LEARNING PHYSIOLOGY FROM CARDIAC SURGERY PATIENTS

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A number of pressures have led to a very great reduction or complete abandonment of the use of animals in the teaching of physiology in most medical schools. Often animal experiments have been replaced by computer simulations, but a simulation is only as good as the model or algorithm on which it is based and can never contain the depth of information or unpredictability displayed by real animals or patients. We used a computer-based system to collect cardiovascular data from patients instrumented for cardiac surgery, allowing students to “replay” an operation. These recordings were annotated with notes, diagrams, and video clips, and a student workbook was written. The resulting package contained a wealth of physiological data and was perceived by students to be very clinically relevant. The very wealth of information, however, tended to overwhelm students, and so a series of introductory computer tutorials were written to provide students with the background necessary to cope with the clinical data.

Key words: cardiovascular physiology; hemodynamics; cardiothoracic surgery; arterial pressure; central venous pressure; pulmonary artery pressure; electrocardiogram

Since the founding of the Medical School at the University of Tasmania in 1965, the majority of systems physiology has been taught in the second year of the six-year course, which was initially divided into three years of preclinical studies and three years of clinical studies. There was a very high number of hours of formal teaching, including a large practical component. An important part of the teaching of practical cardiovascular physiology was the use of anesthetized cats, which were prepared by a demonstrator before the class began. Blood pressure and heart rate were recorded from an arterial cannula, allowing examination of cardiovascular reflexes, the effects of various drugs, and the effects of hemorrhage. Over 25 years this anesthetized cat preparation gave many hundreds of our students their first real understanding of the control of heart rate and blood pressure and a general appreciation of the principles of hemodynamics in a whole animal.

By the late 1980s, however, as in the majority of medical schools, increasing class sizes, increasing costs, and decreasing funds made us examine all aspects of our teaching. Setting up large numbers of cat preparations for individual groups of students became increasingly impracticable and expensive, and this experiment could only be run as a class demonstration. At the same time, there was an acceptance that we should attempt to reduce the amount of formal teaching time and provide students with more opportunities for self-directed learning and a more flexible approach. A final significant factor was increasing pressure from animal rights activists against the use of animals, particularly mammals, in teaching,
making it difficult to use even such environmentally damaging animals as feral cats.

This has been an experience common to most medical schools, and the usual response has been to replace animal experiments with computer simulations. However, computer simulations are only as good as the model or algorithm on which they are based and can never contain the depth of information or unpredictability displayed by real animal or patient data. This subject has previously been discussed in some detail in this forum (1).

A POSSIBLE ANSWER

During a visit to the cardiac surgery unit of the Royal Hobart Hospital it occurred to one of us (S. Nicol) that patients instrumented for cardiac surgery represent much superior physiological preparations than could ever be set up routinely for practical classes using animals. In the cardiothoracic unit at the Royal Hobart Hospital the following are routinely monitored: electrocardiogram (ECG), systemic arterial pressure, pulmonary artery pressure, central venous pressure, nasopharyngeal temperature, pulmonary arterial temperature, partial pressure of expired CO₂, and oxygen saturation of the blood. These data are displayed on a physiological monitor in the operating theater. Other pressures may be recorded if required. The pulmonary arterial pressure is measured with a Swan-Ganz catheter fitted with a balloon, which when inflated gives the pulmonary artery wedge (or occlusion) pressure. Cardiac output is also measured from this catheter by the thermal dilution method. From these data it is possible to calculate the vascular resistance of both the pulmonary and systemic circulations, stroke volume, stroke work, and many other cardiovascular parameters.

