TECHNICAL NOTES

Performance Characteristics of a Commercial ECG Gate

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A commercial ECG gate was tested to evaluate its ability to predict accurately the time of end-systole. The predicted times followed the manufacturer's specifications quite well. These times were compared with the actual times of end-systole as determined by computer-derived left-ventricular time-activity curves using Tc-99m-labeled red blood cells. Although there was moderate scatter, the predicted times of end-systole correlated well with the actual times (n = 59, r = 0.829). If the left-ventricular ejection fraction was calculated using the predicted time of end-systole, the error would be 0.03, or less, for 95% of the subjects.

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Electrocardiographic gating or synchronization of scintillation-camera data with the cardiac cycle is useful both for removing motion artifact and for quantitation of the degree of motion during cardiac contraction. Elaborate systems usually use an R-wave pulse to sequence a series of images, using a computer or other storage device. The least complex system is an electronic ECG gate that defines end-diastole and end-systole and unblanks the camera's oscilloscope only during these phases of the cardiac cycle (*1*). Generally the operator can select the timing of the diastolic or systolic windows, or can set the device to function in an automatic selection mode. The clinical usefulness of an ECG gate is dependent upon its ability to predict accurately the timing of mechanical end-diastole and systole from the ECG signal. While several ECG gating devices are widely used and considered accurate, no data are available regarding the accuracy of these devices over the range of heart rates encountered in clinical practice.

We have studied two ECG gates from a single manufacturer* to determine whether clinical performance meets operating specifications and whether the operating specifications coincide with the scintigraphic timing of cardiac systole. We also measured the change in ejection fraction that would occur if it were determined with an ECG gate, compared with the more sophisticated computerized collection technique.

MATERIALS AND METHODS

Two ECG gates were tested. Using directions supplied by the manufacturer, one was modified to accept heart rates up to 300/min. The other instrument was unmodified.

First, the response of each instrument to a range of R-R intervals was determined using a pulse generator to provide the QRS pulse and an electronic counter to measure the intervals. In addition, the accuracy of the timing marks on the ECG recording strips was determined by comparison with the electronic counter's results.

Thirty-six studies were selected from 29 patients who had undergone resting ejection-fraction measurements between January and October, 1978. Selection was based on the presence of a clearly legible ECG recording showing the end-diastolic and end-systolic windows, presence of normal sinus rhythm with less than 5% premature beats, and a high-quality, computer-generated, left-ventricular time-activity curve. All patients had a QRS duration less than 0.08 sec, except for one patient with right bundle-branch block and left anterior hemiblock. Many of the patients were taking propranolol.

Twenty-three additional studies were selected from eight of the above patients, covering each stage of graded supine exercise to a symptom-limited maximum. Overall, there were 59 studies in which the timing of end-systole, as defined by the ECG gate, could be compared with end-systole defined by the time-activity curves. The ECG-gate time of end-systole, defined as the time from R-wave to the mid-point of a 40-msec systolic window, was measured from the ECG tracing provided by the ECG gate. For both heart rate and time to end-systole, six to ten consecutive cycles were averaged.

Left-ventricular time-activity curves were generated using this laboratory's ECG-synchronized blood-pool imaging techniques as previously described (*2*). The framing rate used was 25/sec, resulting in 40-msec frames. To optimize the determination of the timing of end-systole, the six or seven minimum points of the time-activity curve were fitted with a parabola using the least-mean-squares technique. The minimum point was then taken as the time of end-systole.

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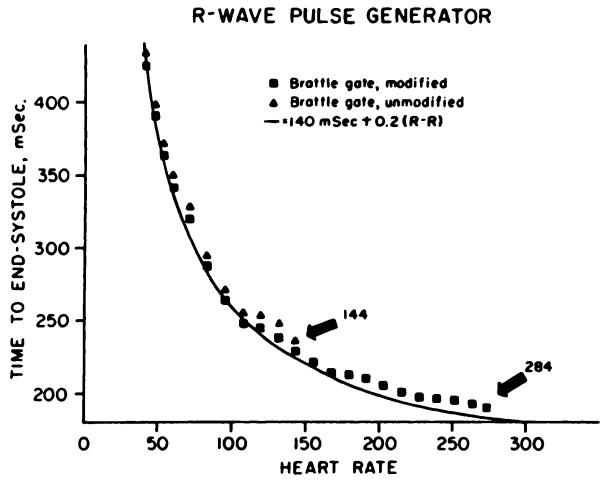

