
Special Article

A Computerized Simulator for Critical-Care Training: New Technology for Medical Education*

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A patient simulator has been developed for training, certification, modeling, and demonstrating problems in the management of critical-care patients. The Critical Care & Hemodynamic Monitoring Training System consists of a personal computer, software, and a replica of a human torso designed to enable students to practice critical-care medicine. The computer displays patient histories, laboratory results, treatment options, patient responses, and a real-time cardiac monitor. The torso apparatus is used to practice insertion of a hemodynamic monitoring catheter; the cardiac monitor displays catheter pressure readings as the catheter is advanced into the heart and also pulmonary artery and wedge position. Special screen calculators in the program may be used to determine hemodynamic, respiratory, ventilatory, and renal function indices. In contrast to previously described simulators and computer oriented instructional programs, this system contains no inherent data base. Instead, authors build a library of informative cases by using the hardware and software tools provided. Individual "modules" of patient information are authored, and these are transparently linked as a student undertakes management of a patient. Although this system is a technologic achievement, determination of its usefulness as an instructional tool or certification aid must come from broader use and controlled studies.

The demand for proficiency among critical-care physicians and nurses has never been higher. In recent years, this demand has been reflected in the dramatic increase in the number of publications focused on critical-care medicine. Board certification has also been instituted to ensure uniformity in training and development of high-quality residency programs and to recognize those physicians who, through special education

and testing in critical-care medicine, have substantiated competence in the field.¹ Recommendations for fellowship training in critical care, published in 1987 by the Society of Critical Care Medicine's Task Force on Guidelines, highlight the importance of an environment in which the trainee has sufficient critical-care responsibilities to develop both patient-care and procedural skills.² Similar concerns for training and certification in Canada have also been published.^{3,4} Standards for educating nurses in critical care, developed during a 3-year period, are now being implemented.⁵

In certain professions, such as aviation and space flight, the need for simulating routine and adverse situations has long been recognized.

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Although an airline pilot or an astronaut would not be expected to assimilate all the skills necessary for their jobs by actually experiencing the many potential disasters that await them, critical-care providers have traditionally depended on actual patient contact for much of their training.⁶ Moreover, many providers who have not achieved certification face the same level of responsibility as those who have. The complexity of treatment modalities and the sophisticated technologies available to providers have strained our traditional educational programs. Although perceived as an important adjunct to medical training, advanced simulators in medical training have been introduced slowly.⁷⁻⁹ In the future, simulators may play a crucial role in continuing education and the granting of privileges for performance of certain procedures.

Patient-management simulators have traditionally integrated various manikin components with computer display of important physiologic events. Some devices are impressive in their ability to duplicate bedside evaluation¹⁰⁻¹³ or administration of anesthesia,¹⁴⁻¹⁷ providing life-like responses for the student. After a 4-year period of development, the system described herein was granted a patent in 1987 from the US Patent and Trademark Office.¹⁸

The system consists of software that operates on a Macintosh computer (Apple Computer, Inc., Cupertino, California), a portable peripheral unit including a replica of a human torso (Fig. 1), and various controls to display a real-time cardiac monitor on the computer (Fig. 2). Trainees can develop manual dexterity skills in performing cardiac catheterization and cognitive skills in interpreting cardiac rhythms and hemodynamic data.

The Critical Care & Hemodynamic Monitoring Training System (Dynacath Corporation, Minneapolis, Minnesota) contains no inherent data base. Instead, authors build a library of informative cases by using the hardware and software tools provided. Expansion and modification of the data base are limited only by the amount of computer storage available. This method promotes timeliness and quality of the

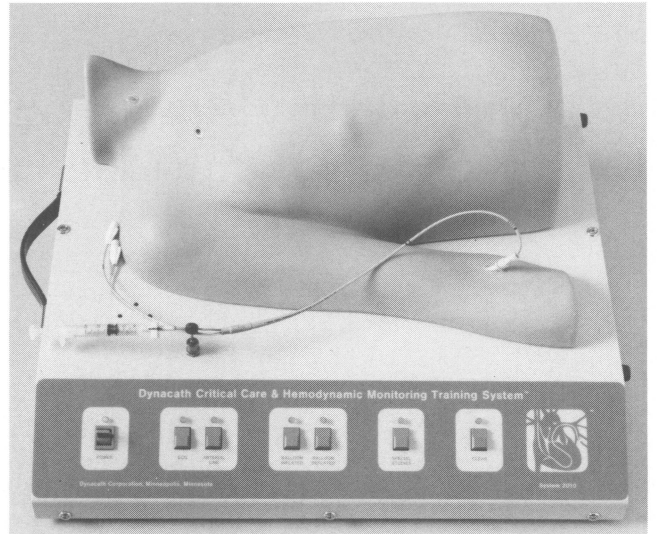


Fig. 1. Photograph of Critical Care & Hemodynamic Monitoring Training System. In this replica of a human torso, a catheter may be placed by using standard insertion components and advanced through cardiac chambers into wedge position. System monitors insertion technique, including improper use of the balloon, prolonged time in wedge position, and "overwedging" of catheter. Anatomic landmarks—such as distance to tricuspid valve—are controlled by software.

