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The Design and Implementation of a Pulmonary Artery Catheterization Simulator

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Abstract. Pulmonary Artery Catheterization (PAC) is a commonly performed procedure. It is used when hemodynamic and other cardiac measures must be accurately monitored in seriously ill patients. A flow-directed, balloon-tipped (Swan-Ganz) catheter is typically inserted into a major vein, passed through the heart, and into the pulmonary artery. This procedure is normally not performed under fluoroscopy. Instead, transducer readings from the catheter tip provide a continuous report of local blood pressure. An experienced practitioner can infer the catheter's location from this information, yet several studies have found that physicians and critical care nurses have a wide variability in competency. A simulator for this procedure can address some of the educational and training issues highlighted. This paper describes our ongoing progress in developing a PAC trainer.

Keywords. Pulmonary Artery Catheterization, Medical Simulation, Common Medical Simulation Platform,

1. Introduction

Pulmonary Artery Catheterization (PAC) is a minimally invasive procedure that is performed to accurately measure a range of hemodynamic parameters. These measurements can be made over an extended time period (days). Conditions that may require PAC include heart failure, shock, acute valvular regurgitation, congenital heart disease, burns, and kidney disease. PAC may also be performed to monitor for complications arising from a heart attack, or to monitor the effects of certain heart medication.

A Swan Ganz catheter [1,2] is used for the procedure. This is a multi-lumen catheter approximately 110 cm in length. The catheter is introduced percutaneously into the body. To accomplish this, the Seldinger technique [3] is normally used. A Cordis introducer is inserted in a major vein. Common access approaches include the internal jugular vein and the subclavian vein. A small inflatable balloon is located near the distal (far) end of the instrument. Once the catheter is inserted, the balloon is inflated. Blood flow causes the catheter to be drawn toward the heart, through the right atrium and ventricle until it becomes lodged in the pulmonary artery. Pressure and temperature sensors are located along the catheter. When inserted correctly, additional openings in the catheter permit measurements to be conducted at strategic points in the heart, such as the right ventricle, right atrium, or superior vena cava. Using this catheter, a number of key cardiovascular parameters can be determined, including cardiac output, and central venous pressure. Blood samples can also be retrieved in some versions of this catheter.

The catheter is normally inserted without fluoroscopic guidance [4,5]. Instead, a sensor near the tip provides continuous real-time feedback of local blood pressure. An experienced physician can interpret the pressure trace and determine the location of the tip.

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A need exists to provide adequate training in this procedure. Recent studies show uniformly poor performance on multiple choice testing of all aspects of pulmonary artery catheterization given to 535 European critical care physicians [6]. Similar findings have been found with several hundred intensive care physicians in the US and Canada [7]. In this study, 47% of clinicians were unable to correctly derive even the most basic information provided by the PA catheter.

To address the training requirements of this procedure, we are building a computer-based PAC simulator. This paper describes the ongoing work.

2. Methods

Building the PAC simulator involves both hardware and software development. In this section, we briefly describe SimPod, a common hardware platform for medical simulation. The main software components of the PAC trainer are also described.

2.1. Hardware

The PAC simulator is built on the SimPod platform. The SimPod is currently under development at Verefi Technologies. Formerly known as VRDemo, the SimPod aims to provide a common hardware platform for simulation development. Medical simulators have many common hardware elements. They include one or more displays, a computer system, and common input hardware such as keyboards and pointing devices. Each simulator must duplicate these elements and integrate them with procedure-specific components. Often, proprietary interfaces are developed. This approach increases the cost and complexity of bringing a simulator to market.

The SimPod addresses these limitations. The current prototype consists of a central hardware core, containing elements common to all simulation systems. The core includes a single-board computer with a Pentium IV 2.8 GHz processor. This provides the computational power necessary for modeling the physical and physiological aspects of the procedure. High-end graphics hardware provides the rendering capability for visual feedback. The graphics hardware drives a touch-sensitive LCD display, which also serves as an alternative input device in place of the mouse. All procedure-specific tools and hardware plug into the central core via a common USB-based communications bus with a well defined, open standard.

This unified architecture simplifies simulation development. An open interface standard encourages the development new procedures. Hardware developers can focus on building only the devices necessary for a new procedure. By developing on a common platform, the cost of adding new simulations can be reduced. Earlier SimPod prototypes have demonstrated the concept of interchangeable, procedure-specific tools for use in laparoscopy. When complete, PAC will extend SimPod's repertoire of supported simulations.

