Computer Contribution

Experience With a Digital Computer for Study and Improved Management of the Critically Ill

Max H. Weil, MD, Herbert Shubin, MD, and Will Rand, MA

Automated techniques, now bolstered by the availability of a computer, have become increasingly important in recent years as medicine seeks to fulfill the need for ever more comprehensive and technically complex services.

Detailed analysis of physiological data by manual methods is inefficient, both for clinical research and for practical use at the bedside. A combination of sensors, with analysis of their output by an on-line computer, offers a means of achieving a comprehensive inventory of patient condition for immediate use by the physician and the clinical investigator.

Automated measurement and collection of biological data in a clinical setting has been used in a number of areas.[1,2] Automated analog devices have been developed for measuring blood pressure by the use of indirect auscultatory techniques.[3-6] These devices are not entirely satisfactory for patients in shock, however, since the indirectly obtained blood pressure loses accuracy under conditions of markedly reduced blood flow (M. H. Weil and F. Rogers, unpublished data). Analog computers have been developed to determine cardiac output by integration of the corrected area under the indicator dilution curve.[7-11] Estimates of cardiac output have also been obtained by calculation of stroke volume from components of the arterial pressure wave,[12] and by an automated technique in which oxygen consumption is related to arteriovenous oxygen differences.[13] Flow through large blood vessels has been measured by ultrasound and impedance techniques in patients during surgery. Respiratory ratemeters, the principle of which is based on pressure or impedance changes during chest movements, are widely used, and more recently both analog and digital techniques have been applied to the acquisition and analysis of transpulmonary pressure and airflow.[14] Automatic measurement of rectal and esophageal temperatures by the use of thermistors is common during anesthesia, particularly during cardiovascular surgery. Analog devices for measuring and reporting heart rate have assumed an important role in the monitoring of patients in critical care areas. Automated analysis of electrocardiograms has provided a new measure of objectivity in electrocardiographic diagnosis,[15-17] while telemetry has been especially useful for continuing electrocardiographic monitoring during physical activity.[18] Analog devices have been used for chemical determinations such as blood glucose, lactate, pH, carbon dioxide pressure (P_{CO_2}), and oxygen pressure (P_{O_2}) and, independently, computers have assumed an increasingly important role for efficient processing of data generated in clinical laboratories. The contribution that automation makes when applied to each of these techniques greatly bolsters the wider availability as well as the accuracy of these measurements.

An important development, for which the Shock Research Unit shares responsibility, is the use of a combination of sensing devices coordinated by a digital computer to develop an integrated picture of a patients' physiological condition on a time-related basis.

Development of the Shock Research Unit

Six years ago initial plans were made for a Shock Research Unit to be staffed by an interdisciplinary research team devoted to the intensive study and care of patients in shock. After 18 months of preliminary investigation and planning, a four-bed Shock Research Unit was opened at the Los Angeles County General Hospital in late 1961. This was complemented by an already existing experimental laboratory in the University of Southern California School of Medicine.

The next two years were largely devoted to clinical investigation of patients in shock,[19-25] as well as study of technical problems involved in the instrumentation necessary to obtain valid measurements. A digital computer system for use at the bedside of critically ill patients was investigated

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RECORD IDENTIFICATION

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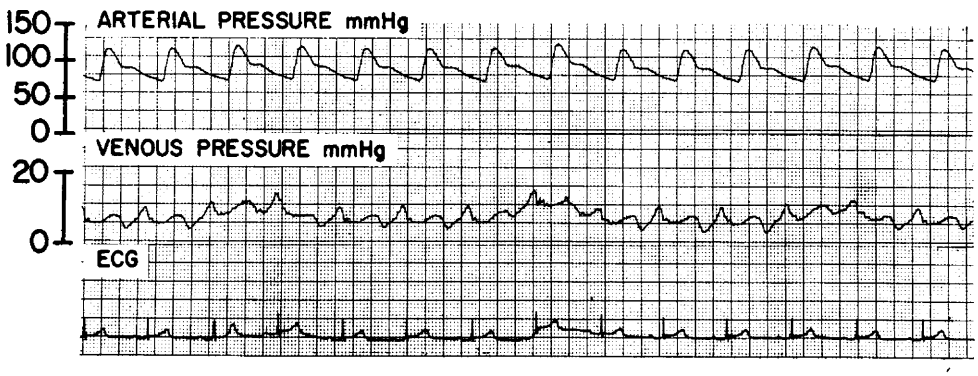
ARTERIAL PRESSURE ANALYSIS