instructional material by allowing incorporation of recent literature, tailoring of cases to specific audiences, and customizing for regional, social, or philosophical approaches to certain management problems.

It is the only available system that allows simulation of complete catheterization of the right side of the heart, with real-time simulation of cardiac rhythms and arterial and catheter pressures. Suitable medical conditions for assessment include arrhythmias, cardiac tamponade, cardiomyopathies, congenital defects, constrictive pericarditis, fluid and electrolyte disturbances, myocardial infarctions and complications, postoperative conditions, pulmonary disorders, shock, and valvular defects.

The system is portable and may be carried by one person. The current cost of the system is less than \$5,000, excluding the computer. The potential users include medical and graduate students, residents, subspecialty trainees, hospital medical staff, nursing personnel, and technicians.

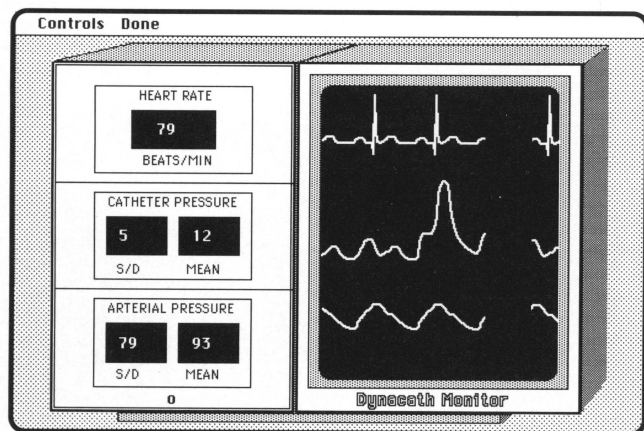


Fig. 2. Simulated cardiac monitor displays rhythm, catheter pressure, and arterial line pressure data. Systolic and diastolic values (S/D) are displayed alternately on left side of monitor, along with mean pressure. Catheter pressure readings show real-time changes as catheter is advanced through right atrium, right ventricle, pulmonary artery, and wedge position. "Overwedging" may be identified by increasing pressure values as catheter is advanced. A "beep" may be added to make the display more realistic. The probability of "missing" the heart—that is, crossing the chest or going down the inferior vena cava—is controlled by software.

MATERIAL AND METHODS

Construction.—The system consists of a simulated adult torso made of rigid polyethylene, with access ports for right-heart catheterization from the median basilic vein in the antecubital fossa, the subclavian vein, and the internal jugular vein. Catheterization is possible from the right side only. An internal guideway leads the catheter to precision-aligned rollers that rotate an optical encoder. The optical encoder provides information about catheter position and direction of motion to the computer. A three-way adapter is connected between the catheter and the balloon syringe for diverting air into a durable internal balloon. A sensor determines the status of balloon inflation, and this information is also provided to the computer. A single cable connects the torso apparatus to the computer's modem port, and power is provided through an Underwriters' Laboratories-approved power supply.

Software.—The software is written in Macintosh Programmers' Workshop Pascal and compiled into machine code for distribution. Source

code modification is not possible by the system user, although suggestions for revisions from test sites have been regularly incorporated into the software.

Two levels of operation are available: a case input and development function for instructors (or "authors") and a simulation function for students (or "trainees"). A computer keyboard is unnecessary during simulations; selections are made by using the apparatus switches or by pointing the computer cursor—with a mouse or trackball—to suitable screen buttons and controls (Macintosh User Interface).

Author Operation.—The system has no inherent knowledge of medical illness or physiologic processes. The "knowledge base" or computer data base is derived entirely by authored material. The system provides both the hardware and the software tools to enable an author to enter all data involved in the management problem. A flowchart of the authoring operation is shown in Figure 3.

