

# The provision of sophisticated critical care beyond the hospital: Lessons from physiology and military experiences that apply to civil disaster medical response

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**Objective:** The provision of sophisticated medical care in an austere environment is challenging. During and after a mass casualty event, it is likely that critical care services will be needed beyond an intensive care unit (ICU) setting. The objective of this article is to explore existing ICU care systems such as military aeromedical transport that may be applicable to disaster medicine and to providing critical care outside of an ICU setting.

**Results:** The U.S. Air Force Critical Care Aeromedical Transport (CCAT) Teams were developed in 1994 in response to an unmet military need for long-range air transport of critically ill and injured patients. This system has transported several thousand ICU patients and is an applicable model for the future develop-

ment of extrahospital critical care capabilities needed during a disaster. We also discuss civilian aeromedical critical care systems, the types of medical devices used, and their applicability to disaster medical response.

**Conclusion:** The U.S. Air Force CCAT Team program, as well as many civilian critical care air ambulance services, provides a workable starting point for the development of disaster medical critical care response capabilities for disaster medical systems. (Crit Care Med 2005; 33[Suppl.]:S13–S21)

**KEY WORDS:** austere critical care; intensive care unit air transport; aeromedical evacuation; portable intensive care unit; disaster critical care

Critical care and intensive care unit (ICU) bed availability are limited resources in most hospitals. Although the critical care unit remains the designated geographical locale in a hospital where the majority of intensive care occurs, there is a growing acknowledgment and discussion about the critical care that is provided everyday to patients away from the ICU (1). We know that critical care is deliberately and nondeliberately provided in other locales, in the hospital and beyond. Who administers this care? What is the training and background of these providers? Do they function as a multidisciplinary team? How are patient monitoring and timing of clinical interventions determined and accomplished? How are these patient parameters and treatment protocols used, and how are they agreed

on? Are there critically ill patients outside of the ICU who are in physiological peril that we fail to recognize and then do not intervene decisively, even when we should? Finally, what can we learn from these evolving experiences that might be applied to the critical care-specific aspects of disaster medical response?

During the last decade, much of our local, regional, and national medical disaster response planning efforts have been directed at prehospital, first-responder, and emergency medicine infrastructures (2). For many locales and scenarios, this remains the current reality. To a large extent, most disaster planning has previously assumed that appropriate critical care will be available to casualties who are triaged, resuscitated, and transported by first-responder infrastructures to hospitals. For example, it is a relatively recent trend to address the logistics of assuring an adequate number of mechanical ventilators would be available for a large-scale respiratory failure scenario. As a second example, the outbreak of Severe Acute Respiratory Syndrome (SARS) underscored the health risks to ICU personnel who cared for afflicted patients with respiratory failure. SARS sternly reminded us that our ICU and hospital preparedness needs additional work. Efforts

to address these kinds of shortfalls are ongoing but will require a significant increment in ICU planning within and beyond the ICU for a successful large-scale medical disaster response.

A well-planned scenario response may require the provision of high-level critical care in locales that were not anticipated. As a parallel, during patient transport, sophisticated care requirements may be greater than anticipated (e.g., sedation and pain control, vasopressor support, patient monitoring in a difficult or austere environment, multiple patients requiring mechanical ventilation). Critical care may be needed for longer transport durations (e.g., long fixed-wing flights as opposed to shorter helicopter flights) and may include care requirements that extend beyond the initial resuscitation phases of treatment (e.g., recognition and support of multiple organ failure).

All of these lessons are directly applicable to the process of planning and establishing the critical care capabilities necessary for an effective disaster response. If a hospital is rendered unusable, for whatever reason, sick patients must still receive appropriate care. Access to hospitals may be blocked, or hospital ICU bed space may be overtaken and may not

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be available. What is “plan B” if any of these events transpire?

Maintaining a consistent and acceptable standard of care for critically ill patients outside the hospital setting is challenging, and especially when or if they develop physiological instability. Issues like availability of compressed medical gases, suction, dust control, and electricity can become difficult logistic issues. Communications, working in a noisy and/or inadequately lighted environment, and maintaining climate homeostasis are additional hurdles to care. Nevertheless, with proper equipment, training, and personnel flexibility, sophisticated critical care can be provided.

Given these conditions, how will this happen, who will provide this care, do they have the necessary training, and do we have the needed equipment to make this happen successfully? In this article, we explore the recent experiences of the military with “far-forward” critical care, as well as critical care air transport as applicable. We will focus our discussion on the aspects of these programs that are directly applicable to civilian aspects of critical care medical disaster response. We also offer opinion regarding useful approaches for future planning, development, and training activities.