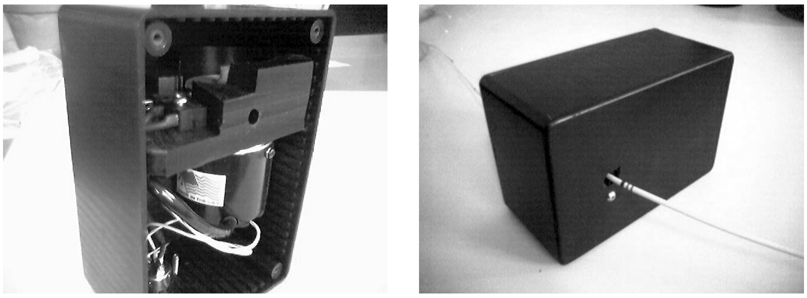
The PAC simulator uses a catheter tracker specifically developed for this purpose. The tracker plugs directly into SimPod. When in use, the catheter is passed through the tracker, simulating passage of the instrument into the body. The device is completely self-contained. Power for the device is drawn off the USB bus. The tracker consists of an opto-mechanical rotary encoder, a complex programmable logic device (CPLD), and a USB-bus interface. Movement of the catheter rotates the encoder. Fig. 1 illustrates the current prototype. The device is self-calibrating, and can reliably measure catheter movement with an accuracy of $0.001cm$ at speeds of up to $5 \times 10^5 cm/s$. A smaller final version will be developed. The reduced size will make it suitable for embedding within a mannequin, thereby providing greater realism.

2.2. Software Components

The main software components of the PAC simulator consists of the Graphical User Interface (GUI), and an AI engine for modeling patient physiology and scenario control. We describe each in turn.

2.2.1. The Graphical User Interface

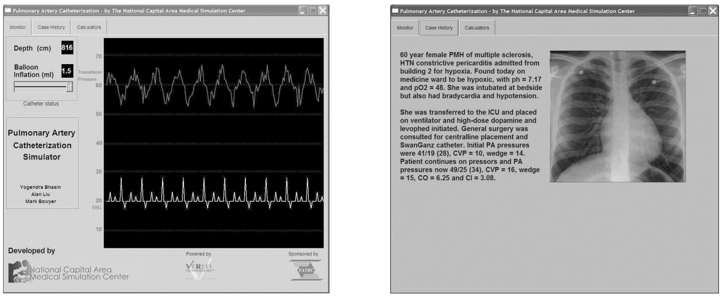
During the simulation, the GUI displays pressure transducer and EKG waveforms. As the catheter is advanced, the waveforms change. The displayed traces are consistent with the present location of the catheter's distal end. The AI module, described in section 2.2.2, controls the nature and type of waveform displayed, depending on the nature of the simulated patient.



(a) (b)

Figure 1. The catheter tracking device. (a) Rotary encoder, (b) The assembled device. A catheter can be seen passing through it.

In addition to transducer and EKG traces, the user can also retrieve material specific to the present scenario, such as the patient's history, and the hemodynamic measurements to be performed. The GUI also serves as a means for students to receive feedback on their performance. Fig. 2 illustrates.



(a) (b)

Figure 2. The graphical user interface. (a) Displaying pressure and EKG traces. (b) Displaying the patient's history.

2.2.2. The AI Module

The AI module controls the scenario and the physiology of the virtual patient during the course of the simulation. It models a particular scenario as a a finite state automaton (FA) [8]. New cases can be added to the simulator by defining a different FA. In our implementation, the FA consists of a set of states S. Each state $s \in S$ represents a particular combination of the patient's condition, and the catheter's position that may occur during the course of the simulation. The initial condition of the patient is given by the start state $s_0 \in S$. A set of states representing possible final outcomes is given by $S_e \subset S$. Both successful as well as unsuccessful outcomes are included.

Each state s has a set of transitions T_s to other states. A transition consists of a set of conditions c, a set of actions a, a destination state, and the probability p that this transition occurs. Examples of conditions include events such as the catheter balloon inflating, or time intervals. When all the conditions of a transition are satisfied, the AI module executes the set of actions specified in a. Examples of actions include: changing the displayed waveform, alerting the student that an error has been made, and updating the patient's condition.

