Precordial Movements over the Right Ventricle in Normal Children

By Ernest Craig, M.D., and Roland E. Schmidt, M.D.

Physical diagnosis of the heart has improved considerably as a result of the availability of recording technics that enable the observer to check the physical signs with an instrumental record and thus to educate himself. This technic has been particularly successful in the application of phonocardiography to auscultation, but the analysis of the cardiac impulse by palpation has lagged behind. The information to be gained by palpation was recognized by James Hope in his classic text of 1839, and the first attempt at recording precordial motion was made by Chauveau and Marey in 1861, using a pressure sensitive capsule. Later pioneers in this field include Frank, Mackenzie, Wiggers, and Dressler. Renewed interest has followed the development of electronic sensing technics and the opportunity to correlate the record with events observed at cardiac catheterization. A number of investigators have made important contributions; outstanding among these is the work of Hartman and his colleagues in the Netherlands. It is hoped that a more scientific analysis and description of precordial motion will result, in place of the "thrust, heave and tap" to be found in most standard textbooks.

The authors have studied precordial motion in normal children and, in particular, movements at the sternal border where alterations may be expected in congenital cardiac malformations affecting the right ventricle. Studies were made in the pediatric age group for three reasons: (1) no systematic study of precordial motion in normal children is available, (2) the mobile, thin chest wall of children is particularly suitable for graphic studies of low-frequency vibrations in the palpatory range, and (3) comparison of the results of these normal children with the findings in pathologic conditions is made easier by the usual absence of complicating degenerative disease of the heart or lungs.

This paper concerns observations of precordial motion in 60 normal children who served as controls and provide a basis for comparison for certain pathologic conditions affecting the right ventricle to be described in a subsequent communication.

Materials and Methods

Sixty normal children, age 1 to 18, were studied. Their age distribution is given in table 1. There were equal numbers of boys and girls.

All records were taken by one or other of the authors with the help of an assistant. Subjects were studied in the supine position with respira-

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Supported by U. S. Public Health Service Grant 5 T1 HE-5486-02, The Commonwealth Fund, and the Research Grants Committee of the University of North Carolina School of Medicine.)

Circulation, Volume XXXII, August 1965
tion uncontrolled in the younger children. In them, we analyzed those cardiac cycles immediately following expiration when a reasonably steady baseline was achieved. In the older children, records were made during held expiration, although care was taken to avoid a Valsalva maneuver. The transducer was of capacitance type*22 and was held on the chest by a web or rubber strap. Its probe (17 by 6 mm.) projected 4 mm. beyond a light aluminum housing, and the tip of the probe fitted easily between the narrow interspaces of the ribs at the left sternal border. The transducer has a flat response between 0.3 and 150 c.p.s. according to Brecht and Boucke.23 Its time constant is 1.2 sec. when connected via a Beckman AC control box, set at longest available time constant. Under these conditions a flat response was found down to 4 c.p.s. with a loss of voltage of 50 per cent between 4 and 0.5 c.p.s. Its sensitivity is 3 mV per 0.001 mm. excursion of the probe.23 An outward movement of the chest yielded an upward movement on the recording paper. In order to check the ability of the AC system, with its limited time constant, to reproduce accurately the very low frequency vibrations which comprise the palpable precordial movements, it was compared with a direct-current system,† (time constant infinite) in 13 subjects and found to be similar though not identical (fig. 1).

Reference tracings, made simultaneously, included a single lead of the electrocardiogram where the QRS complex was well defined (usually lead II), a phonocardiogram, and, when feasible, an indirect carotid pulse and a respiratory tracing. The paper speed was 100 mm./sec. All curves were monitored on an oscilloscope before the actual permanent tracing was made.