## ORGANIZATIONAL ISSUES

### Who Provides Critical Care During a Disaster?

*The Team Concept.* The most reliable approach to medical disaster planning is to acknowledge and incorporate the premise that disaster critical care should be provided by the same personnel, the same teams, and using the same general protocols as are routinely used everyday. Everyone knows their roles and responsibilities. What changes during a disaster are the location(s), patient volume, and the need for triage, chain of command (who is in charge), and the potential need for self-preservation. However, where this starts to “break down” is when demand surges exceed resource availability. At that point, noncritical care medical personnel will become substantially involved in ICU-level care and will likely provide a portion of this care away from a traditional ICU. To a greater or lesser extent, this is our current reality in hospitals everyday.

To address the challenges, and as a possible model for civil disaster ICU med-

ical response, let us consider the approach taken by the U.S. military to support deployed servicemen and women who become critically ill in remote locales away from a “bricks-and-mortar” ICU. In 1994, the U.S. Air Force initiated the development of mobile critical care teams (called Critical Care Aeromedical Transport Teams [CCAT teams]) that carried in their backpacks all of the necessary medical devices, equipment, and supplies to care for three ICU patients per team (3). For example, these patients can range from otherwise healthy young adults with severe traumatic injuries following damage-control surgery to older individuals with life-threatening decompensation of chronic diseases (e.g., myocardial infarction, pulmonary embolism, and diabetic ketoacidosis). Patients may be mechanically ventilated; may require hemodynamic or other cardiorespiratory monitoring (e.g., pulse oximetry, capnography); and may be receiving cardioactive, sedative, or other complex pharmacologic regimens. These teams carry rudimentary diagnostic tools, including a small portable ultrasound device, a point-of-care laboratory instrument, and in some circumstances, portable bronchoscopy. These teams consist of an “intensivist” with formal critical care fellowship training or a physician with significant critical care background (e.g., emergency medicine specialist), a critical care nurse, and a respiratory therapist (4). The original intent of these teams was to augment the existing aeromedical evacuation system, providing routine and regular availability of sophisticated critical care capabilities during aeromedical missions. However, because of the mobility of these teams, they have been used in numerous ground-based austere locations as well.

Each team member must be actively involved in the care of critically ill patients before their deployment as a CCAT Team member. All team members complete a 2-wk comprehensive intake training program introducing all elements of CCAT Team function (3). This program includes aerospace physiology as it applies to critical care, team function and training, and aspects of care specific to functioning in an austere environment. In addition, these teams may complete additional training at a designated Center for Sustainment of Trauma and Readiness Skills (CSTARS) (see the article by Johannigman, this supplement, pp. S22–S28). This is also a 2-wk program that emphasizes team function at an Ameri-

can College of Surgery-designated level one trauma center.

During recent testimony to the U.S. House Armed Services Committee (March 18, 2004), Lt. Gen. George “Peach” Taylor, MD, the current U.S. Air Force Surgeon General, offered the following comments to illustrate the capabilities of these teams:

“Recently, one of our aeromedical evacuation crews augmented by a CCAT Team flew into Baghdad on a C-130, under black-out conditions and while taking fire to retrieve three severely wounded soldiers. These troops, too, needed ventilators to help them breathe. They were quickly loaded and even before the aircraft could take off again, our CCAT Teams were providing life-saving care to their patients. While in the air, the aircraft was diverted to Talil where U.S. forces had come under attack. Two more men were critically wounded there and needed immediate aeromedical evacuation. Both of these troops also required ventilators. All five soldiers were flown that night to an Army medical facility in Kuwait. The Air Force medics on that mission are proud of their accomplishment—never before, or since, has there been a combat aeromedical evacuation mission in which a team cared for five patients on ventilators in one aircraft. I’m proud of them, too. Without the aeromedical evacuation concept and the skills our medics brought to the theater, each of those five soldiers would have succumbed to their injuries.”

The use of CCAT Teams during the recent hostilities in Iraq and Afghanistan has had a profound impact on the early movement of seriously injured patients to higher levels of care. The military has long had the capability to perform damage control surgery in far-forward locations. The rate-limiting step has been the absence of postoperative critical care capability and holding capacity. As a result, some surgical interventions could be delayed rearward. However, the immediate availability of these mobile critical care teams has changed this dynamic and has dramatically reduced the time from injury to resuscitation and surgery. Since the initiation of these surgical and critical care interventions over the last decade, the calculated died-of-wounds rate for soldiers in Afghanistan and Iraq is the lowest in the history of modern warfare (Lt. Gen. [Ret.] Paul K. Carlton, Jr., MD, USAF Surgeon General, personal communication).