The author creates a case by dividing the total management problem into individual operations or "modules." A module is a group of data consisting of a history and physical examination (or subsequent progress note or consultation), hemodynamic data, study options and results, four potential treatment plans, and appropriate discussion. Data are entered for the patient's initial condition and for the consequence of each treatment plan. Histories, physical examinations, progress notes, and consultations are entered by using standard word processing (Fig. 4). Dialog boxes (Macintosh User Interface) are used to enter hemodynamic data, study options and results, treatment plans, and discussion (Fig. 5). Actual waveforms from the critical-care unit or cardiac catheterization laboratory may be used by simply tracing one or more cycles on a digitizing tablet (Fig. 6). The program enables an author to adjust the rate and pressure of the waveforms automatically once they have been entered; thus, the number of waveforms that need to be drawn is reduced. This procedure is accomplished by numerical analysis of the drawn waveform and application of mathematical tools unique to computer raster graphics presenta-

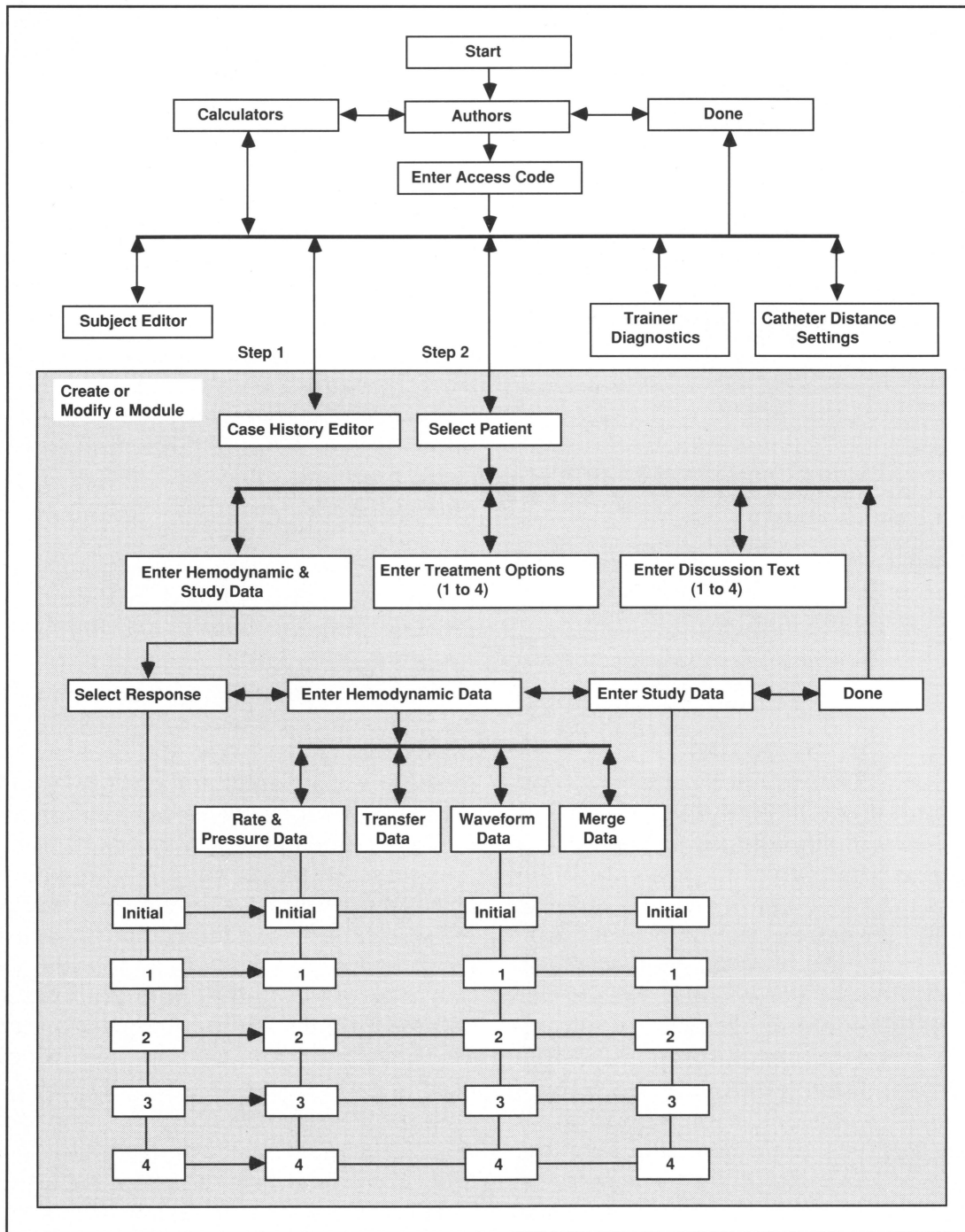


Fig. 3. Flowchart of program operation for authoring cases. Once a history and physical examination have been prepared and entered, all hemodynamic and study data, treatment options, and discussions are entered by using tools provided by the system. Management problems are divided into discrete modules, each containing either the history and physical examination or the progress notes and consultation, as well as treatments, discussions, and "response" data ("initial" data and data resulting from each treatment plan). Trainees do not see the modules but rather progress through the case just as they would in an actual patient-management situation. Modules automatically interconnect on the basis of treatment selected. By limiting treatment options to four per module, the author does not have an unwieldy amount of data; cases can be expanded later by adding more modules. Each management problem may end in a variety of ways, depending on the scenarios created by the author and the action taken by the trainee.

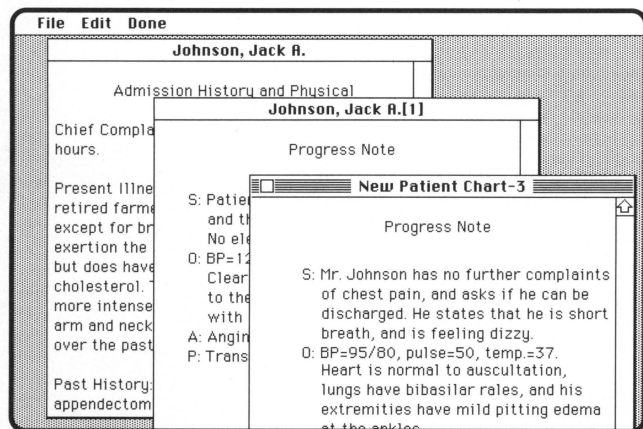


