Cardiopulmonary Bypass Simulation Training
Adapted from Air Force Flight Simulation

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ABSTRACT

Real-time, interactive simulators are used extensively for teaching pilots to employ the operational characteristics of their aircraft. Pilots can "fly" a multimillion-dollar aircraft without risk to the aircraft, other people, or themselves. They can encounter realistic scenarios to prepare them for actual flight situations. They can experience rarely occurring phenomena without risk, and prepare to react to problems before they occur. Medical errors are an increasing phenomenon in military and civilian healthcare systems. Medical simulations have gained widespread acceptance in the military, particularly in combat medical triage. But many medical professionals must react in emergency situations without the benefit of practice training. Rather, they must learn from real-life patient situations. The sophisticated medical procedure of operating the heart-lung machine during open-heart surgery operations is an example. Similar to pilots, perfusionists (the professionals who operate the heart-lung machine) must react to multiple variables, in hurried timed sequences, and in extremely stressful situations. Mismanagement of cardiopulmonary bypass can lead to death or increased morbidity of the patient. Lessons learned in the Air Force for training fighter pilots and other combatants are being applied to medical arenas to increase training effectiveness and to decrease the incidence of medical errors.

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Cardiopulmonary Perfusionist (CP) is a medical professional who works with a surgical team operating heart-lung machines and other systems during cardiac surgery. Like many other medical specialties, CP training focuses on academic instruction together with observing procedures conducted by an experienced practioner followed by hands-on work during actual surgeries under supervision of an instructor. In addition, training surgeries are conducted using animals as patients (Austin & Harner, 1990). Real-time simulation technology is being developed that will support CP training in much the same way that pilots have been trained using simulators since World War II. Creating a high-fidelity simulation of an actual experience, however, is not sufficient for effective training. Instructional strategies, training syllabi, and simulation scenarios must be developed, evaluated, and implemented to take best advantage of real-time simulators as training tools. During the past decade, military simulators have grown from single devices that focused on training individual, procedurally oriented skills to networks of simulators that focus on training team and inter-team, mission-oriented skills (Alluisi, 1991; Ramesh & Andrews, 1999). Lessons learned from training effectiveness research conducted with fighter pilots and air weapons controllers at the Air Force Research Laboratory are being applied to the development of training systems and strategies for CPs.

Flight training simulators range in cost and complexity from personal computer software to multi-aircraft networks of high fidelity simulators. In all cases, the instructional strategy underlying simulator training is to provide the opportunity for students to practice skills first learned in academics in a safe, real-time environment that will prepare them for continued training in higher cost and higher risk training environments. Medical simulator training is providing similar benefits. Students can practice their skills in a real-time, paced environment, see the consequences of their actions, rehearse emergency procedures, and gain experience dealing with unusual events. Emerging developments in military simulator training technologies and strategies will provide additional opportunities for training medical personnel on a wider range of skills.

Distributed Mission Training

Flight training simulators for Air Force pilots have traditionally focused on one pilot or cockpit crew. Training was limited by the number of aircraft functions that could be simulated. In the mid-1970s, it was proposed that training for the many combat skills that require interactions among multiple aircraft could be accomplished using networks of interacting simulators (Hapgood, 1991). Feasibility and effectiveness of networked, real-time simulators was demonstrated for Army tanks in the late 1980s (Thorpe, 1987) and for fighter aircraft in the early 1990s (Bell & Crane, 1993). Based on these developments, the U. S. Air Force's Air Combat Command has adopted Distributed Mission Training (DMT) as a fundamental strategy for acquiring and using simulator systems (Hawley, 1997, 1998). Under DMT, networks of high-fidelity simulators for fighter aircraft, air weapons controllers, and other combatants are being established at operational air wings and not limited to training squadrons. The overall objective of DMT is to complement the current aircraft-based training program with multi-player simulator training exercises.