This same modular, portable approach to critical care is potentially well suited for disaster medical response. It is scalable, mobile, and has capabilities that can be quantitated and proportionately applied to a casualty stream after a civil disaster. What remains somewhat controversial is the answer to the question, "Who should provide this care?" Again, we look at the existing air ambulance model for providing critical care as a possible approach/solution. The "ideal" air medical crew composition for critical care has been a topic of discussion for a number of years without resolution (5–10). The mission requirements, scope of medical responsibilities, and personnel availability all contribute to the composition of the flight crew. A survey of civilian hospital-based flight programs in the United States shows that a nurse/paramedic composition is the most common combination, although physicians, respiratory therapists, and emergency medical technicians are occasional team members (11).

Currently, there are no national standards for the qualifications of medical personnel actively participating in the air transport of critically ill or injured patients (12). Recommended training for these aeromedical crew members include education and experience in altitude physiology, management of patients in the prehospital setting, and flight communications and safety. Additionally, for nonphysician personnel, "they should have the ability and training to function autonomously in a variety of settings with treatment protocols if immediate communications with a physician is not possible or if immediate life-saving actions are required" (13).

*Nurses.* By far, the majority of flight teams include a registered nurse as the team leader. In the evolution of air medical services, the majority of air transports in the United States have been interhospital transports in which patients are moved from the source hospital to one capable of providing a higher level of necessary care. As such, patients should anticipate receiving a level of care comparable to that of the sending facility. The inclusion of registered nurses with specialized skills meets this need in most instances. According to the American Society of Hospital Based Emergency Air Medical Services (ASHBEAMS)-recommended standards, "staffing the aircraft shall be commensurate with the advanced life support environment afforded

by the airborne emergency care facility" (14). This staffing should include, at a minimum, "at least one specially trained registered nurse."

Nowadays, the "specially trained registered nurse" is most commonly a flight nurse. The National Flight Nurses Association has established practice standards for flight nurses and provided numerous position statements regarding the role of flight nurses in the delivery of care during air transport (13, 15, 16). The U.S. Air Force has a 6-wk training program to provide registered nurses with the additional skills and experience to become military flight nurses. By covering the additional training and education described here, these individuals are better prepared to transport the critically ill and injured patients needing a higher level of care than that provided by basic transport services.

*Paramedics/Other Technicians.* The most common air medical crew configuration for use in the United States includes one registered nurse and one paramedic (11). During the mid-1980s, many flight programs turned from predominantly registered nurse crews to ones that incorporated the prehospital skills of the paramedic. The National Flight Paramedics Association (NFPA) (17) has stated that minimal training standards and qualifications for paramedics in this field should include:

1. Successful completion of an approved emergency medical technician (EMT)-paramedic course that uses Department of Transportation EMT-paramedic course guidelines;
2. Biennial successful completion of an American Heart Association Advanced Cardiac Life Support Provider course;
3. Successful completion of either a basic trauma life support course or prehospital trauma life support course with respective refresher courses as required;
4. Successful completion of an additional course of instruction (when available) designed for flight personnel and including specific air medical modalities and issues; and
5. Three years' experience in the field as an EMT working as an advanced life support provider.

Another development that will contribute to the increased use of paramedics in transport is the development of critical care paramedic (CCEMT-P) training pro-

grams. A recent study examined the impact of a paramedic-staffed mobile ICU performing interfacility transports (18). The authors concluded that specially trained paramedics "can monitor and treat patients appropriately during interfacility transfers that traditionally would have required supplementation with additional hospital staff." Although this was a small study, the potential to use less costly personnel may cause some transport services to reexamine their current staffing mix.

*Physicians.* Few transport teams include routine, direct physician support on the aeromedical crew. In an attempt to determine whether the presence of physicians improves patient outcome, a number of studies have examined various programs with differing results. For example, Wright and colleagues failed to demonstrate a change in mortality with physician involvement during the aeromedical transport of patients with traumatic cardiac arrest (19). In contrast, Baxt and Moody reported a decrease in mortality for blunt trauma patients without traumatic arrest when a physician was part of the transport team (5). The majority of studies of this type deal with prehospital management and scene responses when stabilization before transfer is the key issue. In a review of aeromedical transportation, Moylan observed that available data "demonstrate clearly that the interval between the accident and arrival of the helicopter medical personnel at the scene of the accident or outlying hospital—not the speed with which the patient is delivered to the tertiary care facility—is the key factor in improving survival." (20) If physician involvement has an impact on patient outcomes in most scenarios, it lies in the preflight stabilization of the critically ill or injured patient. This is not a trivial consideration because 24% to 70% of transferred patients may be inadequately stabilized before transport (21).

