Real-Time Analysis of Cardiac Catheterization Data Using a Computer System

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SUMMARY
A computer system for real-time analysis of hemodynamic data from the cardiac catheterization laboratory has been developed. The system utilizes a small digital computer and is compatible with the analog recording equipment generally used in a catheterization laboratory. Calculated results are transmitted to the laboratory by closed circuit TV and are available to the operator instantaneously during the course of the procedure. A permanent hard-copy report is prepared on a teletypewriter at the termination of the catheterization procedure. Comparisons of pressures and value gradients calculated by the computer and physician demonstrate excellent agreement. By utilizing a small computer and programs generally applicable in any cardiac catheterization laboratory, this system can be exported without costly modifications into many laboratories. Additional personnel are not required for implementation.

Additional Indexing Words:
Cardiac catheterization Computer programs Pattern recognition
Valve gradients Ventricular pressures

During the past decade, a number of medical centers throughout the U. S. have applied computer techniques for processing physiologic data obtained from patients with cardiovascular disease. A number of different computer configurations have been used for these applications. However, most such developments were made with a large, multiuser, time-shared system, since hospital centers had these systems available. Initial development of a computer system at Stanford University for the analysis of cardiac catheterization data employed such a large, time-shared computer. Although it was possible to develop the necessary pattern-recognition logic and to validate the accuracy of the programs used in analysis of cardiac catheterization data, several major problems were encountered.

The cost of being connected to the time-sharing system during the entire catheterization procedure was prohibitive. In addition, the procedures to put data into the time-sharing system did not allow the laboratory personnel in the cardiac catheterization laboratory to use the system conveniently. Furthermore, the “down time” of the large system gave a lack of reliability and availability, at times critical for real-time analysis of data from the catheterization laboratory. Moreover, large numbers of procedures were being performed in our cardiac catheterization laboratory, and this number was increasing rapidly. These factors prompted the development of a computer system dedicated to the analysis of cardiac catheterization data.

The purpose of this paper is to describe the system for cardiac catheterization analysis which has been developed, and to demonstrate the validity of the analysis of data.
during the 8 months in which this system had been used routinely in the laboratory.

Methods

During early stages of program development, frequent comparisons were made between results obtained by hand measurements of analog signals and those calculated by the computer. Since a large part of the program logic was adapted from pattern-recognition programs previously in existence, extensive comparisons between exact pressures recorded on oscillographic paper and those analyzed by the computer were not made, although a baseline marker was used to indicate which pressure tracings were sampled by the computer. Standard cardiac catheterization procedures are utilized in this laboratory, and all program software development was made with the object of its general applicability to many laboratories.

After initial program development, a rigorous comparison of the computer-calculated values and those measured directly by the physician performing the cardiac catheterization was made, since in many reports describing computer programs for analyzing cardiac catheterization data little evidence of documentation has been presented. For the purposes of this comparison, data collected from 50 consecutive patients studied in the cardiac catheterization laboratory were used. Computer results were not made available to the physician during his measurement of the catheterization data, and the comparisons were made only following the preparation of the final cardiac catheterization report. Statistical evaluation of the information was made by calculation of means, standard errors of the mean, correlation coefficients, regression coefficient, and standard errors of the estimate.

The cardiac catheterization procedures included standard right heart catheterizations with analysis of all right heart pressures. Left heart catheterizations were carried out by retrograde arterial catheterization and transseptal left heart catheterization. Computer analysis of all peripheral arterial and left heart hemodynamic values were performed on data obtained by these methods.

**Figure 1**

A diagrammatic sketch of the overall computer cardiac catheterization system. Flow of data, its analysis, and presentation are illustrated.
System Description

A diagram of the overall computer system is shown in figure 1.

1. Data Acquisition and Signal Conditioning. In general, the data acquisition and signal conditioning equipment necessary for the computerized cardiac catheterization laboratory includes standard commercially available hardware. At Stanford, the system includes a multichannel analog recorder for the electrocardiogram, pressures, densitometers, phonocardiograms, and other DC-coupled signals, such as oximeters. An FM magnetic tape recorder is included in this system as backup for the computer and for legal records. The analog signals are recorded simultaneously on magnetic tape and photographically developed recording paper, and simultaneously are transmitted to the computer. Pattern recognition programs are used for analysis of the pressure waveforms, using a simultaneous electrocardiogram as a marker for timing of the cardiac cycle. For this purpose, an electronic analog circuit is used for identification of the QRS on the electrocardiogram.