FIG. 1. Automatic predictions of time to end-systole from two Brattle Instrument Corporation ECG gates for several different pulse rates, using an electronic pulse generator. Solid line is manufacturer's published response curve for these instruments. Unmodified instrument would not trigger above pulse rate of 144/min. Instrument modified for performance at higher heart rates triggered accurately up to 284 pulses/min.

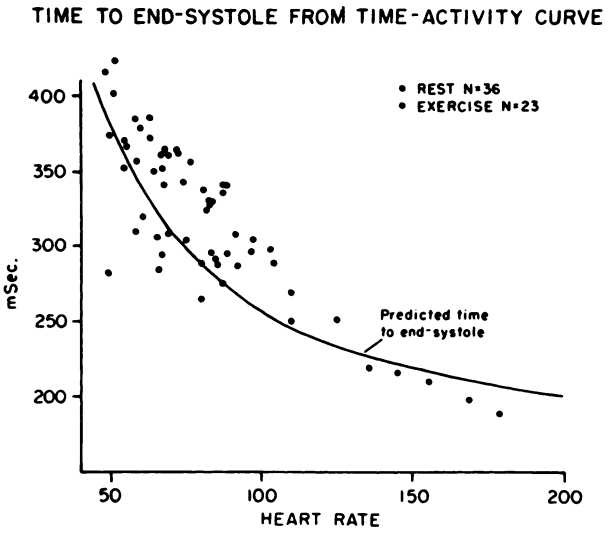

FIG. 3. Calculated times to end-systole from computer-derived left-ventricle time-activity curves. Thirty-six determinations were made with patients at rest and 23 during exercise. Solid line is manufacturer's published response curve for the ECG gate.

RESULTS

The ECG gates tested are so designed that the time to end-systole (TES) is based on the length of the previous R-R interval according to the following formula:

$$TES = 140 + 0.20\,(R\text{-}R \text{ interval}) \text{ msec} \qquad (1)$$

This relationship of TES to heart rate is shown in Fig. 1, along with the actual measured responses of the two gating devices to a known electronic pulse rate. Both gates fall close to that predicted by the above formula and thus function quite well in this regard. Note that the unmodified gate fails to function above a rate of 144/min, whereas the modified gate functions up to 284/min.

Figure 2 shows the relationship between TES predicted by Eq. 1 and that actually measured from the gate's ECG recording strip in 29 patients. Again, the TES selected by the gate falls very close to that predicted by the formula, with slightly more scatter than was noted with the electronic pulse generator (Fig. 1).

Figure 3 compares the TES predicted by Eq. 1 with the TES measured from the computer-generated time-volume curves. Considerable scatter is noted, and it is clear that in some instances Eq. 1 does not predict the TES accurately. The regression equation for the data in Fig. 3 is:

$$TES = 167 + 0.190(RR) \quad R = 0.800 \quad S.E.E. = 32.0$$

Figure 4 shows the relationship between TES derived from the time-volume curve and that selected by the ECG gate. Again there is considerable scatter. The regression equation for the data in Fig. 4 is:

$$B = 82 + 0.68(TA) \quad R = 0.829 \quad S.E.E. = 24.6,$$

where B is the time of end-systole (msec) determined by the Brattle gate, and TA is the time of end-systole (msec) determined from the time-activity curve.

If the ECG gate's time to end-systole were used in the calculation of ejection fraction instead of the actual time to end-systole determined by the computer, an error would be made in the estimation of ejection fraction. This calculation was made for each determination using the parabola that best fitted the computer-derived time-activity curves. Either an increase or decrease in time to end-systole results in a decrease in apparent ejection fraction. The distribution of the changes in ejection fraction is shown in Fig. 5. Ninety-five percent of the changes in ejection fraction are less than 0.03. One patient showed a decrease in ejection fraction of 0.082, but the average patient showed a decrease of only 0.01.