Records of precordial motion were made in the second, third, and fourth left intercostal spaces at the left sternal border, as well as at the apex. Tracings at the apex were taken with the subject in the left lateral decubitus in order to bring the heart nearer the surface of the chest. Apical tracings were recorded with a piezo-electric transducer,‡ since its probe, on the end of a hollow rubber tube, can be more easily moved about by hand on the dependent part of the chest while searching for the optimum location. The current communication, however, concerns the records taken over the right ventricle, and therefore the apexcardiogram will not be further discussed.

Results

The records of precordial motion at the left sternal border in the third and fourth interspaces were remarkably constant and reproducible in this group of normal children. At the second interspace, however, perhaps owing to the greater and more variable distance of the transducer from the heart, the results were not consistent enough to analyze. Of the tracings from the third and fourth interspaces, no differences were found between

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*Infraton D-3 of Brecht and Boucke, distributed in U.S.A. by Beckman Instruments Inc., Palo Alto, California.
†This modification was constructed by Dr. William E. Thornton. It permitted the measurement of capacitative change in the Infraton transducer by means of a bridge and carrier amplifier.
‡Of the several types of piezo-electric transducers that were tried, the Pulse Microphone of Fritz Hellige & Company, Freiburg, proved to be the most satisfactory.
Figure 2
Displacement record of a normal 12-year-old boy. From above downward (1) carotid pulsation, (2) phonocardiogram in the pulmonary area, (3) displacement record of precordial movement in the fourth left intercostal space, and (4) electrocardiogram, lead II. a represents atrial systole. OM, outward movement associated with right ventricular systole with the area of outward movement shaded; duration of the OM is 0.15 sec. O, outward movement. I, inward movement. To, tricuspid opening. a2 and p2, elements of the second sound.

the infants and older children or between the tracings of boys and girls.

The normal record consists of three phases related to atrial and ventricular activity (fig. 2): (1) An atrial wave beginning approximately 0.06 sec. after the onset of the P wave was noted in 35 of the 60 subjects. It was low and rounded in configuration and was believed to be due to ventricular filling resulting from atrial systole.24 Its inconspicuousness in normal subjects is in contrast to its exaggerated appearance in certain pathologic conditions characterized by interference with filling of the ventricle. (2) The onset of ventricular systole was marked by a sudden outward movement (OM) beginning 0.02 to 0.04 sec. (mean 0.03 sec.) after onset of the Q wave. This period of 0.03 sec. represents the electromechanical interval or time between onset of electrical activity and first evidence of mechanical contraction of the ventricle. The onset of ventricular systole, manifest by the sudden outward movement, in turn, preceded the first sound by 0.02 to 0.03 sec. The mean Q-1 time in this series was 0.52 sec. The outward movement at the beginning of ventricular systole in normal subjects was brief in duration, often notched by the time of the major elements of the first sound, and it declined rapidly at approximately the time of onset of right ventricular ejection. A nadir was reached usually by mid-systole, followed by a variable configuration in late systole, and further sharp notches at the time of the second sound. (3) Diastole. The interval from the pulmonary component of the second sound to a dip representing tricuspid opening had a range of 0.03 to 0.08 sec. (mean 0.053 sec.). Immediately following, there was an outward movement associated with filling of the right ventricle. It did not have the briskness of the rapid filling wave seen in the left ventricular apexcardiogram and it merged imperceptibly with further variable undulations during diastasis.

To characterize the curve representing ventricular systole in a more objective fashion for subsequent comparison with abnormal subjects three criteria were adopted (fig. 2).

1. Duration of outward movement (OM). An arbitrary baseline was drawn horizontally from the end of the electromechanical interval across the base of the OM. Its length represented the duration of the OM. Usually no difficulty was encountered in finding the sudden change in direction of the curve which marked the onset of ventricular systole, but occasionally in normal, and not infrequently in abnormal subjects, the waning portion of the "a" wave merged with the OM. Even in these instances, however, locating the onset of the OM was not difficult. The duration of the OM was brief, having a mean duration of 0.107 sec. in the third, and an identical mean duration in the fourth interspace. The range was 0.00 to 0.25 sec. with only two exceptions among the 60 subjects. In them, the prolongation was noted in only one of the two interspaces under anal-
ysis and reached a maximum of 0.34 sec.