2. Signal Identification and Conversion. A small keyboard is used to identify the analog signals being transmitted to the computer (fig. 2). The operating components of the keyboard include all those necessary to operate

A diagrammatic sketch of the keyboard used in the cardiac catheterization laboratory is shown. Numeric keys are shown on the left, function keys are shown in the middle, and the keys signaling the computer for pressure measurements are shown on the right. Control for other instruments used in the cardiac catheterization laboratory are at the top of the keyboard.
the entire system except for stopping and starting the oscillographic recorder. The keyboard has three general sections: first, a pressure measurement section, which allows for identification of pressure information; second, a control section which can command the computer to accept outputs from a densitometer for cardiac output, and signals the computer that other signals frequently used during cardiac catheterization will be transmitted for analysis; third, a series of numeric keys, which are available for manually entering data such as oxygen saturation and Cardio-Green dye dose-injected and for choosing a specific command for the computer to perform from a numbered list of possible events presented to the physician via a closed-circuit television system. In our laboratory the keyboard is operated by the nurse who is assisting in the cardiac catheterization procedure. The keyboard could easily be covered with sterile plastic, so that the doctor performing the catheterization could operate the keyboard.

In addition, the keyboard contains switches which will permit control of automatic transducer valving circuits, stopping and starting the analog tape recorder, and marking events. This portion of the keyboard allows laboratory instrumentation to be operated from one central location. All data are input to the computer through an analog-to-digital converter. The sampling rate for pressure and the ECG QRS detector is 100 samples/sec. The output of the dye densitometer for determination of cardiac output is sampled at 10 samples/sec. All pressure data inputs to the computer are filtered by a digital filter,\(^7\) which aids in the smoothing of curves prior to analysis by the computer. The waveform analysis and calculations are performed on a small digital computer (Hewlett-Packard 2115A) with 8,192 words of core memory, disc-storage capability, and a teletypewriter. The computer system also has a storage oscilloscope scan converter, which is used for transmission of the results instantaneously to the cardiac catheterization laboratory, and other sites in the hospital, via a closed-circuit television system.

This computer system is readily programmable in Fortran, using the same teletypewriter which produces the final hard-copy report.

3. Waveform Analysis and Calculation. The logic used in pattern recognition and calculation from pressure and dye curves has been published previously.\(^2\)\(^,\)\(^3\) The computer analyzes nine consecutive pressure waveforms from the left and right ventricles, left and right atria, pulmonary artery, pulmonary artery wedge position, and aorta. Maximum pressure, beginning diastolic pressure, end-diastolic pressure, mean pressure, and a- and v-wave analyses are performed on the appropriate pressures. These pressure values are ranked, and the middle third are selected for averaging. The gradients across the aortic and mitral valves are calculated. Cardiac outputs are determined by waveform analysis of the standard Cardio-Green dye curves. Valve area, diastolic-filling and systolic-ejection periods, resistances, rate of pressure rise, stroke volume, and stroke-work index are then calculated automatically by the computer.

These programs for pressure measurement have been designed to handle most situations encountered in a catheterization laboratory. Pressure tracings with large amounts of fling and wedge tracings with prominent valve-closure artifacts are calculated without difficulty. Valve gradients are measured accurately, irrespective of the cardiac rhythm (e.g., atrial fibrillation). The gradients can be determined either by pullback across the valve or by simultaneous or nonsimultaneous measurement through two catheters, one on either side of the valve. Changes in the contours of pressure tracings due to valvular or myocardial disease do not influence the accurate detection of a and v waves and of systolic and diastolic pressures.