T	T1	T2	DP	SP	
073	11	22	066	111	*
075	11	23	065	112	*
070	10	22	066	115	*
071	11	23	067	113	*
071	12	23	066	111	*
071	11	23	065	111	*
072	11	23	065	112	*
070	11	23	066	115	*
070	12	23	066	110	*
070	12	23	064	110	*
071	11	23	064	111	*
069	10	22	066	113	*
069	11	22	065	111	*
069	11	23	065	110	*

ROUTINE MONITORING

TIME HRS	SP DP	MAP MVP	ΔS RR	HR PR	RECT AMB	TOE DEL	THIG FING
1713*							
14-17	111	083	005	083	36.7	32.5	30.4
066.6	065	06.5	018	083	25.1	31.4	33.6



1. Printout of special program which permits beat-by-beat comparison of arterial pressure waves as recorded on multichannel recorder and by computer. Time is given in sec/100, pressure in mm Hg, and temperature in degrees centigrade. Abbreviations: *T*=time from QRS to following QRS; T_1=time from QRS to diastolic pressure value; T_2=time from QRS to systolic pressure value; *DP*=diastolic pressure; *SP*=systolic pressure. In printout of monitoring report, pressure is given in mm Hg, rates as per minute, and temperature in degrees centigrade. Abbreviations: *=computer record number; *HRS*=time since admission to shock ward, hours; *SP*=systolic pressure; *DP*=diastolic pressure; *MAP*=mean arterial pressure; *MVP*=mean central venous pressure; *ΔS*=maximum change in systolic pressure over read cycle, *RR*=respiratory rate. *HR*=heart rate. *PR*=pulse rate. *RECT*=rectal temperature. *AMB*=ambient air temperature; *TOE*=skin temperature, toe; *DEL*=skin temperature, deltoid; *THIG*=skin temperature, thigh; *FING*=skin temperature, finger.

both to bolster efficient monitoring of the physiological condition of the patients and to serve as an aid in interpreting the acquired data. Such a system was designed, and in mid-1963 an IBM 1710 process control computer system was acquired.

This system consists of a central processing unit to handle the arithmetic and direct the logic of the system, a magnetic disk for storing data and programs, and a card read-punch for inputting instructions to the system and for outputting data.[26] Units for the entry of manual data are included in the computer system as well as a device for converting the voltage output of sensors to numbers which can be manipulated by the central processing unit. To make the data available to ward personnel, a plotter and output typewriter are also included in this system.

The next year and a half was devoted to the integration of the computer system into routine ward usage. Programs were written and special devices designed and built to allow the computer to aid ward personnel in their mangement of the critically ill patient by collecting data from the patient, processing it, and presenting it to the medical staff.[27] After the computerized procedures were validated, training classes in the operation of the system were held for the nurses and technicians. The system became operational for routine use on Jan 1, 1965.

Operation of the Computing System

The computer system functions 24 hours per day, seven days a week, and forms an integral part of the Shock Research Unit. More than 200 patients have been monitored during the first 17 months of its operation. A unique feature of this system has been its reliable operation unattended by specialized computer personnel.

Information on patient condition is obtained by a number of sensing devices, including pressure transducers for arterial and venous pressures, electrodes for the electrocardiogram, thermistors for six separate temperature measurements, an optical densitometer for use in determination of cardiac output, and a unit designed to measure urine flow. Algorithms have been derived to convert the signals from these devices to their customary units and to check them for internal consistency. Computer programs translate these data into numbers which have significance for the attending clinician.[28-31]

Special programs have been written which permit a beat-by-beat comparison of pressure waves as recorded on an analog recorder and by the computer (Fig 1). At the option of the physician and at intervals as often as every five minutes, cardiac output, peripheral vascular resistance, appearance and mean circulation time of dye, central blood volume, and total work of the heart are automatically reported (Fig 2). In addition to these measurements, blood is sampled and plasma volume, red blood cell mass, pH, P_{CO_2} and P_{O_2} are determined with the computational aid of the computer system. The values for arterial and venous pressures, heart and respiratory rate, temperatures,

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and urine output are reported at intervals requested by the physician. These are usually every five minutes but may be as often as every minute (Fig 2). Summary reports are generated at the request of the physician, as well as routinely for the patient's files at the end of each 8 hour shift (Fig 3) and every 24 hours. Trends of selected parameters are displayed on a plotter in the ward (Fig 4). Reports on the patient's condition are printed automatically on a typewriter and are also transmitted via closed circuit television to a screen at the patient's bedside (Fig 5).

