Numerical Indication of Indirect Systolic and Diastolic Blood Pressures, Heart and Respiratory Rate

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When Wunderlich1 in 1868 published his paper describing the variations of body temperature in disease, he virtually established the clinical charting of vital signs. In 1903, Harvey Cushing2 advocated the addition of blood pressure measurements to the chart. Two years later when Korotkoff3 described the auscultatory technique for measurement of blood pressure, a reliable method became available for clinical use. Cushing noted that while the clinical charts of that era usually indicated the pulse rate, they rarely included respiratory rate. Since Cushing’s time, measurement of the vital signs has become a standard procedure in hospitals. The wealth of technology presently available has aroused interest in the development of devices which automatically measure vital signs. Although many so-called patient monitors have been developed, few present the data in numerical form, the method of presentation acceptable to the largest number of persons. This paper describes an operating system which automatically measures indirect blood pressure, heart and respiratory rates and displays the magnitude of these events numerically. The monitoring equipment also transmits these events by wire to a magnetic tape recorder and several recording areas within and without the hospital.

At the start of the instrument development program it was recognized that the numerical values for the vital signs indicated by the monitoring system ought to correspond with those determined manually. This required that the measurements be made according to the criteria established in clinical practice.

This imposed no particular limitations in the determination of heart and respiratory rates, but required that blood pressure be determined by the auscultatory method. Because the acquisition system was destined for monitoring critically ill patients, other important considerations included minimum inconvenience to the patient and minimum interference with routine nursing procedures.

Blood Pressure

Of all of the vital signs, blood pressure has been the most difficult measurement to automate. Various devices have been described which measure indirect blood pressure.4–14 In nearly all of the instruments described to date, there have been difficulties in distinguishing the Korotkoff sounds from spurious noise. The addition of filtering circuits to accept only the harmonic spectrum of the Korotkoff sounds reduces the chance of reading noise as meaningful sounds. However, this technique alone does not at all times satisfy the needs of all measurement situations. When an observer listens to the arterial sounds, he not only accomplishes filtering by “tuning” his ears to the frequency of the expected sounds, but, in addition, he expects their rhythmic appearance with each beat of the heart and thus disregards sounds that appear at an inappropriate time. The same technique can be applied electronically by incorporating an interrogation circuit to control the time-of-inquiry for the presence of the sounds. Thus noise occurring at an inappropriate time will not be interpreted as Korotkoff sounds. Because the R wave of the electrocardiogram must always occur well in advance of the auscultatory sounds, it can serve as an interrogating signal to open a gate for a predetermined time to allow a computing circuit to read the cuff pressure at the appearance of the first or systolic sound and at the disapp-
The appearance of the sounds which signals diastolic pressure.

The method of measuring blood pressure by the auscultatory method can best be described by reference to figure 1 in which are displayed with a rapid paper speed the electrocardiogram, arterial pulse, and cuff pressure, with Korotkoff sounds superimposed. The auscultatory sounds were recorded from the left arm and the arterial pulse from the same area on the right arm. As the cuff was rapidly deflated from 200 mm. of mercury, the first Korotkoff sound appeared, signalling systolic pressure. In this subject the systolic sound appeared 300 msec. after the peak of the R wave. As this cuff pressure continued to decrease, the delay between the auscultatory sounds and the R wave decreased. The last Korotkoff sound before silence appeared 170 msec. after the peak of the R wave. The interval between the R wave and the earliest and latest sounds indicates the time for the arterial pulse to rise from slightly above diastolic to systolic pressure. The interval between the peak of the R wave and the appearance of the Korotkoff sounds is a composite of several times, the spread of excitation over the heart, the time for the development of mechanical energy by the myocardial fibers, the isometric period and the pulse transmission time from the left ventricle to the compressed artery under the cuff and the time of the sound on the rising phase of the pulse. This total interval varies with heart rate, size of the subject and the pulse wave velocity. In the subjects studied thus far, the appearance times encountered have varied between 75 and 300 msec. This time defines the “gate-open” time for the interrogation circuit. Sounds occurring outside this time will not be detected as arterial sounds.