Fig. 4. Example of computer screen appearance when history and physical examination are entered. Multiple documents may be open at one time, including the initial history and physical examination, progress notes, and consultations. Editing features include "cutting and pasting" of text within or between documents. Because each document is saved by a patient pseudonym, memory is also reserved for storage of module-specific data. BP = blood pressure; S = subjective; O = objective; A = assessment; P = plan.

tion. Because part of one case may be shared with another—either directly or through a library of waveforms—the time needed to author a case can be shortened.

Although many problems in medical management can be demonstrated with a single module, a case consisting of multiple modules enables the trainee to provide "continuing care" for the patient. After the first module, progress notes or consultations are presented rather than the history and physical examination. During the simulation, only those modules appropriate to the trainee's action are presented.

Authoring a case may take from an hour to several days, depending on the number of modules needed. The author must consider the consequences of each treatment option provided to the trainee and enter the conforming data. An outline of the information necessary for authoring a single module is shown in Table 1.

Although having the latitude to allow the trainee to select any treatment at any time would be ideal, no available instructional system could predict the outcome. This range of options may be possible in the future by incorpo-

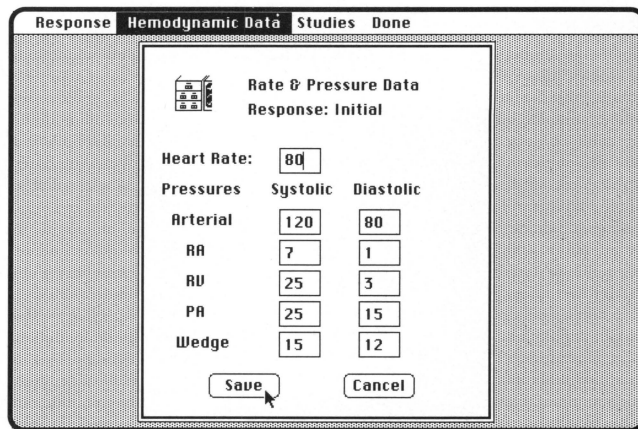


Fig. 5. Entry of module-specific data is by means of dialog boxes, such as example shown here for heart rate and hemodynamic values. Similar dialog boxes are used for entry of study options and results, treatment plans, and discussions. Computer cursor is moved to appropriate entry point above, and values are typed on computer keyboard. Default values (previously stored data) are shown when dialog box first appears. New data are incorporated into module by selecting "Save." PA = pulmonary artery; RA = right atrial; RV = right ventricular.

rating cardiovascular and other models. Authors may use models currently available to assist them in constructing cases.