The data that are presented to the ward personnel are also punched onto cards. These cards, together with the nurses' and physician's notes, form the data source for detailed studies on separate aspects of shock. At the same time, the data serve as a feedback to the computer specialists and engineers who are continually modifying the operation of the computer system to achieve practical advantage for clinical management and to better serve the medical researchers.

The computer has become an accepted part of the medical environment in which we work and provides a stimulating training experience for faculty, house staff, and paramedical personnel of the University of Southern California at the Los Angeles County General Hospital, and, indeed, for the Los Angeles medical community. The presentation of critical data on patients in both digital and analog form, in a format which is readily understood by the clinician, serves as a very valuable clinical teaching experience in our medical school setting. A new measure of interdisciplinary collaboration is focused on the ill patient through the joint efforts of clinical investigators and biological, physical, and mathematical scientists.

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PATIENT 0625 BED 1 DATE 03-25-66      PAGE 091

DC NO = 022     CBV = 00.97  MAP = 082
DATE  = 03-25   RES = 02981  MVP = 13.3
TIME  = 03-54   WRK = 02453  HR  = 087
CO    = 02.20   RES2= 02498  BSA =  1.81
CIA   = 01.21   ATC =  03.8  INJ = 02.500
SV    = 025.2   MCT =  26.5  DSC = 06

TIME   SP MAP   ΔS  HR  RECT TOE THIG  U05
HRS    DP MVP   RR  PR  AMB  DEL FING  U60
1419*
04-00 126 085  008 089 38.7 25.2 32.9 0002
034.8 069 11.4 027 089 23.0 31.6 27.0
007* BOTTLE 01 RT 07 SYR 50 AT 0400