For longer, fixed-wing transport, the same controversy exists. The U.S. Air Force has used a mix of flight nurses and aeromedical evacuation technicians since the 1960s for the movement of patients by air. With recent changes in missions and logistic support, there has been increasing emphasis on physician involvement. During Operation Just Cause when U.S. Forces went into Panama, the aeromedical evacuation system designed to move stable patients found itself with a requirement to transport fresh casualties

(22). The inclusion of physicians on these flights and those generated during the Gulf War (23) led to the creation of the CCATT program, as described previously.

Beyond direct contributions to the transport team, physicians also provide support as air or transport service medical directors with established programs. A well-prepared medical director contributes greatly to the development of treatment protocols, quality processes, crew training, and administration. The degree of involvement, however, varies widely (24). Currently, most physician directors lack experience in air medical practice, particularly in the areas of medical training, practical experience, and longevity in their current position. Many of these positions are unpaid and performed on a part-time basis with responsibility for a wide range of skills not typically acquired during medical training. These deficits are similar to those associated with the air crew members in which there is a lack of standardization in training, education, experience, and function. Organizations such as the Association of Air Medical Services (AAMS) and the Commission on Accreditation of Medical Transport Systems (CAMTS) have published standards that should improve this process.

In summary, during a disaster medical response, a surge in casualties will likely drive a spike in the quantity of critical care services required. It seems tenable that the models for staffing and emergency response that are currently used for aeromedical transport (military and civilian) could reasonably be applied to initial disaster medical response for critically ill patients. In particular, we believe the three-person model used for the CCAT Teams is a flexible and workable option that should be considered.

### **Necessary Equipment for Critical Care Response During a Disaster**

*Medical Devices.* The care and monitoring of patients in the aeromedical environment or during a disaster scenario requires the use of modern biomedical equipment. Devices that work perfectly fine in the ICU on the ground may not function as expected when taken to even moderate altitudes, or may experience total dysfunction after loss of cabin integrity and rapid decompression. Similarly, the stresses of a disaster medical response environment may also limit the use of much of the standard equipment we use

everyday in the ICU. Beyond tolerating the direct effects of altitude and other stresses of flight, aeromedical equipment must also be able to function safely in conjunction with the radiofrequency (RF)-transmitting equipment found on the aircraft. Not only must the medical devices not interfere with the communication and navigation systems found on the aircraft, those same systems should not produce electromagnetic interference (EMI) with the monitoring equipment. In 1989, 70% of neonatal transport equipment failed military-specific testing for potentially excessive EMI (25). In addition, when such medical devices are carried outside of the ICU and hospital, they are subject to climate and other environmental impact that may alter their function.

At Brooks City Base in San Antonio, Texas, the U.S. Air Force Aeromedical Research Group is devoted to evaluating and certifying biomedical equipment for use in military air transports (26). Their testing procedures evaluate the impact of vibrations, acceleration/deceleration, rapid barometric pressure changes, and wide temperature shifts on a variety of medical devices. Testing requirements are less stringent in the civilian community, although recommendations exist for equipment used in air ambulances (27).

One of the more unique considerations in the flight environment is the power requirement for biomedical equipment. Unlike commercial power, which provides 110 VAC at 60 Hz, most fixed-wing aircraft operate on 110 VAC at 400 Hz or 12-V DC, whereas rotary-blade aircraft generally operate on 28-V DC systems. With average rotary wing missions in the United States taking a little less than 2 hrs and fixed-wing transports lasting over 4.5 hrs (28), transport equipment must have longlasting battery support or be able to convert aircraft power to conventional 110 VAC at 60 Hz. This can be accomplished through frequency inverters or direct DC-to-DC conversion adapted to equipment battery packs (29).

Although frequency inverters are large and heavy, fixed-wing flights may necessitate their use as a result of the length of the mission. If lead-acid batteries are used, they must be sealed and protected to ensure case integrity. When estimating transport time in relation to battery life, do not forget ground transportation time because this will most likely be accomplished on batteries and can take a significant period of time.

In an austere environment, or even away from the hospital, an external power source for medical devices may not be reliably available. During these circumstances, battery life and durability become vitally important for life support equipment. A power failure can become life-threatening. Therefore, these time elements are crucial planning elements of the critical care disaster response plan. Timelines for critical care response algorithms (away from a hospital) must incorporate the useable battery life for each class of ICU portable medical device.