RECORDING AND PRESENTATION OF DATA

We were fortunate that the physiological monitor used in the cardiothoracic unit (Siemens 1281) provided analog outputs of the raw physiological data, which we were able to record on a Macintosh-based system. Data were digitized and recorded using hardware and software from ADInstruments (MacLab/8 and CHART, ADInstruments, Castle Hill, NSW, Australia) and an Apple Macintosh Powerbook 180c computer. In most cases we recorded six channels of physiological data from the monitor: two ECG channels (lead II and V5), systemic arterial pressure, pulmonary artery pressure, central venous pressure, and end-tidal CO₂. Heart rate and mean arterial pressure were derived from these data and recorded on the other two input channels. A sampling rate of 40 Hz appeared to be optimal, providing acceptable resolution of the fast components of the ECG. At this sampling rate, a 4-h operation produced a 2.5-Mb file. For the tutorials (see below), which used only small sections of these CHART recordings, a sampling rate of 100 Hz was used to record the data to give better resolution of the ECG. A suite of recordings was made of different cardiac procedures on a wide range of patients with a variety of clinical conditions. CHART uses a chart recorder metaphor, producing recordings that can be played back or scrolled through by students in the computer laboratory. Figure 1 shows an excerpt from one of the patient records, demonstrating a change of rhythm from normal sinus rhythm to atrial fibrillation. CHART also has a number of features that allow easy analysis of data. Values of any of the variables can simply be read off the chart by moving the cursor to a point of interest. A zoom window allows channels to be overlaid (Fig. 2) and sections of the record to be examined in more detail, and a data pad provides functions such as calculation of the mean, maximum, and minimum values in a selected area of the chart, as well as the rate of change (Fig. 3). From the suite of cardiac patient recordings, we selected five for use in the teaching exercises:

- coronary artery bypass graft (CABG) procedure on 43-yr-old male
- atrial septum defect repair (1.8:1 shunt) in 29-yr-old male
- aortic valve replacement (incompetent bicuspid valve) in 30-yr-old male
- CABG on 73-yr-old male
- CABG + mitral valve replacement (incompetent valve) in 77-yr-old male

In addition, an example of a recording from the cardiac catheter laboratory was included in the exercises. This recording was from an investigation of mitral valve stenosis in a 55-yr-old female patient.
These recordings displayed a range of underlying cardiac rhythms, including normal sinus rhythm, sinus bradycardia, junctional rhythm, and atrial fibrillation. Also, many rhythm disturbances were recorded, such as atrial, junctional, and ventricular ectopics, temporary conduction blocks, paroxysmal ventricular and supraventricular tachycardias, and ventricular fibrillation.

The hemodynamic features displayed in these recordings included venous and arterial pressure waveforms evident with the various underlying cardiac rhythm, as well as changes caused by changes in rhythm and rhythm disturbances. By recording the ECG together with the pressures it was possible to directly correlate changes in rhythm with changes in cardiac function. There were examples of abnormal venous pressure waves resulting from valvular pathologies, such as elevated a and v waves in the central venous pressure and pulmonary artery wedge pressure recordings. The effects of infusion of vasodilators, vasoconstrictors, and other agents and actions on hemodynamics were well illustrated.

These records were annotated with appropriate text-based comments, for example, marking the start of infusion of a vasodilator or labeling a particular ectopic beat.

Work sheets were written for each recording. These contained a brief patient history and then proceeded through the recording, pointing out salient features and encouraging investigation and exploration of the physiological data. Examples of the data presented and the questions asked in the work sheets are given in Figs. 1–6. Other investigations included the effects of increased heart rate, calculations of systemic and pulmonary vascular resistance, determination of mitral valve cross-sectional area, calculation of stroke volume, investigation of the effects of P-R interval changes (with electronic pacing), and investigation of the contribution of atrial function to ventricular filling.
The exercises were incorporated into the second-year physiology teaching course in 1995 as two 3-h practical sessions. A videotape showing the surgical procedures and how the data were recorded from the patients was shown at the start of the first practical session.