008* 0150 CC IN BOTTLE 02 AT 0400

1420*
04-05 126 085  006 089 38.7 25.1 32.9 0000
034 9 069 11.5 031 089 23.0 31.6 27.0 0069
```

2. Typewriter printout of cardiac output and other values with the same time line. Abbreviations are as follows: *DC NO*=dye curve number; *CO*=cardiac output, liters/min; *CIA*=cardiac output, liters/min/sq m; *SV*=stroke volume, ml; *CBV*=central blood volume, liters; *RES*=vascular resistance, dyne sec cm^{-5}; *WRK*=cardiac work, gm-m/min; *RES2*=vascular resistance calculated on basis of mean arterial pressure minus mean central venous pressure, dyne sec cm^{-5}; *ATC*=appearance time of dye, corrected for delay in transit of catheter, sec; *MCT*=mean circulation time corrected for delay in transit, sec; *MAP*=mean arterial pressure, mm Hg; *MVP*=mean central venous pressure, mm Hg; *HR*=heart rate, beat/min; *BSA*=body surface area, sq m; *INJ*=amount of indicator injected, mg; *DSC*=dead space correction for delay in transit of catheter, sec.

This printout also shows the routine monitoring report. Printout abbreviations, in addition to those explained in the legend for Fig 1, are as follows: *U 05*=urine output during preceding 5 minutes, ml; *U 60*=urine output during preceding 60 minutes, ml.

Limitations of the Present System

Hemodynamic parameters are now sensed automatically; however, much additional data must be entered manually into the system by the nurse or technician. This is accomplished by setting the dials of a manual entry unit. Since all information must be entered as numeric codes, this requires the careful attention of the operator. This area of man-machine communication is one of the most important considerations in the design of a system which is to assist in the efficient operation of a critical care evnironment. Electronic devices which accept a great variety of input and give the medical user direct two-way communication with the operating system are now available and would substantially increase the efficiency of the system.

The analyzed data are presented to the ward staff by means of a typewriter and a point plotter. Both of these devices are noisy, slow, and relatively unreliable. They require an inordinate amount of computer time and storage space. Display units have recently been developed which utilize digital oscilloscopes and are silent, fast, and flexible. These devices would make the recall of large amounts of data practical and obviate the need for plotting data, except as an indication of trends. An improved system would include such oscilloscopes and trend plotters. Permanent copy of all data

FLUID INTAKE TABLE, PATIENT 5600 1500 TO 2300, 06/22/66

FLUID		1600	1700	1800	1900	2000	2100	2200	2300	8 HR TOTAL
5D/.5NS	CC	0045	0045	0045	0045	0041	0099	0114	0005	00439
5 D/WATER	CC	0000	0000	0000	0001	0014	0022	0014	0000	00051
PK CELLS	CC	0000	0000	0000	0000	0000	0050	0285	0014	00349
TOTS/HOUR		00045	00045	00045	00046	00055	00171	00413	00019	000839

MEDICATION		1600	1700	1800	1900	2000	2100	2200	2300	8 HR TOTAL
K CL	GM	0000.13	0000.13	0000.13	0000.13	0000.07	000000.	000000.	000000.	000000.5900
ISUPREL	MG	000000.	000000.	00.0000	00.0100	00.1400	00.2200	00.1400	00.0000	000000.5100

3. A representative summary report of intake of fluid and medications administered: *5D/.5NS*=5% dextrose in 0.5 *N* saline infusion; *5D/WATER*=5% dextrose in water infusion; *PK CELLS*=Packed red blood cell transfusion; *TOTS/HOUR*=Total volume per hour; *K CL*=potassium chloride; *ISUPREL*=isoproterenol.

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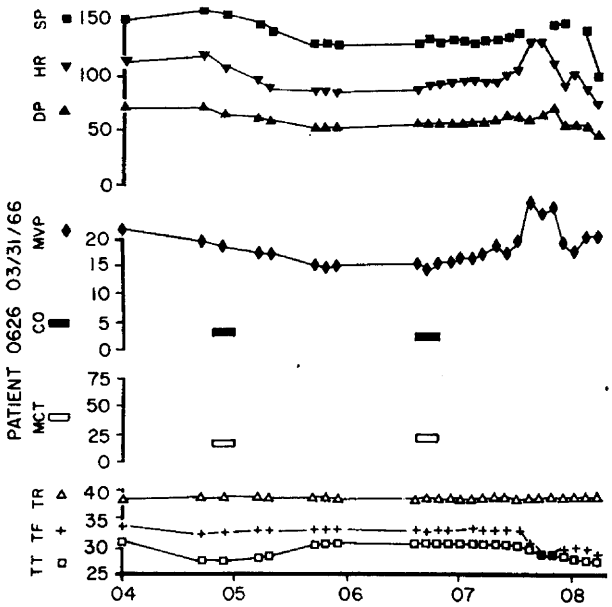
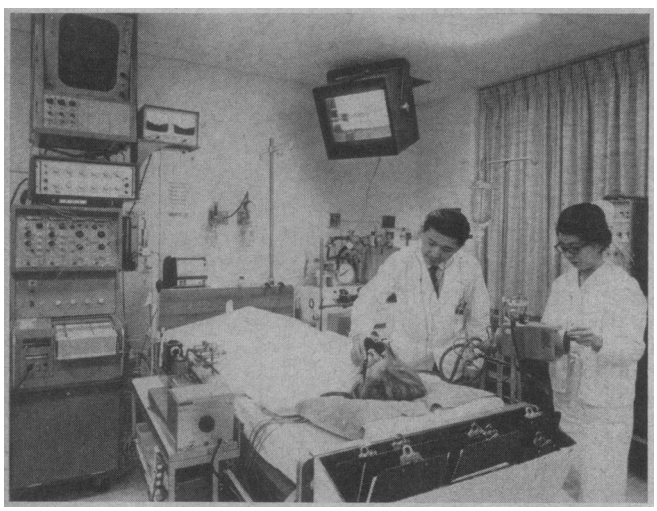


4. Plot of selected parameters over a four hour period. Temperatures are in degrees centigrade; pressure in mm Hg: *TT*=skin temperature, toe; *TF*=skin temperature, finger; *TR*=temperature, rectum; *MCT*=mean circulation time of dye, sec; *CO*=cardiac output, liters/min; *MVP*=mean central venous pressure; *DP*=diastolic pressure; *HR*=heart rate, per min; *SP*=systolic pressure.



5. Bedside arrangement of automated analog data-collection device. Combination of sensors and on-line computer allows physician to make detailed analysis of physiological data and to develop an integrated picture of patient's condition over time. Oscilloscope for continuous display of arterial and venous pressure waveforms and electrocardiograph are shown on *upper left*. Beneath it are manual entry unit and four channel recorder. Arterial and venous pressure transducers, densitometer, and withdrawal-infusion pump are on top shelf of mobile rack mounted on left side of patient's bed. Thermistor box is on lower shelf. Heart and respiration rate-meters and dye recorder are above foot of bed. The television screen is at *upper right* and beneath it there is a volume-controlled respirator. Patient is being ventilated with pressure-controlled respirator. Immediately to left of nurse are pacemaker and defibrillator.

would be produced at regular intervals away from the ward.