2. Ratio of outward to inward movement. Although duration of certain phases of the cardiac cycle can be accurately measured by studies of precordial motion, amplitude of pulsation cannot. The uncertain contribution of thickness of the chest wall and lung make for variations in amplitude which may be misleading. Therefore, it has been found convenient to measure the height or depth of outward and inward movements in relative terms.12, 13

A ratio of outward movement to inward movement (O/I) was calculated for the third and fourth interspace locations (fig. 2). Height of OM was measured from the baseline at the end of the electromechanical interval to the peak achieved in early systole. Inward movement was measured as the extent of inward retraction from the peak of OM to the lowest point reached prior to the aortic component of the second sound. This point was chosen rather than the pulmonary component because the latter could not be clearly seen in some of the abnormal subjects.

Outward movement was less than inward movement, giving a ratio less than 1.0 in all except two instances. The mean ratio was 0.47 in the third and 0.39 in the fourth interspace. The two exceptions showed a ratio of O/I above 1.0 in only one of the two interspaces analyzed.

3. The area under the OM, a function of its height and duration, was found to be small. Again, for reasons mentioned above, the area of the OM is expressed as a ratio or Area Index (fig. 3). This ratio gives one an index of the height and duration of the OM relative to the depth and duration of retraction during systole. It was found to be less than 1.0 in all except three instances. In these exceptions, the index was greater than 1.0 in only one of the two interspaces studied.

The shape of the downward curve which followed the peak of the OM was found to be concave in all except one subject.

In summary, these three criteria are all expressions of the brevity and low amplitude of the OM which is confined to early systole in records taken over the right ventricle in normal children.

Discussion

The subject of precordial pulsations is confused by the variations in technics of recording that lead to a variety of curves, all purporting to represent vibrations related to cardiac activity. It is important, therefore, to state what is being recorded. The vibrations emanating from the heart are modified and diminished in intensity as they pass through overlying structures to the surface of the chest. Here they present a spectrum of frequencies, some of which are in the audible range and are appreciated with the stethoscope. Some are lower and may, if strong enough, be perceived by palpation. Since the amplitude of these vibrations diminishes greatly with increasing frequency,25 there is relatively enormous energy in the very low frequency portion

Figure 3
Displacement record of a normal child at the fourth left intercostal space to illustrate calculation of the area index. The area of OM (cross-hatched) is small in comparison to the area representing retraction during systole (stippled). The ratio of the OM to the area of retraction is 0.11—the area index. a2, aortic component of second sound. p2, pulmonary component of second sound. To, tricuspid opening.
of the spectrum. The ear selectively discriminates, thus permitting one to appreciate faint, high-frequency sounds and murmurs that would otherwise be blotted out by the more powerful low-frequency vibrations. Transducers used in studies of vibratory phenomena vary in their ability to respond to vibrations of low or high frequency, and further discrimination can be obtained by means of filters. An adequate sensitivity in the lowest frequency range is necessary to obtain an undistorted displacement tracing.26 Our transducer, when connected with its Beckman AC control box, had a moderate fall in response below 4 c.p.s. This did not result, however, in serious alteration in configuration of the tracings as shown in comparative studies with a DC system (fig. 1). No filtering is required, since the energy of the extremely low frequency vibrations effectively dominates the resulting tracing. A system of filters emphasizing the slightly higher range of 5 to 25 c.p.s., such as that employed by Rosa, yields useful curves but of a completely different configuration and for different purposes.9