STUDENT RESPONSES

Discussion during and after these sessions, and a subsequent questionnaire, showed that although students appreciated the clinical significance of the recordings, they were overwhelmed with the amount of information that they contained. However, it seemed to us that the wealth of information in the recordings was their strength, and students would be able to gain greatly from working with the recordings if they were adequately prepared. Central venous pressure, for example, would rarely be recorded in animal-based teaching experiments but provides invaluable information on the patient's hemodynamic status during surgery. However, textbooks aimed at undergraduate medical students provide little information on dynamic changes in central venous pressure. Most commonly this information will be restricted to a Wiggers diagram. It was not really possible for students to appreciate the interrelationship of dynamic changes in central venous and other pressures in the circulatory system, or the effects of drugs, in health and disease, until they were able to identify the a, c and v waves in the central venous pressure recording, for example. Patient pathologies resulting in abnormal waveforms and pressures (e.g., Figs. 4-6), although obviously of great value to the advanced student, also caused confusion to the beginning student.

Clearly, there was a need for a gentler introduction to this material, and to provide this we used selections from the chart recordings to produce a series of tutorials. To make these readily available to all mem-
FIG. 3.
Response to infusion of glyceryl trinitrate (GTN; at point marked by comment 22) and demonstration of Data Pad function. Top line of data shows values from period indicated by shading on AP trace. Bottom line shows preinfusion values. Students are asked, “Infusion of glyceryl trinitrate (GTN) had what effect on: arterial pressure; pulmonary artery pressure; central venous pressure; heart rate? What is the action of GTN (vasodilator/vasoconstrictor)? What is a likely explanation for the slight increase in heart rate? Suggest an explanation for the increased CVP.”
bers of the class, and to provide a degree of interactivity, these were written in HTML (Hypertext Mark-up Language) and placed on our Internet web site. Two tutorials were developed, one covering hemodynamics and the other dealing with cardiac rhythms. The interested reader will find these at http://www.healthsci.utas.edu.au/physiol/tute1/Intro.html. The hemodynamics tutorial has sections covering venous, atrial, and arterial pressure waveforms. The main aim of this tutorial was to describe the origin of the components of venous pressure waveforms, namely the a, c and v waves, and to describe a simple means of identification of these waves in the venous pressure traces. Explanations of the genesis of the venous waves are excerpts from the patient recordings illustrating the relationship between the venous waves, the ECG, and the arterial pressure waveform, under various circumstances. Numerous exercises reinforce the message. The aim of the rhythms tutorial was to describe and explain some common rhythms and demonstrate the effects of these rhythms on cardiovascular hemodynamics. A didactic introductory approach, consisting of illustrated examples and explanations, soon makes way for exercises requiring application of the newly acquired knowledge. In both tutorials the exercises consist of chart excerpts from the patient recordings, with the student asked, initially, to identify nominated features, and, subsequently, to interpret and analyze the hemodynamic and ECG data more deeply. A feature of these tutorials is the integration of cardiac electrical activity (from the ECG) with cardiac function (from the hemodynamic data). Figure 7 shows an example exercise from the rhythms tutorial.

In 1996 and 1997, second-year physiology students worked through the tutorials before attempting the patient record exercises, which were revised and updated with graphic and video annotations to illustrate more clearly procedures and instrumentation.
Observation of students working through these tutorials illustrated a major benefit of computer-based learning. Each student appeared to take a different approach, with some going home and working via modem, some taking copious notes, some working together, others alone, some trying to understand everything the first time, and others going through several times, and some deciding to leave and do the work later. One practical problem with the tutorials was that the students were scheduled for a 3-h session, which resulted in cognitive overload. Several shorter sessions would have been more effective.

One result of placing these introductory tutorials on the Internet was that a variety of students and health professionals have come across them while “surfing the Net.” Some of the unsolicited comments we have received are summarized in APPENDIX A. There appears to be a gap in published resources in this area, and our initial attempt at production of tutorials appears to be a considerable step forward.

We are now in the process of converting these introductory Web-based tutorials to a more interactive form using the software package Authorware. Those students who have trialed the first Authorware version have reported it be easier to use than the Web-based version. When completed, the introductory tutorials and the annotated charts will be transferred to CD-ROM, which will be made available to other institutions, as well as to our own students.