The computing system which the Shock Research Unit has presently in use is a valuable tool for both the clinical and the nonclinical staff. It fills its initially projected role of collecting and displaying data. Its use has pointed out other areas in which it would have immense value, such as detailed study of selected physiological parameters and comparisons and correlations of the total data set accumulated by the system. Its use has also shown how such a system, using more recently developed techniques and equipment, could serve better the needs of this unit. In applying the experience we have gained over the past few years, we are now constrained by the limited capacity of the present system. We desire to examine the data we are gathering at one more level of complexity. However, our system is fully occupied with its present tasks. The design and capacity of the equipment and programs do not allow this expansion. Recent developments in the use of small computers to handle different tasks simultaneously now provide systems which are designed to handle more sophisticated analysis without sacrificing the capability of gathering the essential data.

Plans of the Shock Research Unit

Our group is presently planning expansion to a system centered on a process-control computer, with a direct data link to a large general purpose computer. The experience we have gained from the clinical and biological studies and the computer oriented mathematical-statistical work has led us to the recognition of the great potential of the man-machine approach in the study and care of disease. Indeed, improvements in medical diagnosis, treatment, and efficient management of the critically ill patient will undoubtedly bring a new measure of competence to the care of the critically ill and especially the patient in shock. Continued progress is contingent on the solution of a number of biomathematical problems. Greater computer capacity and flexibility than was available initially is required, as well as a higher degree of interdisciplinary interreaction. Basic system design must be extended so that the system not only will aid the individual clinical researcher but also will provide all users of the system with cross-access to data and procedures.

The ultimate objective of this project is the development and utlilization of these facilities to simulate the patient's physiological disturbance. In the development of this program, the data gathered from patients in the Shock Research Unit are being used to develop hypotheses expressing the interrelationship of hemodynamic, biochemical, and clinical parameters and their change with respect to time and treatment. These hypotheses are expressed mathematically and tested for validity against actual data. Statistical techniques such as multiple-regression analysis, principal-component

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analysis, canonical analysis, and discriminant analysis are being used to investigate and express the interrelationship of these data. Efforts are increasingly directed to the construction of mathematical models of basic pathophysiology and techniques by which such models may be used to simulate and thereby predict the effects of selected modes of treatment. The derivation and testing of these hypotheses require that the system accumulate accurate data in a form which it can use efficiently. Initial efforts are being devoted to the design of this file of data. Bolstered by such a matrix of reliable reference data, the physician's understanding of the pathophysiology and the means by which this data can be converted into meaningful terms will provide a new degree of clinical competence. Based on objective evaluation and decision making, precision of treatment rather than trials will characterize medical management. We are confident that this ultimate purpose will reduce the costly "errors" of the "trial and error" management of life-threatening states such as circulatory shock.

Impact on the Hospital Community

This communication would not be complete without reference to the psychological impact of automation and computer techniques on the clinical environment. An occasional, though by no means uncommon, misconception is demonstrated in the following quotation attributed to Sidney Rubin, MD, of Kansas City, Mo, in the *AMA News* of April 4, 1966, under the title "Automation—Who's Boss?"

> Technological advances have effected many improvements and while there were those who feared the unemployment resulting from automation, job loss has not proven to be the avenue of concern. . . .
>
> While there is ever increasing demand for expanding diagnostic procedures concurrent with sociological change, such as medicare, the physician is confronted with similar problems. The opposing forces at work are evident in the facility and superior manner in which a patient may be examined. At the same time the individual loses identity and is reduced to a part of the whole physical and psychological being. This minification of the whole being is deteriorative to the psyche of the individual, who is more in need of compassion and understanding than ever before.
>
> Medicine must avoid the trend . . . that would create an "IBM-like" robot physician with a statistical predetermined accuracy. Our time welcomes the understanding doctor who is empathetic and will continue to offer the patient warmth. Efficiency in itself is not a laudable goal.