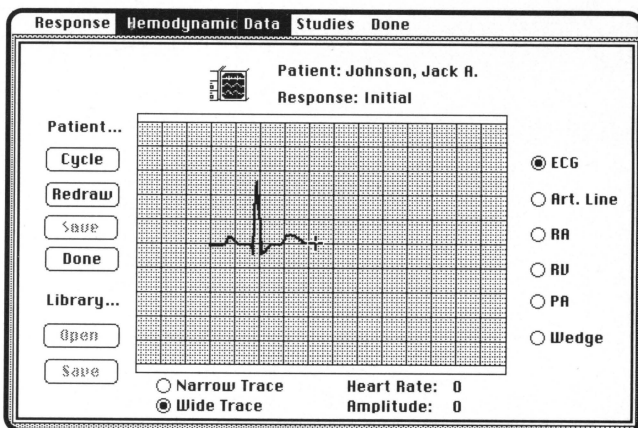


Fig. 6. One or more waveform cycles are either drawn freehand or traced on a digitizing tablet. Once entered, the waveform is automatically cycled, adjusted for rate and pressure, and positioned for proper display later on the cardiac monitor. Numerical analysis methods are used to merge the drawn waveforms with the previously entered heart rate and pressure data. Art. = arterial; ECG = electrocardiogram; PA = pulmonary artery; RA = right atrial; RV = right ventricular.

Table 1.—**Outline of Information Needed for Authoring a Single Module in Construction of a Simulated Case**

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- I. History and physical examination (initial module)
 - A. Identify with a pseudonym (base name)
 - B. Type appropriate information *or*
Progress notes and consultations (subsequent modules)
 - A. Identify with an identification number appended to the base name (for example, Smith, John[1...99])
 - B. Type appropriate progress note or consultation
 - II. Hemodynamic data
 - A. Enter rate and pressure data for the initial examination and consequence of each treatment option
 - 1. Heart rate
 - 2. Catheter pressure readings (right atrial, right ventricular, pulmonary artery, wedge)
 - 3. Arterial pressure (systolic and diastolic)
 - B. Enter waveform data for the initial examination and consequence of each treatment option (actual tracings may be used)
 - 1. Rhythm strip
 - 2. Hemodynamic monitoring catheter
 - 3. Arterial line
 - C. Merge data (process waveforms to match rate and pressure)
 - III. Study options and results
 - A. Enter studies for the initial examination and consequence of each treatment option
 - 1. General laboratory
 - 2. Cardiac studies
 - 3. Pulmonary and respiratory studies
 - 4. Microbiology
 - 5. Nuclear medicine studies
 - 6. X-ray and imaging studies
 - 7. Additional
 - B. Include reserved words with study results*
 - 1. "Unnecessary" and "inappropriate" synonyms
 - 2. Performance score (-100...100)
 - 3. Cost of study or procedure (\$n,nnn.nn)
 - IV. Treatment options
 - A-D. Enter up to four treatment plans
 - V. Discussion text
 - A. Enter up to four discussion replies to the treatment options above
 - B. Include reserved words with each discussion
 - 1. Next module's identification number ([1...99])
(This indicates to the system which module to link automatically once a given treatment option is selected)
 - 2. "Unnecessary" and "inappropriate" synonyms
 - 3. Performance score (-100...100)
 - 4. Cost of treatment (\$n,nnn.nn)
-

*See "Performance Evaluation."

Trainee Operation.—The trainee begins a simulation by selecting a case from the library (a listing of cases is presented on the computer screen by selecting the appropriate menu item) and reviewing the information provided on the initial history and physical examination. A

flowchart of the trainee operation is shown in Figure 7.

As in a real-life situation, students may order studies, select a treatment plan, seek consultation, or connect the patient to a cardiac monitor. Studies are performed by selecting from study