4. Temporary and Permanent Data Output. Immediately following the calculation of any given parameter, the results are presented to the operator on TV monitors at two
locations in the cardiac catheterization laboratory. One of these monitors is the fluoroscopic monitor, which continuously displays the catheterization data when the patient is not being fluoroscoped. The second monitor is a small-screen display used by the laboratory technician. In addition to providing the measured values, the display will indicate which pressures have been sampled and analyzed and which have not. Initially, the calculated pressure values, cardiac output from dye curves, and oxygen saturation are provided with a delay of less than 5 sec. When the necessary information is available for calculation of gradient and valve area, these are also instantaneously available to the operator. Pressures, dye curves, and gradients may be measured under different conditions during the course of the catheterization. Pressures and cardiac outputs may be determined at rest, with exercise, and following drug administration. All of these data are available immediately and are included in the final typewritten report.

The permanent output of the computer system is a typewritten report which contains the pertinent patient data, including height, weight, age, sex, hospital number, and name. This information is entered into the computer teletypewriter terminal. These data are followed by the presentation of data calculated by the computer.

### Table 1

<table>
<thead>
<tr>
<th>Pressure</th>
<th>No.</th>
<th>Correlation coefficient</th>
<th>Regression line</th>
<th>Standard error of estimate (mm Hg)*</th>
</tr>
</thead>
<tbody>
<tr>
<td>PA diastolic</td>
<td>49</td>
<td>0.96</td>
<td>0.97</td>
<td>0.46</td>
</tr>
<tr>
<td>PA systolic</td>
<td>49</td>
<td>0.97</td>
<td>0.91</td>
<td>0.50</td>
</tr>
<tr>
<td>Ao diastolic</td>
<td>50</td>
<td>0.95</td>
<td>0.97</td>
<td>2.70</td>
</tr>
<tr>
<td>Ao systolic</td>
<td>50</td>
<td>0.97</td>
<td>0.97</td>
<td>0.88</td>
</tr>
<tr>
<td>LV systolic</td>
<td>50</td>
<td>0.98</td>
<td>0.94</td>
<td>1.44</td>
</tr>
<tr>
<td>LV end-diastolic</td>
<td>50</td>
<td>0.90</td>
<td>1.04</td>
<td>1.52</td>
</tr>
<tr>
<td>Ao gradient</td>
<td>16</td>
<td>0.98</td>
<td>0.76</td>
<td>11.13</td>
</tr>
<tr>
<td>Mi gradient</td>
<td>13</td>
<td>0.94</td>
<td>0.99</td>
<td>0.48</td>
</tr>
</tbody>
</table>

*Refers to 95% confidence intervals.

Abbreviations: PA = pulmonary artery; Ao = aortic; LV = left ventricular; Mi = mitral.

**Results**

During the period of evaluation, right heart pressures were obtained in 49 of 50 patients, since one patient had a left-sided study only. A comparison was made of the computer and physician measurement of resting-state values obtained during these catheterizations. Attempts were made to guarantee that the analyses done by the physician were made on the same beats analyzed by the computer. All physician-calculated values were checked by at least two individuals. Correlations between physician- and computer-calculated data from these parameters were excellent (table 1), despite the fact that different physicians, albeit similarly trained, measured the pressures and gradients. Examples of some of the important comparisons of pressures and gradients measured by the computer and physician for pulmonary arterial systolic, aortic systolic, and left ventricular end-diastolic pressures, and for aortic valve gradient are illustrated in figures 3-6. Previous studies of reproducibility and accuracy of manual measurements versus computer measurements of analog signals, where the computer was treated as a single observer, have demonstrated better reproducibility by the computer than that achieved among different human observers.8, 9

After these studies, a slight modification of the pattern-recognition program for analysis of the left ventricular end-diastolic pressure was made, but all other programs have
been maintained as they were originally described.\textsuperscript{2, 3}

**Discussion**

The dedicated computer system which was used to obtain these data, and which is described in this paper, was designed with a number of considerations that were thought to be essential to the successful operation of a functionally automated system. These factors include: (1) that there be no increase in the staffing of the laboratory, compared to the staffing patterns prior to introduction of the automated system; (2) that the complexity of the operation of the catheterization laboratory should not be increased; (3) that the data analyzed by the computer system be made available to the operator instantaneously, so that the procedure could be changed to collect additional data if necessary; (4) that there be no operational constraints on the operator in terms of the sequence of data collection and analysis; (5) that adoption of the system not require extensive training beyond that which the average technician in a catheterization laboratory could master; (6) that the data analysis performed by the computer be at least as accurate as that performed by a trained physician; (7) that the cost of the computer system be commensurate with the operation of a catheterization laboratory and the physician time saved; and (8) that an adequate backup built into the system be designed so that data are not lost if the