In support of Air Combat Command's DMT initiative, Air Force Research Laboratory's Warfighter Training Research Division has undertaken a program of training effectiveness research using a prototype network of four F-16 simulators equipped with full field-of-view visual display systems, an Airborne Warning and Control System (AWACS) air weapons controller station, a system for providing computer-generated entities including enemy aircraft, a

control and observation station, and a mission replay and debriefing system (Crane, Schiflett, & Oser, 2000). Results from DMT effectiveness research exercises have revealed that DMT provides pilots with opportunities to prepare for higher cost training events and to gain experience on infrequently practiced tasks and missions. The skills that are best suited for enhancement include both individual skills within a team context and skills that involve coordinated actions from multiple pilots. Two examples illustrate the value of DMT.

Task Management by Upgrading Flight Leaders. Newly qualified fighter pilots first gain experience as wingmen where their primary responsibility is to execute the mission plan as briefed by the flight leader. This includes radar search, targeting (locking the fire control radar onto a group of enemy aircraft in accordance with the plan), sorting (selecting a particular aircraft within the group), and weapons employment. After gaining experience as wingmen, pilots are selected for Flight Lead Upgrade Training (FLUG) where they learn the skills required to plan, brief, lead, and debrief two- and four-aircraft formations. Review of training records and interviews with instructor pilots demonstrated that the four vs many (four F-16s opposed by four or more enemy aircraft) is both a difficult mission for FLUG pilots to master and costly to repeat if the upgrading pilot requires additional training (Crane, Robbins, & Bennett, 2001). In training research exercises at AFRL, instructor pilots used DMT to augment aircraft training for upgrading FLUG pilots. A highly rated benefit of DMT-FLUG training was the opportunity to practice previously learned skills such as targeting, sorting, and weapons employment along with new responsibilities such as communicating with AWACS, maintaining situation awareness for the entire flight, assigning responsibilities to wingmen, and continually assessing the tactical situation. Early during a week of DMT, upgrading pilots experienced considerable difficulty keeping up with all of these tasks while engaging four enemy aircraft. By the end of several days of training, upgrading pilots successfully engaged multiple waves of six or more enemy aircraft. For this application, DMT provided the opportunity for upgrading pilots to refresh their existing skills in a more demanding environment and master new skills. Instructors rated FLUG pilots who had trained using DMT as better

prepared for aircraft training and less likely to require repeating a training mission.

Team Tactics in Defensive Counter Air Missions. A second high-payoff application of DMT is advanced air-to-air training for experienced teams of pilots and an air weapons controller. Research has demonstrated that pilots and controllers show continual improvement for individual tactical skills such as sorting, targeting, weapons employment, and tactics selection over five days of training using a building-block syllabus. Improvements in team skills such as communication, leadership, situation awareness, and tactical execution, however, showed a noticeable decline when teams switched from Offensive Counter Air (OCA) to Defensive Counter Air (DCA) missions at mid-week. In OCA missions, teams were tasked to find, engage, and defeat flights of four or more enemy aircraft. In DCA missions, teams must establish a Combat Air Patrol and defend their airspace for 15 – 25 minutes. Debriefings with participants revealed that several skills that are integral to DCA missions are infrequently practiced in the aircraft due to cost, airspace, and resource constraints. These skills include: grinder tactics in which the four-ship flight separates into two elements that alternate attacks against incoming enemy aircraft; pause mechanics when all F-16s turn away from the enemy, increase range, and then turn to re-engage; and de-louse procedures in which one aircraft or element engages an enemy aircraft that is pursuing another F-16. In this application, DMT provides not only a real-time environment in which to practice selected skills, but also the opportunity to review missions, discuss what went well and badly, and how events might have been handled differently. After a day's experience and discussion, team skills for DCA missions increased sharply (Crane et al, 2001).

Fighter Pilots and Cardiovascular Perfusionists

While the responsibilities of pilots and perfusionists are dramatically different, many of the skills within the two domains are remarkably similar. A perfusionist is a person skilled by academic and clinical education, who operates a heart-lung machine during cardiopulmonary bypass--a surgical procedure that uses the heart-lung machine to enable a surgeon to repair or replace portions or all of the heart and/or to make corrective surgical

manipulations. Successful utilization of cardiopulmonary bypass equipment requires decision-making and skilled reactions from an experienced perfusionist. Blood from the patient is diverted to an extracorporeal circuit where the blood is continuously processed. Oxygen is added, carbon dioxide is removed and the critical acid-base balance of the patient is controlled while the temperature of the blood is regulated, and the flows of gases and rate of flow of blood are adjusted. These activities must be performed skillfully to meet the needs of the patient and of the surgical team while the heart is often stopped to accomplish a surgical repair (Cooper, et al, 1984). The simultaneous monitoring and control of many variables at one time characterize cardiopulmonary bypass (Austin, 2000). Variables, when viewed singularly, can be confusing and can lead to misinterpretation of the physiological status of the patient. A significant portion of perfusionist training is dedicated to recognizing and understanding the physiological significance of each of these variables individually and in context.