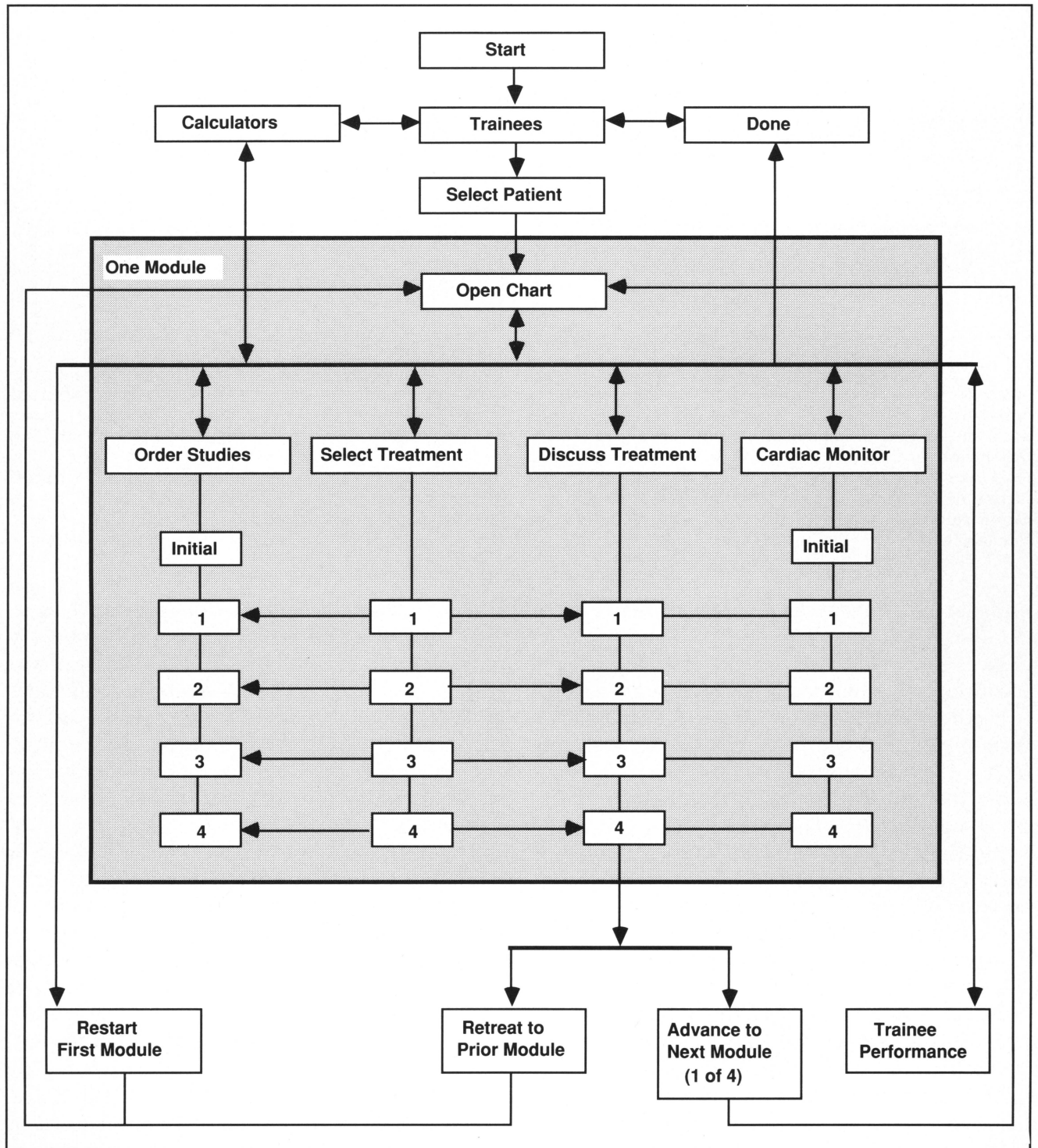


Fig. 7. Flowchart of program operation for trainee level. Once a patient has been selected and the history and physical examination have been reviewed, the trainee may elect to order studies, select a treatment plan, review discussion material, or connect the patient to the cardiac monitor. "Initial" data are presented if no treatment has been selected. After one of four treatment plans has been selected, ordering further studies or review of the cardiac monitor will reveal the consequences to the patient (numbered boxes). If appropriate, the trainee may—by selecting "Advance to Next Module"—review the chart again for progress notes or consultations and thereby continue management of the patient.

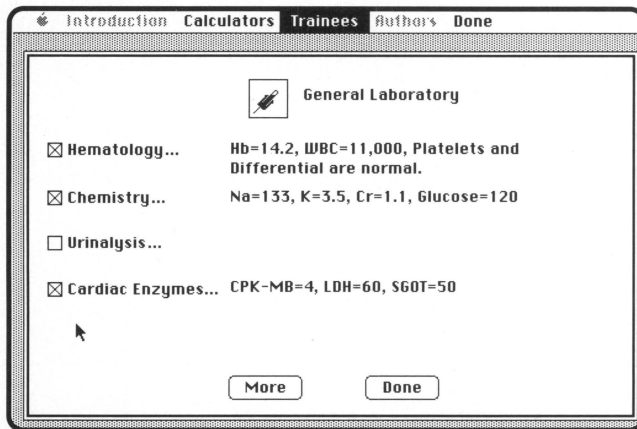


Fig. 8. Laboratory studies are ordered by checking an option from a list of studies made available by the author, as shown in example. Several categories of study are available, and most departments of a major referral center are included. *CPK-MB* = creatine kinase MB isoenzyme; *Cr* = creatinine; *Hb* = hemoglobin; *K* = potassium; *LDH* = lactate dehydrogenase; *Na* = sodium; *SGOT* = serum glutamic-oxaloacetic transaminase; *WBC* = white blood cells (leukocytes).