*Monitors.* In 1993 the American College of Critical Care Medicine and other groups published Guidelines for the Transfer of Critically Ill Patients (30). Although these guidelines were targeted to generic intra- and interhospital transports, by extension, many of the recommendations are directly applicable to the provision of critical care during a disaster scenario. In their approach to monitoring, the basic tenet was to provide the same physiological monitoring during transport as received in the ICU before transfer, if technologically feasible. They further established a minimal level of monitoring to include continuous monitoring with periodic documentation of electrocardiogram (ECG) and pulse oximetry; and intermittent measurement and documentation of blood pressure, pulse rate, and respiratory rate. In addition, certain patients, based on their clinical status, might benefit from monitoring by capnography; continuous measurement of blood, pulmonary arterial, or intracranial pressures; and intermittent measurements of central venous and pulmonary arterial occlusion pressures or cardiac output.

The most basic of monitoring skills require no mechanical devices beyond a stethoscope and sphygmomanometer. In the flight environment, however, noise significantly limits the ability of the provider to use these simple tools for assessing blood pressure and heart/breath sounds. The noise level typically seen in medical helicopters is 95 to 100 dB and is approximately 2,000 times louder than heart tones and breath sounds (31). Even transport by fixed-wing aircraft does not guarantee an environment that will be adequate for auscultation. Military aircraft such as the C-130 Hercules and C-141 Stratolifter have noise exposures approaching those seen in rotary wing aircraft (32). Assessment during transport by quieter commercial aircraft is not

immune from interference either (33). The use of amplified stethoscopes and monitoring devices has not solved this problem (31, 34), although the advent of new techniques such as esophageal stethoscopy may resolve some of these limitations (35).

To compensate for the noise factor, other monitoring techniques must be used. Use of palpated systolic blood pressures taken at the radial or brachial site can be readily accomplished, although they are notably inaccurate in the critically ill even when they can be obtained (36). Automated blood pressure monitors, either as standalone devices or as components of an integrated monitoring package using oscillometric or other methods of noninvasive measurements, are commonly used in this environment. Reported problems with the use of this technology in the air transport environment include unreliability resulting from vibration or movement, difficulty visualizing screens as a result of positioning and ambient light, not suitable for hypotensive patient, high-power requirement, and lack of compatibility with disposable cuffs (37). They are, however, more accurate than those obtained by palpation (36).

Alternative methods for the noninvasive assessment of blood pressure include the use of Doppler and pulse oximetry occlusion techniques in which systolic blood pressure determination after blood pressure cuff release is detected by the return of blood flow or oximetry waveform, respectively (38, 39). Alternatively, invasive blood pressure measurements may be desirable, particularly in those patients at risk for significant hyper- or hypotension during transport. Current transport monitors such as the ProPaq Encore (Protocol Systems, Beaverton, OR) include two channels of invasive pressure monitoring in addition to noninvasive measurement using oscillometric techniques.

Electrocardiographic monitoring, a fundamental requirement in most situations involving the critically ill and injured, is prone to mechanical and electrical interference (26). Although the ECG is useful in the diagnosis of pulseless electrical activity and arrhythmias, during long-term transports, or in a portable ICU setting during a disaster, the ability to monitor for myocardial injury and ischemia is also highly desirable. Unfortunately, many transport monitors lack the resolution required to detect subtle

changes. Some units such as the ProPaq Encore provide an extended bandwidth in which ST segments may be accurately displayed and printed. The lack of automated ST segment monitoring, however, means that the transport team is directly responsible for detecting and analyzing any changes in this parameter. Care should be exercised in this regard because erroneous determinations can be made in patients based on ST segment monitoring using transport equipment (40).

The measurement of oxygen saturation and end-tidal  $\text{CO}_2$  ( $\text{EtCO}_2$ ) do not replace the need to assess the quality and distribution of breath sounds, although these values can be useful in managing the critically ill patient. Pulse oximetry has been used in the aeromedical evacuation environment for a number of years with great success (41–45), although not all models are suited for use in transport (46). With one model, as much as 25% of the measurement time was subject to interference during helicopter transport (47). The ProPaq Encore and some other models incorporate electrocardiograph synchronization that significantly reduces motion artifacts during pulse oximetry measurements during rotary wing patient transport (48).

Similarly,  $\text{EtCO}_2$  monitoring provides information on the adequacy of minute ventilation and the position of the endotracheal tube. Although breath-to-breath values may be misleading, trending the  $\text{EtCO}_2$  provides a better estimate of  $\text{CO}_2$  exchange and minute ventilation requirements (49). The presence of sustained  $\text{EtCO}_2$  after intubation provides evidence of correct positioning when other methods such as auscultation are not available in the flight environment. Additionally, the presence of  $\text{EtCO}_2$  may help with assessment of cardiopulmonary resuscitation because poor cardiac output is associated with a marked decrease in  $\text{EtCO}_2$ . Evaluations of several different models shows that they will should have a defined role in the air transport of intubated patients, particularly when combined with an integrated monitoring package (50, 51). An alternative  $\text{EtCO}_2$  detection device is the disposable colorimetric  $\text{CO}_2$  detector such as the Easy Cap (Nelcor, Hayward, CA). This simple device incorporates metocresol purple into a detection chamber where the presence of  $\text{CO}_2$  changes the color of the detection paper from purple to yellow with some quantitative capability based on the degree of

change. A significant limitation in the traumatized patient with significant airway secretions or the intubated patient receiving humidified gas is inactivation of the indicator strip if it becomes moist. The principle use of this device is the confirmation of tracheal placement of the tube after intubation.