To achieve an adequate representation of ultra-low frequency vibrations, the transducer-recording system must have a time constant (TC) of adequate length.28 With too short a TC, either at the level of the transducer, control box, recorder, or connections, tracings of a sustained pressure are distorted by rapid decay. Thus the plateau, which should represent graphically a sustained thrust at the precordium, would appear as a peak with rapid decline and exaggerated negative phase. For ideal recordings of systolic pressure waves of duration 0.3 sec., a TC of 10 times this duration might be sought.28 Some of the most widely used commercially available transducers, however, have a TC of only 0.3 sec., thus producing serious distortions in the duration and configuration of important features of the apexcardiograms in published papers. Our records were made with a TC of 1.2 sec. which is probably shorter than ideal. That this TC was satisfactory for our purposes, however, was demonstrated by comparison of companion tracings made with DC circuitry having a TC of infinity (fig. 1). Although theoretically superior, the DC method was not adopted for routine use, since it is technically slightly more difficult to use in the younger subjects whose breathing cannot be controlled. Furthermore, we preferred to use a system that is commercially available.

Further confusion is added by methods that do not measure displacement, but rather rate of displacement (velocity) or rate of change of velocity (acceleration). We have preferred to concentrate on a method measuring insofar as possible displacement rather than the two types of differentiated curves. Displacement records in the very low frequency range probably represent most closely the movements appreciated by palpation.

Another source of difference in published reports on precordial motion is the method of applying the transducer to the chest wall. The method of holding the probe rigid from an overhanging bar or stand10, 14 has the advantage that absolute movements of the chest wall are recorded with reference to a fixed point in space. Where the transducer is held by a web or rubber strap, as in our method, a record is obtained of the difference between the movement of the probe and the far smaller movement of its housing which is firmly pressed against the ribs. Theoretically, where the whole chest moves in a heaving manner, this method would fail to represent the movement adequately and falls short of being a true displacement record. In comparative studies, however, we have not found that this is a serious problem. As a practical matter, in children, where one cannot control respiration, the suspension of the transducer on a rigid bar is unsatisfactory, since the gross movements of respiration completely dominate the resulting record.

In brief then, as regards technic, for comparable tracings to be obtained in different laboratories, investigators should use transducers that are adequate in their frequency response to pick up the vibrations under study, and the system of filtering (or absence of filtering) must be known, as well as the time constant. It must be made clear whether a
study is being made of displacement, or velocity, or acceleration. Finally, and of somewhat less importance, is the manner in which the transducer is applied to the chest.

The interpretation of the graphic records is very complicated. The records no doubt reflect the heart beat, but the relative contributions of volume and pressure changes, thrusts, recoil, and torsion are difficult to assess. The overlying lung and chest wall modify and diminish the curves and there are further alterations depending on technical aspects of the transducer-recording system. Analysis of simultaneous reference curves, however, including the indirect carotid pulse, phonocardiogram, electrocardiogram and, in abnormal subjects frequently, the intracardiac pressure pulses, enable tentative conclusions to be drawn about the genesis of the various features of the tracings.

The "a" wave that follows the onset of the P wave of the electrocardiogram by about 0.06 sec. probably represents filling of the ventricle with atrial systole.\(^{20, 25}\) It is absent in atrial fibrillation and follows the P waves in complete heart block. It is exaggerated in certain conditions characterized by altered compliance of the ventricle, or powerful contractions of the right atrium. A large "a" wave is often accompanied by an atrial sound, since it is merely the palpable component of a spectrum of low-frequency vibrations some of which are in the audible range.

The ventricular complex begins approximately 0.03 sec. after the onset of the QRS. No doubt there is some contraction of individual muscle fibers before the gross movement that marks the end of the electromechanical interval. This outward movement preceded the upward stroke of right ventricular systole in simultaneous intracardiac pressure pulses in a number of abnormal subjects who were studied at catheterization. In them, the pressure pulse began its rapid upward movement at an average time of 0.06 sec. following the onset of Q. Even allowing for a catheter transmission time of 10 msec., it is apparent that the OM precedes the onset of the right intraventricular pressure pulse by approximately 20 msec.