The system which employs the electrocardiogram and Korotkoff sounds to determine blood pressure as described above is shown in figure 2. The ECG, detected by transthoracic leads, is amplified and remotely displayed by a graphic recorder. The Korotkoff sounds are detected by a piezo crystal element applied directly to the skin over the brachial artery distal to the biceps muscle and under the lower edge of the occluding cuff. The cuff pressure and arterial sounds are fed into a mixer. The output of this device is remotely displayed by a graphic recorder which produces a record similar to that shown in figure 1.

The cuff is inflated by a manually-initiated or time-programmed cuff-pump which quickly pressurizes the cuff to 200 mm. of mercury, then linearly decreases the pressure to 20 mm. of mercury in 30 seconds, then exhausts the cuff rapidly. At the end of this cycle, it short-circuits the output of the amplifier driving the pen recording the cuff pressure and auscultatory sounds. Thus, when no determination of blood pressure is made, the channel is silent.

The blood pressure computer, shown third from the bottom in the left of figure 2, is
diagrammed in figure 3. For simplicity of explanation, relay contacts are shown in place of solid-state logic circuits which are actually employed. The operation of the computer can best be understood by starting with the cuff inflated (200 mm. of mercury) and the logic circuits reset in the "program start" position as shown in figure 3. As the cuff pressure falls, processed R waves energize the R relay for 300 msec. When the first Korotkoff

**Fig. 2.** Block diagram of acquisition and display system.

**Fig. 3.** Schematic of blood pressure computer.
sound appears within this interval, it energizes the K relay and allows the + voltage supply to pass through all of the upper relay contacts and gain access to the clamp on one of the milliammeters tracking cuff pressure, arresting the pointer and illuminating the scale to display a systolic pressure. At the same time the reset relay A is activated preventing further access to the systolic meter.

As the cuff pressure continues to decay, the processed R wave and K sound energize the R and K relays. Each time then two events occur, the diastolic meter is not clamped because a 1.2 second delay circuit is interposed between it and the + supply. With each R wave and K sound, the delay is reset for another 1.2 seconds. When an R wave occurs without a following K sound the delay is not reset and the time elapses, causing the second meter to be clamped to read diastolic pressure. Thus diastolic pressure is read in the silent period 1.2 seconds after the last coincidence of an R wave and a K sound. With a cuff deflation rate of 200 to 20 mm. of mercury in 30 seconds diastolic pressure is read no more than 6 mm. of mercury below the last Korotkoff sound.

Correlation of the readings obtained with the criteria adopted and those which are obtained with the procedure advocated by two committees on standardization of blood pressure readings15-16 can be estimated by examination of their recommendations. They advocated a cuff deflation rate of 2-3 mm. of mercury per heart beat and decided that the occurrence of the first regularly heard sound signals systolic pressure. For diastolic pressure they stated that “it appears that the point of complete cessation (of sound) is the best index of diastolic pressure.” Under these conditions, the systolic pressure in the brachial artery is on the average of 3-4 mm. of mercury too low and show a scatter of ±8 mm. of mercury. If for diastolic pressure the point of muffling is chosen for reading the cuff pressure, the pressure read is 8 mm. of mercury too high. For this reason they recommended the silent phase.

The deflation rate chosen in this investigation is a compromise to minimize the time of occlusion of the arm and coincides with the recommended deflation rate for a cardiac frequency of 120 beats per minute, the range encountered in the patients on whom this device is employed. Thus it is slightly fast for a normal cardiac rate and slightly slow for the high heart rates found in some subjects. A rapid exhaust at 20 mm. of mercury was also adopted to minimize venous congestion and discomfort in the subject.

The readings obtained with the blood pressure computer can be compared with those determined by use of the standard procedure recommended by the committees by reference to the following table. No difference in readings is obtained for systolic pressure, the criteria being the same except for small variations due to heart rate. The diastolic pressure differences to be encountered are as follows:

<table>
<thead>
<tr>
<th>Heart Rate Per Minute</th>
<th>Recommended 3 mm. Hg/Beat</th>
<th>Differences in mm. Hg Indicated by BP Computer</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>3.6</td>
<td>-3.6</td>
</tr>
<tr>
<td>120</td>
<td>1.5</td>
<td>-5.7</td>
</tr>
<tr>
<td>200</td>
<td>1.0</td>
<td>-6.2</td>
</tr>
</tbody>
</table>

With experience accumulated to date with use of the blood pressure computer described here, certain improvements have suggested themselves. One is reducing the interrogation time by delaying the opening of the gate which will further improve the rejection of unwanted noise. It is possible to add this feature because a finite time must elapse between the R wave and the appearance of the earliest Korotkoff sound in the smallest subject with the highest pulse wave velocity. Another improvement in the same direction, now being evaluated, is the incorporation of an automatic control for the duration of the interrogation gate to shorten its period with an increase in heart rate.