Other monitoring modalities such as cardiac output, temperature, and neuromuscular function, which are commonly used in the ICU, may still be useful in the transport environment or during disaster medical response. Currently, there are no portable monitoring systems with integrated cardiac output measurement capability. The use of a portable blood gas analyzer to assess arterial and mixed venous oxygenation in combination with oxygen consumption calculations based on the Fick equation is possible during longer, fixed-wing transports provided a pulmonary arterial catheter is in place to obtain samples. Temperature monitoring is possible through a number of approaches, including liquid crystalline probes, thermistors, and infrared thermometers. Potential monitoring sites include aural, oral, nasopharyngeal, rectal, bladder, skin, and esophageal locations. The exact location chosen will depend on the equipment available, patient tolerance, and the degree of core temperature accuracy required for patient management. Beyond patient comfort, effective temperature management plays a role in the patient's outcome, particularly in the trauma setting (52).

Besides the reliability aspects of portable medical device use in an austere environment, other aspects of equipment design may additionally limit their functional use. As previously noted, noise may significantly impair the ability to assess a patient directly. Ambient noise levels in an aircraft cabin or other noise-saturated environment will limit the ability of the caregivers to detect the auditory alarms used by most medical devices. This results in increased reliance on visual alarms as well as direct physiological data visualization of medical devices such as ventilators, monitors, and other pieces of equipment. This requires direct attention as opposed to responding to auditory cues without having to divert from other tasks. Fromm and colleagues noted the potential for significant delay in observation of visual alarms in the flying environment with the loss of auditory signals (53). In addition, many of the information displays used in transport-capable

equipment were not designed for use in direct sunlight. Many of these screens can be visualized at limited angles, if at all, when used in an outdoor environment under direct sunlight conditions.

**Ventilators.** The need to develop special transport ventilators for the movement of military casualties was recognized during the United States involvement in Vietnam (54). Branson and McGough outline the definitions, characteristics, classifications, and necessary criteria for an ideal system in a 1990 review of transport ventilators (55). These characteristics included:

- Variable tidal volume (for example, 100–1500 mL);
- Variable ventilator rate (2–30 breaths/min);
- Variable minute ventilation (4–20 L/min);
- Intermittent mandatory ventilation (IMV) and controlled mechanical ventilation (CMV);
- Low- and high-pressure alarms;
- Continuous positive airway pressure (1–20 cm H<sub>2</sub>O);
- Demand-flow valve (for example, 100 L/min peak flow rate on demand); and
- Monitoring of airway pressure.

When addressing the special requirements for transport by air, the ideal ventilator should also deliver a continuous  $V_M$ , without alteration in  $V_T$  or rate, across a wide range of barometric pressures. The newer transport ventilators in use and under development incorporate all of these features and more. Desirable additions such as built-in air compressors or other mechanisms to allow for the delivery of a variable  $FIO_2$  are also available on many of the current models without the need to carry a separate air compressor.

When mechanical ventilatory support is required, how will altitude and the other flight stressors impact ventilator performance? The potential for a decreased (or increased) barometric pressure to affect transport ventilator function has long been recognized (56). In 1969, Kirby and colleagues reported on the function of the Bird Mark VIII Respirator at altitudes up to 34,000-ft equivalent (barometric pressure of 188 mm Hg) in dogs (57). They noted a decrease in ventilator rate and an increase in  $V_T$ . The drop in the ventilator rate was attributed to alterations in the performance of the

expiratory timer cartridge that became overpressurized with the decrease in barometric pressure. The increase in tidal volume was only moderate and the overall  $V_M$  was relatively unchanged.

More recently, Thomas and Brimacombe evaluated a modern transport ventilator, the Dräger Oxylog, under hypobaric conditions (58). This ventilator is a time-cycled, volume-constant ventilator with pneumatic logic controls. Like the Bird Mark VIII Respirator, the Dräger Oxylog showed a moderate increase in TV from 700 to 1442 mL at 30,000 ft with a decrease in ventilator rate from 12 to a little over 8 breaths/min. The overall effect was an increase in  $V_M$  of 13% and 45% at 6676 and 30,000 ft, respectively. Neither of these ventilators is microprocessor-controlled, and the interplay of pneumatic controls limits the impact of altitude on the delivered  $V_T$ .