Both pilots and CPs work in a real-time, externally paced environment requiring both highly skilled psychomotor skills and well-developed cognitive skills. Pilots and CPs must learn both individual and team skills, attend to multiple sources of information, and perform multiple tasks simultaneously. Effective performance in both domains requires maintaining situation awareness, effective communication, decision making, plus task and time management. Both environments can also be characterized by hours of limited activity interspersed with moments of intense action. In addition to being prepared for anticipated events, pilots and CPs must also be prepared for rarely experienced emergencies. Given these similarities, training strategies and interventions that have proven to benefit pilots and air weapons controllers should be applicable to CPs even if the simulation technologies used are very different.

Training Using Multi-Participant Simulation

For fighter pilots, DMT represents a middle ground between single-ship simulator training and large-force exercises. In single-ship simulator training such as responding to in-flight emergencies, an instructor introduces an emergency such as an engine malfunction and then waits for the student to respond. Events are highly scripted and the instructor can easily evaluate good vs poor performance. In contrast, large-force exercises are much less scripted at the level of individual pilots. Evaluators will know where and when forces will engage but will have only limited control over each pilot's experience. The training methodology being developed for DMT takes advantage of the instructor's ability to script the actions of computer-generated forces. The goal of this system is to create training scenarios that will exercise specific skills and provide instructors with the tools required to determine proficiency (Crane, 1999). Similar approaches to multi-participant simulator training exercises have been developed by U. S. Army (Campbell, Quinkert, & Burnside, 2000) and Navy (Smith-Jentsch, Zeisig, Acton, & McPhearson, 1998) researchers. For all three services, scenario design and selection is the instructor's primary training intervention.

Design of a training syllabus for a given application such as FLUG or advanced air-to-air combat begins with listing the competencies required for the selected mission together with specification of the required supporting skills and knowledge (Colegrove & Alliger, 2001). Based on these competencies and the needs of student pilots, instructors define training objectives for a DMT exercise. Given these training objectives, instructors and other subject-matter experts then identify trigger events that can be programmed into scenarios. Trigger events are defined as the actions of programmed entities that require trainees to exercise the selected skills. For example, if the selected competency is to conduct multiship air combat operations using beyond-visual-range tactics, the required skills will include radar search, targeting, sorting, weapons employment, and communications in accordance with standards. Trigger events for different scenarios will include enemy aircraft entering the defended airspace in various formations and performing multiple maneuvers. Pilots being trained will plan and brief their mission, fly multiple scenarios, and then replay and debrief all scenarios. During debrief, instructors can assess the team's actions, suggest alternative tactics, assess the team's level of proficiency for the selected competency, and decide on the next training activity. The capability to replay, review, discuss, and repeat training missions is a valuable component of DMT.

CP Simulation Using Scenario-Based Training Strategies

Scientists from AFRL are working with educators at Midwestern University's Glendale, Arizona campus, College of Health Science, and medical simulator designers to develop a CP training laboratory based on instructional principles developed from DMT. The goals of this cooperative effort are to: 1) develop an effective simulator for CPs and other members of the surgical team, and 2) implement a program of scenario-based training based on principles developed for DMT.

CP Simulator Development

Design and development of a simulator for CP training will require integration of many medical simulation and training technologies. Three additional elements are required to incorporate lessons learned from DMT.