**Figure 3**

The pulmonary artery systolic pressure in mm Hg determined by the physician (MD) is plotted against the pulmonary artery systolic pressure determined by the computer. The circled crosses represent more than one value which was at the same level. The line is the regression line which was mathematically determined.
computer fails during the course of a cardiac catheterization.

The system has been developed with the goal of being easily adapted into any cardiac catheterization laboratory. Software to accomplish all routine procedure has been developed, and, since Fortran has been used for programming, the addition of special programs will be accomplished relatively easily by a skilled computer programmer. While initial development of the entire software package would be extremely costly at every institution, the adaptation of such a system as described, to be utilized with existing transducers, amplifiers, and recorders in a catheterization laboratory, is possible in most other hospital centers with a volume of more than five procedures per week.

The cost effectiveness of the present system is supported by three facts. First, no additional catheter laboratory personnel were necessary to operate the system after initial development. Secondly, analysis of data was instantaneous rather than requiring 2–4 hours of costly physician time for such an analysis of a complicated case. Thirdly, it has been possible to perform more procedures in a shorter period of time in the laboratory of the senior author. Furthermore, more complete data are available to the physician when determining the options for care open to a specific patient.

The automated system is designed to complement the work of the physician by providing him with accurately calculated data during the course of the catheterization, thus allowing him to do more-sophisticated evaluation of patients, or to change the planned

Figure 4

Aortic systolic pressure in mm Hg determined by the physician (MD) and the computer.
course of the procedure completely during its performance, in order to obtain a different kind of data. Because the results of analysis are immediately available to the physician, he is able to do his hemodynamic evaluations in a stepwise fashion and plan additional procedures as needed.

The standardization of measurements, as provided by this well-defined program logic, provides for improved accuracy and consistency over that obtained when a large number of physicians might be doing the analysis. Although the comparisons of data calculated by the physician and computer showed excellent agreement, several points merit emphasis. In measuring left ventricular outflow-tract gradients due to aortic stenosis, the computer apparently measures low-level gradients with values higher than those obtained by the physician. This is shown clearly in figure 6 and documented by the statistics in table 1, where the slope of the regression line was 0.76, and the intercept was 11.13 mm. The filtering techniques used may be responsible for this observation. Moreover, the computer logic used to calculate left ventricular end-diastolic pressure has been changed slightly after the wide variations between computer- and physician-calculated data became apparent. As a consequence, a more reliable set of normal values for a laboratory can be generated, and these values can be used as a standardization among laboratories, when other catheterization laboratories use a similar system. In addition, the measurements made by the computer eliminates the need for

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Figure 5

Left ventricular end-diastolic pressure in mm Hg (LVED) determined by the physician (MD) and by the computer.
The mean aortic-valve pressure gradient in mm Hg determined by the physician (MD) and by the computer.

The system, as designed, can be operated by the existing personnel, with only a few hours of additional training.

Clerical time in preparing permanent records is also minimized. The standard permanent report generated on the computer can be attached directly to the patient's chart and a diagnostic statement later appended after the physician has reviewed the data. This eliminates the need for a secretary to type and attach permanent catheterization reports to each patient's chart.

This system provides rapid, real-time cardiac analysis of cardiac catheterization data which is available to the physician during the course of the procedure and is as accurate and reliable as that data generated by a series of physicians measuring analog pressure recordings. It is simple to operate and provides for improved personnel utilization.

The system can be exported to other laboratories without additional program development, and minimal engineering competence is required for installation. Special noncomputer hardware, such as oscilloscopes for displaying output, a keyboard for communicating with the computer, and a teletype-writer for printing hard-copy reports, will be necessary for this system to be used in another hospital center. As the system is to be marketed, all these components will be
included in the package. Thus, the system should be completely exportable.

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References

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