The Univent, Model 750 and Univent Eagle, Model 754 (Impact Instrumentation, West Caldwell, NJ) are electronically controlled, time-cycled, pressure-limited transport ventilators. The observed increase in tidal volume of the Univent, Model 750 comes close to that predicted by the application of Boyle's Law. Because the delivered  $V_T$  comes from a pressurized gas source at 45 to 55 psi, a certain "mass" of gas is delivered in the microprocessor-controlled time interval that expands by a factor of two at an altitude equivalent of 18,000 ft. This problem, however, is readily avoided in the field by disconnecting the patient from the ventilator and performing a recalibration of the ventilator after significant changes in cabin altitude. Because the calibration process takes almost 60 secs to perform, certain patients may require manual ventilation during this procedure.

The Univent Eagle avoids this potential problem by the inclusion of an internal barometer. Changes in barometric pressure are continuously fed to the on-board microprocessor. In the microprocessor, the current pressure is compared with those located in a lookup table. At 5000-ft intervals, the microprocessor automatically adjusts the flow rate to compensate for the change in barometric pressure based on the correction factors in the lookup table (Les Sherman, Impact Instrumentation, personal communication). These calibration factors are set at 5,000 ft intervals up to 25,000 ft beyond the preset range, the ventilator can be expected to show an increase in tidal vol-

ume similar to that seen in the Univent, Model 750. In the event of decompression at a high altitude, the increase in peak airway pressures should be blunted by the preset peak pressure limits. When these limits are exceeded, the ventilator stops the delivery of gas to decrease the risk of barotrauma. Both ventilators have this pressure-limiting feature.

In addition to the automatic compensation for changes in barometric pressure, the Univent Eagle incorporates a built-in air compressor to allow for an  $FIO_2$  of 0.21 to 1.0. The air compressor output is minimally affected up to 15,000 ft and should perform well in the aeromedical evacuation role. The Aeromedical Research Group has accomplished additional testing of these and other ventilators at the Armstrong Laboratories.

**Infusion Devices.** Infusion pumps are the most common piece of equipment available in today's air medical services (37). Similarly, disaster medical response will require the widespread availability of infusion pumps when or if critical care is required outside of a normal hospital environment. There are a large number of transportable infusion devices available for use. Although patients can receive intravenous fluids through a passive, flow-controlled system, any change in pressure in the intravenous fluid bag as a result of gas expansion can affect the delivery rate. Although this should not be a significant problem at usual cabin altitudes, cabin decompression can significantly alter the flow rate. In addition, rapid decompression can lead to rupture of pressurized bags used to drive higher flow rates when infusion pumps are not available (26). Thus, infusion devices are the preferred method of delivering both maintenance fluids and emergency medications.

Key considerations for selection of a transport infusion device include robustness, operation in multiple orientations, adequate anchorage, extended battery life, pressure-activated occlusion alarms, and a lightweight, compact size. Devices such as the IVAC MedSystem III (IVAC Medical Systems, San Diego, CA) are well suited for this environment with the capacity for three independent delivery channels and 6-hr runtime using all channels at a rate of 125 mL/hr. The Armstrong Laboratory, Brooks AFB, Texas, have approved this system for use in military aeromedical evacuation missions.

**Point-of-Care Testing Devices.** More recent additions to the equipment avail-

able for in-flight use are the point-of-care testing (POCT) systems. POCT allows medical providers to assess a wide range of clinical conditions in a rapid fashion at the site of patient interaction. Although POCT has begun to impact on the delivery of care in the hospital setting, its potential for use in remote field environments or during aeromedical evacuation is just being realized. There are, however, challenges to providing this capability in the field. The environmental considerations are one of the greatest threats for the use of POCT in remote or environmentally hostile environments. Not far behind is the issue of ensuring the repeated accuracy (quality control) of the equipment.

Both the IRMA (Aligent Technologies, Andover, MA) and i-STAT (Abbott Laboratories, Bedford, MA) systems have operating temperature ranges that can easily be exceeded in field and flying conditions. The IRMA will operate from 15 to 30°C, whereas the i-STAT has recently been upgraded to 16 to 30°C. In our experience, this is one of the more common operating errors encountered when using the IRMA or i-STAT outside of the hospital setting. Both devices are capable of working in a low-humidity environment down to 0%. However, their upper operating limit is around 65% according to the manufacturer's recommendations. Barometric pressure should not be a problem under most operating conditions. The IRMA is reported to function from 350 to 900 mm Hg (59–86 kPa). An onboard barometer calibrates the system for the current barometric pressure before each use. The i-STAT has completed testing at the Armstrong Laboratory, Brooks City Base, San Antonio, Texas, where there were no reported problems when using both electronic and liquid controls in a hypobaric environment. This testing resulted in an "approved" rating for its use aboard selected U.S. Air Force aircraft used for aeromedical evacuation.