The first is integration of multiple participants in the simulator exercise representing other members of the surgical team. In DMT research at AFRL, these individuals are either other trainees using real-time simulators or programmable, computer-generated entities (see Crane, Schiflett, & Oser, 2000). Most often computer-generated entities represent enemies, however, friendly assets such as tanker aircraft or the AWACS are also computer generated. An alternative approach has been used in DMT research efforts in the Royal Air Force. In these exercises, a cadre of role-players who either communicate over the radio or use limited-fidelity simulators represent enemy and supporting friendly forces (McIntyre & Smith, 2000; Greig, Mayo, & Crush, 2000). Both approaches provide for training team and interteam skills by requiring trainees to communicate with others, coordinate their actions, and maintain situation awareness with respect to friendly and enemy forces. For CP training, capabilities must be developed to represent members of the team including the surgeons, anesthesiologist, and others.

The second requirement is the capability to introduce programmed trigger events into the training scenario. These will include normal surgical events and procedures together with unanticipated events. Trigger events provide the means to link training objectives to selected scenarios and to evaluation criteria.

The third requirement is for capability to record, replay, and review a simulation exercise. In the AFRL DMT testbed, information from each cockpit including radar and radio communication is recorded together with a map-like view of the engagement. This information is then replayed in a separate debrief facility with controls for pause, reverse, replay, and fast forward. Replaying missions gives teams the opportunity to review their actions, assess tactics, and identify strong and weak aspects of their performance, and discuss alternatives. Instructors use the replay facility to point out trigger events together with the situational cues that provided critical information. Instructors also use the replay facility to assess team performance in response to trigger events. Using this capability, instructors can readily assess whether trainees should progress to more complex scenarios or receive additional training on more basic skills. For CP training, replay must include recording of patient data, CP actions, other surgical activities, and communications.

Training Applications

The effectiveness of scenario-based, real-time simulator training for enhancing the skills of cardiovascular perfusionists is being assessed for three training applications: 1) initial skill acquisition and consolidation for students, 2) capstone training for recent graduates entering the profession, and 3) continuation training for experienced practitioners.

Initial Training. Simulator exercises will be used at Midwestern University to augment academic and laboratory training with the goal of consolidating particular skills, increasing situation awareness, and preparing the student for practice within the team environment of an operating room. The training scenarios will be based on a building block approach in which students will first practice particular skills in isolation and later in context with other skills. In addition to developing procedural skills, emphasis in simulator training exercises will be placed on developing skills in patient/system monitoring, communication with other surgical team members, and situation awareness.

Training effectiveness will be assessed in two ways: progress checks during training and performance on the national certification examination compared to students in other

Master's in Cardiovascular Perfusion training programs.

Capstone Training. Recently graduated CPs from Midwestern University and other programs who are ready to enter the workforce will receive scenario-based, simulator training. Skills to be emphasized in these scenarios will include: patient/system monitoring, situation awareness, communication, and decision making. Effectiveness of simulator capstone training will be assessed by comparing on-the-job performance evaluations of entering practitioners who received simulator training with a baseline comparison group of recent graduates who have not received this training.

Continuation Training. Simulator scenarios will be developed to enhance the skills of experienced practitioners. The skills to be emphasized in these exercises will include: rarely experienced events such as emergency procedures, operation of new equipment, and employment of new perfusion techniques.

Conclusion

A new generation of military simulator systems is extending the range of applications for simulator training. In addition to mastering individual, procedurally oriented skills, multi-participant simulator networks are being used to complement aircraft training for operational teams including fighter pilots and air weapons controllers. A critical element in the success of DMT has been development of training strategies based on design and sequence of DMT scenarios. Incorporating selected trigger events into scenarios that are tied to both training objectives and evaluation criteria allows instructors to tailor simulator training to the needs of the students and enhance the effectiveness and efficiency of simulator training.

Lessons learned from advances in simulator-based training for the military are being applied to medical training for CPs. Incorporating capabilities for introducing trigger events into training scenarios together with tools for replay and review into the design of surgical simulators will enhance the effectiveness and increase the range of applications of medical simulator training.

About the Authors

Barbara Sorensen is a Senior Research Psychologist at the U. S. Air Force Research Laboratory. She holds a Ph.D. from the University of Iowa in a multidisciplinary domain of Mathematics, Educational Psychology, and Computer Science. She has an extensive background in training and simulation crossing domains of air, space, force protection, and medical technologies.

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