likely in this field.