The quickly rising outward movement reached a peak coinciding approximately with the onset of ejection from the right ventricle and was followed by a rapid decline.

The curves of precordial motion over the right ventricle in normal subjects are, no doubt, profoundly influenced by pulsations of the underlying, more powerful left ventricle. The low-frequency contribution of the ventricles (principally the left) to the whole surface of the precordium has been called the "basic pattern" by Lohr.\(^{27}\) It is positive during systole at the apex with the subject in the left lateral decubitus and inverted, in complete mirror image, medial to this point. At the left sternal border, however, a smaller early systolic thrust of right ventricular origin is seen. Evidence that curves at the sternal border are not merely inverted images of the apex tracing, but are influenced by right ventricular emptying and filling as well, is afforded by the trough at the time of tricuspid opening and the outward moving filling wave immediately following.\(^{29}\)

The diminished intensity of the "basic pattern" at the left sternal border and the relative weakness of the right ventricular contribution result usually in the necessity of turning up the amplitude of the recording apparatus. Thus the sharp notches, which are infrasonic counterparts of the heart sounds, become comparatively prominent in records taken over the right ventricle.\(^{27}\)

Interesting data from animal studies by Anzola\(^{28}\) (fig. 4) throw additional light on the possible genesis of the precordial curves over the right ventricle. In his experiments, dimensional gauges were fastened to dogs' hearts and recordings were made with the chest closed. Normally, a prominent upward deflection was noted following the R wave of the electrocardiogram. This movement, representing expansion of the ventricle at onset of systole, corresponded to a change in shape of the right ventricular cavity without a change in its volume. This early systolic spike, (I.S.E. in fig. 4) was abruptly terminated at onset of ejection, at which point there was a sharp
downward deflection. The shape of these curves of right ventricular dimensions resembles very closely those obtained over the surface of the chest in our normal subjects. Anzola attributed the initial spike to early contraction of papillary muscles, drawing the tricuspid valves down into the chamber, associated with a simultaneous assumption of a spherical shape by the left ventricular cavity with bulging of the interventricular septum into the right ventricular cavity and outward displacement of the wall of the right ventricle. The subsequent sharp decline occurred with ejection of blood and loss of volume from the right ventricle. In early diastole a trough was noted at the time of opening of the atrioventricular valves followed by a rapid filling wave (1, fig. 4) and a slow filling wave (2, fig. 4).

The effect of increasing age on the configuration of precordial records has been investigated by Coleman et al., using the technic of kinetocardiography of Eddleman. Although the method differs from ours in some respects, the curves obtained over the right ventricle are quite similar. The “right parasternal upstroke” at the onset of right ventricular contraction is attributed to closure and bulging of the tricuspid leaflets. Its pattern is similar to the OM noted in our records and to the “initial systolic expansion” described by Anzola. It is of interest that Coleman et al. noted a progressive decline in motions attributed to right ventricular activity with increasing age—a fact that probably explains the lack of attention paid to curves from the right ventricle in many of the studies of apexcardiography dealing primarily with adult subjects.

The measurements of duration and relative height and the configuration of the OM just described were selected to give some objective criteria for the normal precordial pulsation over the right ventricle in children. The measurements of duration and relative height of the OM are similar to those introduced by Eddleman. Insofar as possible, one would like to employ existing criteria, so that comparisons can be made between studies in different laboratories. The brief duration of the OM and its relatively low amplitude with respect to the depth of the systolic retraction in our normal subjects are similar to the results of Eddleman. Our studies, however, are not altogether comparable owing to differences in technic, apparatus, and age of subjects. The criteria for defining the systolic movement disclosed a striking uniformity among the curves of normal children and a useful basis for comparison with abnormal situations characterized by increased pressure in the right ventricle owing to outflow obstruction.