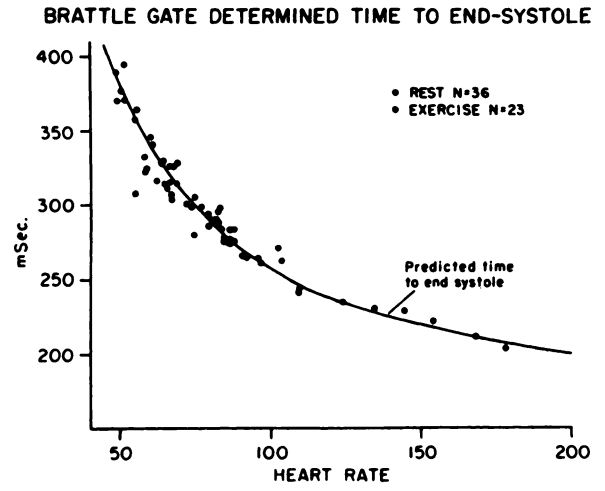

FIG. 2. Automatic predictions of time to end-systole from Brattle Instrument Corporation ECG gate using actual ECGs from 29 patients. Thirty-six determinations were made when patients were at rest, and 23 while they were exercising. Solid line is manufacturer's published response curve for this instrument.

DISCUSSION

The two ECG gates investigated function as described by the manufacturer. The timing marks on the paper strips accurately reflect the actual timing of the electronic end-diastolic and end-systolic pulses, and the timing of the end-systolic pulses follows the curve described by the manufacturer. The unmodified instrument performed well up to 144 pulses/min. Above that rate, the timing became very irregular and the output pulse sporadic.

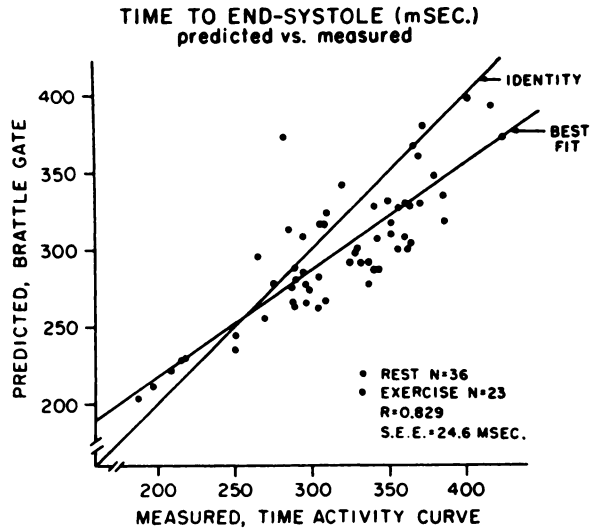

FIG. 4. Comparison between ECG gate's automatic predictions of time to end-systole and actual times to end-systole as calculated from computer-derived left-ventricular time-activity curves. Line of identity and linear least-mean-square error fit of data are shown.

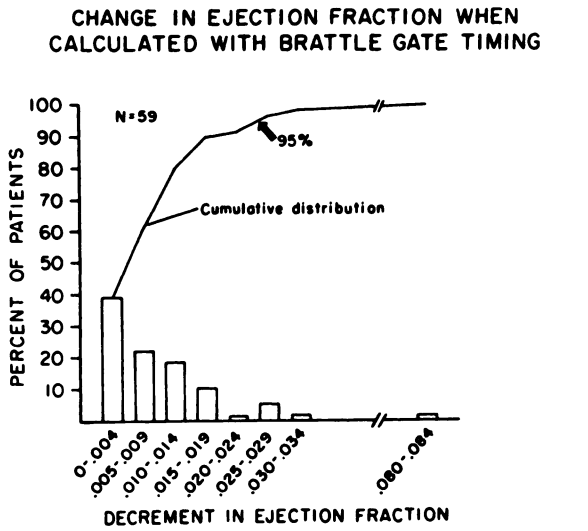

FIG. 5. Distribution of expected absolute decrements in calculated left-ventricular ejection fraction if ECG-gate-predicted time to end-systole was used, with computer-derived left-ventricular time-activity curve as reference. Since computer-derived ejection fraction was calculated using the minimum of time-activity curve, any other time would yield lower calculated ejection fraction. Cumulative distribution shows that 95% of decrements are 0.03 or less.