**Heart Rate**

Cardiac frequency can be determined from a variety of sensors which detect some epi- phenomenon of cardiac action. A peripheral pulse detector and the electrocardiograph are...
Fig. 4. Typical recording of the ECG, respiration and indirect blood pressure.

the devices most frequently employed. Because the ECG signal was employed for the blood pressure computer, it was already available, and was therefore used for the determination of heart rate.

When the electrocardiogram is used to determine heart rate, the R wave is usually chosen as the indicator of each beat. It is to be noted that the ECG does not indicate the force of ventricular ejection and, in many of the arrhythmias, the productive beats are less numerous than the number of R waves.

Although the locations for electrodes in clinical electrocardiography are standardized, for monitoring purposes it is more advantageous to place the electrodes in nonstandard locations to derive the largest and most artifact-free signal. One location favored by the authors is the manubrium-xiphoïd (MX) configuration. With one electrode at either end of the sternum, a large amplitude signal is recordable in most subjects. Because there is little muscle mass between the electrodes it is possible to obtain clean recordings while the subject moves. The other location favored for monitoring is the transchest array shown in figure 2 because it is possible to obtain a clean ECG and respiration from the same electrodes.

The ECG signals detected from transchest electrodes are amplified, fed into the blood pressure computer, transmitted to remote recorders and led into and processed by the cardiotachometer shown in the center of figure 2. The scale on this unit indicates average heart rate. Processing by this device involves first the electronic removal of the P and T waves with a high-pass filter. The remaining signal, largely the R wave, is then passed through a threshold circuit which amplifies the processed R waves above a predetermined level to prevent the chance of counting spurious noise as heart beats. The derived R waves are then converted to square pulses and counted by an average rate-indicating meter.

Respiratory Rate

Respiratory frequency with an indication of the amplitude of each breath can be obtained from the signals produced by transducers placed directly in the air stream or by devices which measure changes in chest circumference. All of these devices involve some restraint of the subject, and because trans-chest ECG electrodes were employed, it was advantageous to use them for simultaneous measurement of respiration by the impedance method. With this technique, a small 50 kilocycle per second current is passed through the electrodes. With respiration the magnitude of the current is modulated. The varying current is amplified and rectified to produce a varying voltage proportional to the depth of each breath. The impedance pneumograph illustrated in figure 2 supplies the current, detects its changes with respiration and produces a recordable signal, which is also transmitted to remote recorders and forwarded to the respiratory tachometer shown in the lower part of figure 2. The tachom-
eter processes each breath by first admitting only those which wash out the dead space. Each breath above this level is compressed to a signal of the same amplitude. This signal is then squared, differentiated and fed to a totalizing circuit which counts the number of breaths in one minute and holds this reading for one minute. It then clears the reading and starts another cycle. An example of the type of respiratory signal produced by the impedance pneumograph is shown in figure 4, channel 2. In this illustration, inspiration is signalled by an upward deflection of the recording stylus; expiration by a downward movement.

The instrumentation described in this paper has been under development and use for two years. To date a total of 870 hours of monitoring experience has been accumulated with the equipment as described, with the exception of the blood pressure computer which has recently been added.

The type of data transmitted to the tape recorder and remote stations is shown in figure 4. In this illustration are displayed the ECG, respiration and indirect blood pressure. To make this figure, the cuff pump was repeatedly cycled to illustrate the constancy of the blood pressure readings. In practice blood pressure readings are made less frequently.

Summary

A monitoring system which indicates the numerical value of heart rate, respiratory rate and indirect systolic and diastolic blood pressure is described. The ECG is employed for determination of heart rate and the impedance pneumograph for respiratory rate. Blood pressure is determined by the auscultatory method using a small computer which employs the ECG R wave as an interrogating pulse to control the time-of-inquiry for the Korotkoff sounds.

References