alternatives programmed by the author (Fig. 8). Similarly, a treatment plan is selected from choices provided by the author (Fig. 9). Once a treatment plan has been chosen, all data change to conform with the intervention. Cardiac catheterization may be performed at any time simply by selecting the cardiac monitor from the computer menu and introducing a catheter into the torso apparatus. The initial data presented (including both digital and analog display of waveforms) undergo real-time changes that correspond with the treatment provided. This process is made possible by the author's having previously entered the data as a consequence of the selected treatment.

Simulated care is continued by reviewing progress notes and consultations, ordering additional studies, and selecting additional treatment alternatives. Continued care is possible because of automatic linking of previously authored modules. The care rendered may improve, worsen, or cause no change in a patient's condition. The final management of the patient is dependent on the *sequence* of modules selected and may vary from one trainee to the next.

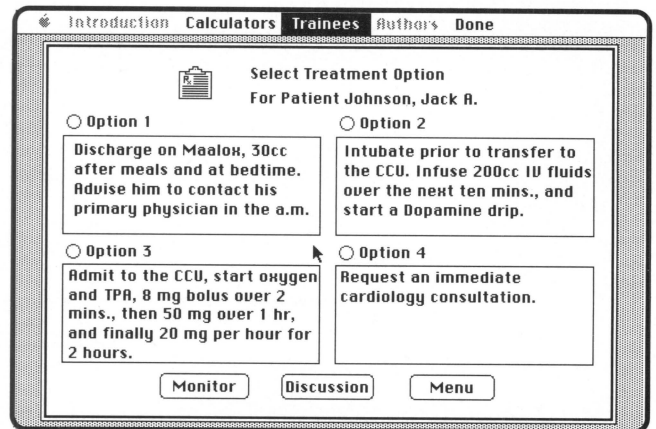


Fig. 9. Trainees may select from one of four treatment plans with each module. Once a treatment has been selected, further ordering of studies or review of the cardiac monitor will reveal the consequences to the patient. A trainee may select another treatment plan if the initial choice is less than favorable. The author determines which treatments (if any) will cause the case-management problem to progress beyond the current module. *CCU* = critical-care unit; *IV* = intravenous; *TPA* = tissue-type plasminogen activator.

Performance Evaluation.—Trainee performance is monitored for both cognitive skills in patient management and procedural skills at catheterization (Fig. 10). The former is accomplished by assignment of a numerical score for the care delivered, determination of the numbers of unnecessary and inappropriate studies or treatments, and cost analysis of the care delivered.

The author assigns a point value (positive or negative) to each study and treatment; thus, evaluation is based on utilization and quality of care. In addition, because the author assigns a dollar amount to each study and treatment, the total cost for rendering the specified care can be determined.

Determination of unnecessary or inappropriate studies or treatments is accomplished by automatically scanning an author's text for reserved words. For example, if the trainee orders a lumbar puncture, the following authored response could appear:

Patient refuses. Performing a lumbar puncture would be unsafe in light of the head computed tomographic findings. (-10) \$125.00

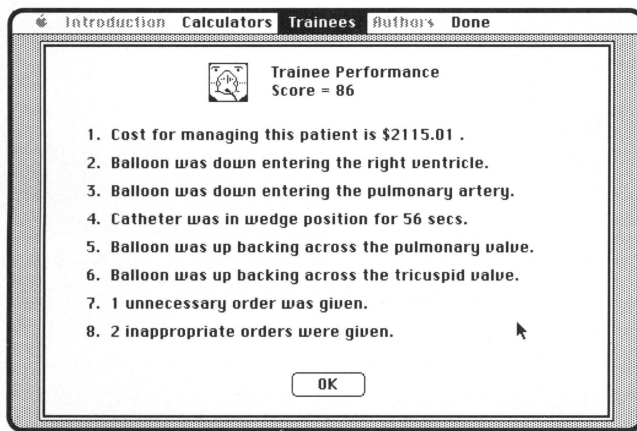


Fig. 10. Performance is assessed for both cognitive and manual dexterity skills. The system automatically processes authored information to identify unnecessary or inappropriate actions taken by the trainee.