This is rarely a problem with patients at rest but could be disastrous during exercise studies. The modified instrument gated accurately to rates of 284/min, far in excess of those encountered clinically.

In any given patient, the initial trigger pulse (end-diastolic pulse) fell at virtually the same time in relation to the R wave on all the cardiac cycles. This property is a result of the design of the instrument and ensures that there is practically no random uncertainty in the timing of the end-diastolic and end-systolic pulses (see Appendix).

It is well known that the duration of systole is approximately inversely proportional to heart rate, but the exact relationship does not appear to be well defined. The duration of electrical systole, the Q-T interval, has been determined by a number of investigators over a broad range of heart rates. It would be expected that the time of mechanical systole should parallel the electrical time, but because of changes in electromechanical coupling and mechanical inertia, the relationship may not be constant with changes in heart rate. The Brattle Instrument Corporation used the available data on Q-T intervals to determine the curve used to predict time to end-systole in their ECG gate (*3*). When the Q-T interval is plotted against the cardiac cycle duration, the best straight line fitted to the data is TQT = 0.180 + 0.2 (R-R interval). Since the ECG gate triggers on the R wave, a delay of 0.04 sec was subtracted from the TQT line, yielding TRT = 0.140 + 0.2 (R-R interval). This was taken as the time from the R wave to end-systole and is the relationship used by the Brattle ECG gate to predict time to end-systole.

From Fig. 4 it is obvious that there is considerable spread in the times to end-systole as predicted by ECG gate, compared with the computer-derived timing. Inevitably, an instrument that bases its timing of end-systole on the R-R interval alone will be in error much of the time. In addition, the curve used by the Brattle gate does not appear to be the optimum curve for our population of patients. This may be because the patient population used in the original determination of the Q-T interval may have been relatively normal, whereas our patient population generally has some type of cardiovascular disease.

If the Brattle gate's timing pulses are used to define the end-diastole and end-systole images for the calculation of left-ventricular ejection fraction, an error will be made in the calculation because of the error in the timing of end-systole. However, the error is not very great because the volume changes little near end-systole. During the period of isovolumetric relaxation between the closure of the aortic valve and the opening of the mitral valve, the photon flux from the left ventricle should remain essentially unchanged.

In this group of patients, the ejection fraction ranged from 0.17 to 0.64, with an average of 0.37. Ninety-five percent of the time, the error in the calculation of ejection fraction, if based on Brattle-gate timing, would be less than 0.03. For most clinical purposes, this level of error is acceptable and the Brattle-gate timing should be entirely adequate for the determination of left-ventricular ejection fraction.

FOOTNOTE

* Brattle Physiological Synchronizer Model 202, Brattle Instruments Corp., Cambridge, MA.

ACKNOWLEDGMENT

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APPENDIX

Triggering operation of the brattle gate. The ECG signal is amplified, rectified, and passed through a band-pass filter to remove baseline drift and high-frequency noise. A peak-detection circuit then detects the peak of the QRS complex and sets a trigger threshold level at 80% of the peak voltage. The trigger threshold level decays exponentially with a time constant of 3.8 sec. If the R-R interval is 1 sec, the threshold level will have dropped to 61.5% of the peak value after 1 sec. Whenever the ECG voltage exceeds the trigger threshold level, an output pulse is produced indicating

that an R wave has occurred. The peak detector senses the peak of the QRS immediately thereafter, a new threshold level is set, etc. To prevent too rapid triggering—for instance, on the R^1 wave in right bundle branch block—the trigger circuit is inhibited for a short period after triggering on the R wave. This also limits the maximum triggering rate, which is nominally 300/min in the current Brattle ECG gates.

Small changes in the amplitude of the R wave will have little effect on the timing of the R-wave pulse, because of the rapid voltage change in the R wave. The reproducibility of the timing of the R-wave pulse relative to the R wave is less than 5 msec for patients with normal sinus rhythm.

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