SUBSEQUENT EVALUATION OF TOTAL PACKAGE

Several months after using these teaching packages students were asked to complete a questionnaire asking how well the total package (introductory tutorials plus CHART recordings) had helped them learn and understand a number of areas. Twenty students returned questionnaire forms, and the results are summarized in Table 1. In the areas emphasized in the introductory tutorials, such as the identification of...
venous pressure waves, the interpretation of ECG recordings, and the identification of cardiac rhythms, the package was very successful. In areas covered only in the CHART recordings, such as the calculation of vascular resistance, the package was less effective. Asked to give an overall rating of the Internet-based introductory tutorials and the CHART recordings on a scale of 1 (poor) to 5 (very good), students gave a
CONCLUSIONS

It has taken more than three years to go from the idea of using computerized recordings of patient hemodynamic data to producing a teaching package based on these recordings. The resultant package overcomes one of the major disadvantages of computer simulations that produce results that are predictable and repeatable. By contrast, recordings of patient data show true biological variation, and students will encounter the unexpected and unpredictable. Indeed, there is so much information in these recordings that it is possible for the enthusiastic student using the analytical tools in the CHART program to examine phenomena or relationships that have not been fully described in the literature. However, the open-ended nature of this material means that beginning students are rather intimidated, and the more didactic tutorials developed from the patient records were perceived by our students to be more useful than the patient records themselves. Students with some prior experience of hemodynamic monitoring tended to show more enthusiasm for the patient chart recordings, perhaps because they were better able to grasp their significance. For example, students with nursing experience indicated that they were able, finally, to make sense of hemodynamic recordings.

Although we developed the introductory tutorials to prepare students for the CHART recordings, they have turned out to be very useful by themselves. The dramatic rise in use of the World Wide Web has meant that a package developed for Tasmanian students has, at the same time, been used and appreciated by students and health professionals around the world.

APPENDIX A

Extracts From E-mail Comments From People Who Have Found the Hemodynamics Tutorial on the World Wide Web

Hi! I've just done the haemodynamics tute on the www and thought you might like to know that I found it VERY useful. In fact, it brought everything together (finally) that I didn't really understand properly for all this time!

Hi. Just browsing and came across this tutorial. I am a nurse educator in the USA and teach hemodynamics to new critical care nurses several times a year. Enjoyed your tutorial and will recommend it as a review to my students. Thanks.

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Thanks for the work you're doing with the cardiac tutorials on the web. I am a nursing student and when I found your page I came close to calling my instructor in excitement. (Yea, I have a pretty boring life!) I find the cardiac system extremely fascinating and will certainly visit your site again. I wish I had more time to explore it tonight but I've got to focus on my pharmacology. Thanks again!

I'm an RN in an ICU in a small city in Pennsylvania (Altoona). I just stumbled across your hemodynamic waveform page and found it very interesting.

I am a Critical Care Clinical Nurse Specialist. I am writing to ask permission to download some of the Hemodynamic Tutorial wave-
forms onto slides and transparancies to teach other critical care nurses more about waveforms. I will print the WWW page on the bottom of each image, and give full credit for the source. Your site is one of the best medical resources on the internet.

I'm a third-year Medical resident at Northwestern University School of Medicine in Chicago. I'm starting a Cardiology fellowship at Emory University in Atlanta next year. Your page has been quite useful for me, in that it facilitates teaching of my medical students. I find it quite helpful. Keep up the good work!

There I was sitting at my desk, preparing for my three h lecture on pneumothorax in the NICU, when I thought to have a small browse on the net. Two hours later I have been undertaking your fantastic tut. Could you give my lecture in the morning?

Hi. Just browsing and came across this tutorial. I am a nurse educator in the USA and teach hemodynamics to new critical care nurses several times a year. Enjoyed your tutorial and will recommend it as a review to my students. Thanks.

I will be doing a lecture in February on the Use of the Internet for Nurses. I may want to show your site either in a handout or in a live session. I will promote your site and list it in a list of nursing internet sites. I look forward to your reply.

Thanks, the tutorials were very helpful. I work as a nurse and would like to see info. on the effects of drugs on PA, wedge and A-line tracings.

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