In such a situation, the system would recognize the word "unsafe" and would increase the "inappropriate" score by one. In addition, selecting this test will decrease the trainee's "performance score" by 10 and increase the "cost of care" by \$125.00.

Critical-Care Calculators.—Special screen calculators allow rapid determination of essential indices in critical-care management and thus are an important adjunct for selection of treatment or assessment of outcome. Subject areas include hemodynamic, respiratory, ventilatory, and renal function (Fig. 11). The trainee or author may use these calculators at any time. "What if..." analyses can be performed by simply changing one or more input variables and again selecting "Calculate" on the screen. These calculators are being tested for use as a separate tool in the critical-care unit. Several monitor manufacturers have incorporated similar calculator features into their own displays.

OBSERVATIONS

Each author must be responsible for the validity of the curriculum developed. This requirement is particularly important if the system is to be used for testing or certification purposes. Because no standard of care is purported by the

system, authors must give the same attention to detail and accuracy of cases as they would a lecture or publication.

Once a case has been created, it should be observed in use to ensure its clarity, utility, and module-to-module consistency. To enter waveform data, instructors must have either (1) a complete understanding of the hematologic consequences of the disease or therapeutic intervention or (2) representative data (actual patient tracings) for direct entry into the case.

Before using the system, trainees should be oriented to the torso apparatus and Macintosh computer, as well as instructed in the proper technique for insertion of a catheter. Once this orientation has been completed, they may work independently with the system and may check their own performance at any time.

Once created, cases may be modified at any time or deleted entirely. Moreover, they may be exchanged with other system users by simply copying and exchanging disk media.

The initial impressions of specific users of this computerized system have been favorable. In particular, the ease of use by the true computer novice and the quick ability to program cases and monitor tracings into the equipment were considered important features.

DISCUSSION

Potential.—This system is not intended to replace actual patient contact but rather to prepare the trainee before encountering certain management problems. The trainee may be a medical student learning basic skills or an experienced cardiologist desiring to study problems rarely encountered. In addition, the system may be used to demonstrate models of unusual cardiovascular function, such as an artificial heart.

The system has been used with overhead projection of the computer display for conference presentation; thus, in effect, a physician or nurse can bring a "patient" to the conference by being able to present a real-time cardiac monitor. This system also enables the presenter to demonstrate the sequence of events in a patient during

Fig. 11. Hemodynamics calculator is one of four calculators available in this system. Once all input values have been entered, selecting "Calculate" will cause immediate display of indices. Selecting any rectangular box brings up a display that contains the definition, derivation or formula, and comments. *ABP* = arterial blood pressure; *BSA* = body surface area; *CI* = cardiac index; *CO* = cardiac output; *CVP* = central venous pressure; *HR* = heart rate; *Ht* = height; *LCW* = left cardiac work; *LCWI* = left cardiac work index; *LVSW* = left ventricular stroke work; *LVSWI* = left ventricular stroke work index; *PAP* = pulmonary artery pressure; *PAWP* = pulmonary artery wedge pressure; *PVR* = pulmonary vascular resistance; *PVRI* = pulmonary vascular resistance index; *RCW* = right cardiac work; *RCWI* = right cardiac work index; *RVSW* = right ventricular stroke work; *RVSWI* = right ventricular stroke work index; *SI* = stroke index; *SV* = stroke volume; *SVR* = systemic vascular resistance; *SVRI* = systemic vascular resistance index; *Wt* = weight.

the hospital stay or to review problems as they exist for the patient.

Finally, this computerized simulator offers an alternative to animal-oriented workshops in catheter use and may lessen the need for experimental animals for this purpose.¹⁹

Limits.—This system is currently limited in its ability to simulate ventilator management, and the torso apparatus is not designed for placement of airways, chest tubes, or intra-aortic balloons or for performance of thoracentesis or pericardiocentesis.

A potential drawback of the system is the prospect of a poorly authored case becoming widely used; thereby, unacceptable procedures or methods may be learned. This risk can be reduced by peer review of authored cases, simi-

lar to the peer-review process for scientific manuscripts.

CONCLUSION

Although a computerized simulator for critical-care training is a technologic achievement, determination of the system as a useful instructional tool or certification aid must come from broader use and controlled studies. Investigators may wish to determine the system's usefulness in the following areas: (1) as a training, testing, certification, or modeling aid; (2) in evaluating utilization and quality of care delivery; and (3) in identifying discrimination patterns in patient care based on insurance, age, sex, religion, or race.

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