The pattern of the curves of precordial motion in early diastole reflects the effects of tricuspid opening and filling of the right ventricle. As in the case of the systolic movements, it is impossible to separate altogether
the effects of left ventricular activity. Nevertheless, the fact that there is a trough at the time of tricuspid opening followed by an outward movement is consistent with the supposition that we are observing the effects of right ventricular filling rather than merely the inverse mirror image of left ventricular activity as seen at the apex. The trough of tricuspid opening is located 0.03 to 0.08 sec. (mean 0.053 sec.) after P2. This point corresponds with the apex of the V wave in the jugular venous pulse, which has been found in a series of normal subjects to be 0.056 sec. after P2 by Kesteloot and Joosens.33 The measurement of the interval between P2 and the trough representing tricuspid opening may be of some value, since it has been found by Hartman20 to be prolonged in pulmonary hypertension owing to a lengthening of isometric relaxation.

The definition of the range of normal ultra-low frequency records of displacement over the right ventricle may be of value for several reasons: (1) timing of events of the cardiac cycle, particularly where pulsatory tracings are taken in conjunction with other reference tracings; (2) assessment of the range of normal on palpation with improvement to be expected in technic of this aspect of the physical examination in much the same fashion as auscultation is improved by phonocardiography; (3) comparison with abnormal curves obtained in conditions of right ventricular overload. Here, the inexpensive and nontraumatic aspects of the method are advantageous.

The limitations of the method should also be listed and include the following: (1) the results are largely nonspecific and empirical; (2) great care and experience are required in order to obtain accurate and reproducible curves; (3) unless the equipment is capable of sensing and recording displacement curves in the ultra-low frequency range, misleading artifacts may be encountered; (4) much work has to be done to standardize and make comparable the results from different laboratories. Mackenzie summarized the situation in 1925 by saying "The whole subject of cardiography is in need of thorough and pains-taking review." This is still true.

Summary and Conclusions

1. Sixty normal children were studied by means of ultra-low frequency displacement records from the chest wall over the right ventricle, in conjunction with other reference tracings.

2. The record of normal children in this location is characterized by (a) an inconstant and small movement associated with atrial systole; (b) a brief outward movement beginning 0.03 sec. after Q and of only moderate height with respect to the subsequent inward movement which begins at approximately the onset of right ventricular ejection; (c) quick vibrations at the time of the elements of the second sound followed by a trough marking tricuspid opening and an outward movement representing filling of the right ventricle.

3. Criteria for measuring the outward movement are described: (a) duration of outward movement is less than 0.25 sec.; (b) ratio of outward to inward movement is less than 1.0; (c) the area under the outward movement is small relative to the area of the curve representing systolic retraction; (d) the falling slope of the outward movement is concave.

4. The possible genesis of the main features of the displacement record are discussed.

5. Ultra-low frequency displacement records over the right ventricle in normal children are useful in timing events of the cardiac cycle, in improvement of palpation by means of graphic records, and as a basis for comparison with abnormal records in conditions of right ventricular overload.

6. The limitations of the method are given.

Acknowledgment

We are indebted to Dr. A. Leatham and Mr. G. Davies and the staff of the Cardiac Laboratory of St. George's Hospital for help and advice as well as for providing the physiologic and angiocardiographic studies on many of the patients. Dr. H. A. Lohr and Mr. E. van Vollenhoven of Utrecht provided many valuable suggestions, and we are grateful to the Institute of Medical Physics of Utrecht for testing the frequency characteristics of our transducer. Additional help was provided by Dr. H. Harned and Dr. W. E.
Thornton of North Carolina Memorial Hospital and Dr. Jack Fleming of Pensacola, Florida.

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Circulation, Volume XXXII, August 1965
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Circulation. 1965;32:232-240
doi: 10.1161/01.CIR.32.2.232
Circulation is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231
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Print ISSN: 0009-7322. Online ISSN: 1524-4539

The online version of this article, along with updated information and services, is located on the World Wide Web at:
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