Our experience fails to corroborate Dr. Rubin's fears. To the contrary, we recognize unusual opportunity for the use of automation at the bedside to reduce the routine demands on the physician and particularly on the nurses, much of whose time is devoted to purely mechanical chores. Is there special advantage for the patient who is critically ill if measurements of temperature, blood pressure, and respiratory rate are accomplished by manual techniques rather than by automated sensors? Is the patient either psychologically or physically more appropriately managed if the intravenous infusion rate is adjusted and readjusted at frequent intervals by manual rather than by highly reliable mechanical means to deliver the volumes of fluid which have been ordered by the physician? Is it better to measure the output of urine with a graduated glass cylinder than to utilize a urinometer which provides a continuous and highly accurate indication of urine flow? Would the patient in fact lose identity because of the improvement in efficiency and reliability of such automated measurements? Of course not!

To the contrary, mechanization frees the physician and nurse to provide the very empathy and warmth in doses far exceeding those previously possible. As for the statistical accuracy of diagnosis (and treatment), would even the least humble physician among us not gladly have the additional information and insight which it provides to guide his judgment? Would this not strengthen our hand when at the bedside of our patients we face mortalities in excess of 80%, as in the case of patients in whom shock complicates an acute myocardial infarction?

The clinician who has available to him a computer system at the bedside is fully cognizant that the machine is only a tool to assist the professional efforts of the physician and no more. If the efficiency of automation improves the scientific competence of the physician by extending the scope and accuracy of his judgment, and particularly if it frees him to attend more closely to the decision making and humanitarian aspects of care, the machine fully justifies its existence. It does so in the same way that the scalpel has an advantage over the kitchen knife and the measurement of temperature for documentation of fever compares favorably with even the most perceptive mother's palm.

In this framework the machine is not constructed as a robot which makes decisions and takes independent actions in place of, or parallel with, the attending physician. It is neither expected to nor called upon to make medical judgments. It is expected to—and does—rapidly provide the physician with reliable information. By freeing the physician from many routine tasks of patient monitoring it enables him to devote himself more fully to critical judgments in patient care.

The acceptance and interest in the computer by the medical faculty and house staff at our hospital have assured us that responsible physicians are neither fearful nor distracted by computers. They rapidly assess its proper place as a useful machine. They welcome its efficiency and particularly the speed and accuracy with which it provides them with data at critical times.

Summary

Patients in the shock state are intensively studied and treated in the Shock Research Unit located in the Los Angeles County General Hospital. A high-speed digital computer is used to accumulate

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data from patients and report them immediately to the medical staff in the ward. Measurements of physiological and biochemical parameters are obtained by analog transducers. Clinical observations, medications administered, treatments performed, and diagnostic information are coded and entered manually into the system.

All data are reported to the medical staff for immediate use in evaluating both the clinical status of the patient and his response to treatment, and these data are also stored in the computer. Use of this computer system in over 200 cases has demonstrated its acceptance and value in a clinical setting.

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COMPUTATION AND MEDICINE.—Can we make an estimate of how much work would be involved in the examination and standardization of the signs and symptoms for all areas of medicine? I think we can make a rough estimate on the basis of the study of the field of hematology made at Rockefeller Institute. A careful examination of a very large body of hematology literature and the data of patients with hematologic diseases by Lipkin, Atamer and Berkley took about 4-5 man-years. The investigators located inconsistencies in the literature and came to the conclusion that future activity could best be directed toward collecting a new body of hematology data on the basis of carefully defined and agreed upon signs and symptoms. The latter would have to be worked out by hematologists.

From this pilot study I have extrapolated on the basis of the number of medical specialties to arrive at a figure of 500-600 man-years as the amount of effort required to define signs and symptoms and to start the careful collection of data to cover the entire medical field.—Lusted, L.B.: "The Development of National Biomedical Computing Capability," in Enslein, K. (ed.): *Data Acquisition and Processing in Biology and Medicine,* New York: Pergamon Press, 1962, p 7.

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