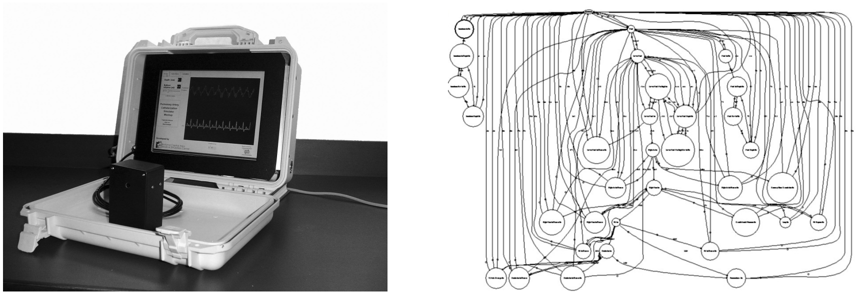
When the simulation begins, the AI's current state is set to s_0. The student's actions changes current conditions in the simulator. When these conditions match one or more transitions from the current state, a transition occurs and the current state is changed. The patient's condition changes in response. The student notes these changes and proceeds further, which in turn causes the AI to enter a new state. This cycle continues until a final state is entered, at which point the simulation ends. If the student correctly performed the procedure, a successful end state is reached. Otherwise, an unsuccessful end state is reached, and the patient suffers an undesirable result, such as death.

Transitions can also be probabilistic. When conditions for more than one transition are satisfied, a transition is randomly chosen with a probability given by its value of p. Probabilistic transitions can be used to model different patient responses to treatment. They also permit a range of complications to be simulated with varying frequency. By changing the value of p for different transitions, the same scenario can be made easier or more difficult by allowing complications to occur with different degrees of likelihood.

3. Results

Fig. 3(a) illustrates the current PAC simulator running on a prototype SimPod. This version of the SimPod was designed to be portable, and has been ruggedize for use in austere environments. The entire simulator, including the LCD touch-panel display and computer, is built into a hard-shell carrying case. The catheter tracker fits within the case.

Fig. 3(b) is a graphical illustration of the state machine for a typical case. The scenario includes a number of common complications, such as the catheter looping within the right ventricle.



(a) (b)

Figure 3. (a) The PAC simulator running on a prototype SimPod. (b) A visual representation of a FA for a sample scenario.

4. Discussion

The PAC simulation focuses on imparting cognitive skills. To provide a comprehensive learning experience, it must be capable of presenting a wide range of cases and varying levels difficulty.

A FA is a flexible method for representing medical case content. Both normal outcomes and complications can be modeled. As there can be an arbitrary number of of states and transitions, the detail to which the case is modeled is fully determined by the case author. The instructor can begin with a straightforward case, then add complexity as required to address advanced training requirements. Probabilistic transitions allow for more realistic patient responses to treatment. Complications can occur with varying probabilities, given the nature of the patient. Differences in the patient can cause that individual to behave differently given the same treatment. These variations can also be modeled using probabilistic transitions. By changing relative probabilities, the same scenario can be made easier or more difficult as required based on the student's skill level. In this way, the same scenario can be revisited multiple times as the student gains experience. Finally, the random nature of such transitions implies that no two simulation experiences are exactly the same, even with the same scenario. This variation challenges the student, and helps sustain the individual's interest.

A disadvantage of using a FA is the large number of states required, even for simple cases. We are currently investigating semi-automated methods for constructing FAs that model case content. One promising approach is to present only relevant portions of the FA in detail, and to collapse non-relevant states for display as aggregate states. An interactive visual editing tool for this purpose is currently being planned.

5. Conclusion

PAC is a procedure that is performed to monitor hemodynamic parameters in seriously ill patients. Proficiency in this procedure requires the ability to correctly interpret blood pressure waveforms during catheter insertion, and the ability to perform calculations of hemodynamic state based on sensor readings. This paper presents the design of a PAC simulator. Development of the simulator is currently ongoing. Our development effort differs from previously developed simulators by adopting a common platform. This approaches permits new hardware development to be minimized. The result is reduced cost and development time. The simulator also includes an AI module that uses a FA to model patient physiology. This approach is both flexible and powerful. The patient's physiology can be modeled with as much or as little detail as desired. The ability to use probabilistic transitions permits the difficulty level of a scenario to be changed without rewriting the case. It also enables the simulation experience to be slightly different every time, even when practicing on the same case.

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