In two studies that have taken this type of analytical capability out of the hospital and into the field setting, environmental temperature was a consistent problem (59, 60). Both of these studies examined the use of the i-STAT in this role, one in an ambulance service and the other in a helicopter rescue unit. The i-STAT performed well with excellent consistency between samples obtained "on the move" and those run in the emergency department. However, both studies

reported problems when the ambient temperature was cold and had to design special insulated bags to protect the analyzers.

**Drugs.** The same space limitations that dictate the need for compact, efficient hardware also limit the amount of medications available during a transport mission. In addition, the weight and volume of space consumed by intravenous fluid bags is substantial and can be limiting to portability. It is also important to carry a range of medications that provide adequate coverage for emergent efforts to stabilize circulation, improve respiratory function, abolish seizures, reduce pain or stress, and treat toxicities. In a survey of 230 German physicians involved in emergency medical services, ten essential emergency drugs and 13 important drugs (according to >70% of respondents) were identified for inclusion in a transport kit (28).

For longer flights that include a larger number and variety of patients, the U.S. Air Force also has a recommended list of medications for in-flight use:

1. Controlled drugs:
  - Demerol inj tubex 50 mg, 100 mg
  - Morphine sulfate inj tubex 10 mg
  - Percocet tabs 5 mg
  - Tylenol #3 tabs
  - Valium inj 10 mg
  - Valium tabs 5 mg
2. Routine drugs:
  - Pseudoephedrine nasal spray
  - Atropine 0.1 mg/cc
  - Diphenhydramine caps 25 mg
  - Diphenhydramine inj 50 mg/mL
  - Chlorpromazine inj 25 mg/mL
  - Dextrose 50% inj
  - Digoxin 0.25 mg/mL
  - Digoxin tabs 0.25 mg
  - Phenytoin caps 100 mg
  - Phenytoin inj 50 mg/mL
  - Dopamine 40 mg/mL
  - Dramamine tabs 50 mg
  - Epinephrine inj 1:1000 and 1:10,000
  - Haldol inj 5 mg/mL
  - Heparin lock flush 100 U/mL
  - Inderal inj 1 mg/mL
  - Isuprel 0.2 mg/mL
  - Furosemide 10 mg/mL
  - Liquid tears
  - Antacid
  - Naloxone (adult) 0.4 mg/mL
  - Nitroglycerin 2% paste
  - Nitroglycerin IV 50 mg/vial
  - Potassium chloride 2 meq/mL

Note that neither list provides for the routine availability of neuromuscular-

blocking (NMB) agents despite the fact that they are the most commonly administered medication during preparation for interhospital transfer (61). Because they induce apnea, these agents present risks for serious complications, and their use by inadequately trained personnel can be disastrous. The use of NMB agents during patient transport will typically be driven by one of two considerations. First, they are often used to facilitate airway management and endotracheal intubation. In the out-of-hospital setting, their use is controversial, although a number of studies have documented protocols that are effective when combined with adequate training, even by nonphysician air medical personnel (27, 62–64). Alternatively, a patient with a secured airway may require muscle relaxation as part of their in-flight management plan or continuation of preflight treatment (6). This includes the use of NMB agents as "chemical restraints" when a combative patient poses a threat to the crew (65). Although the use of NMB agents in combination with a sedative/amnestic agent can produce the desired control, this does not obviate the need to evaluate for other, reversible causes of agitation such as hypoxia, hypoperfusion, and central nervous system derangements. An adequate amount of required medications, a 2-day supply for in-country moves, and 5-day supply for international moves should be available in the event of diversion to an unanticipated location as a result of aircraft malfunction or hostile weather conditions.

**Personal Equipment.** Beyond those items necessary to provide direct patient care, air medical crews have a requirement to maintain personal protective gear for use in the flying environment. Depending on the mode of transport, fixed- vs. rotary wing, these items can include helmets with face visors, long-sleeved Nomex uniforms, flame-retardant gloves, natural leather hightop boots, and some form of hearing protection. Helmets may "reduce the risk of a fatal head injury eight fold" and, clearly, are indicated in personnel involved in rotary-wing transports (66). Nomex is designed to withstand high temperatures for a brief period allowing crew members a chance to evacuate the aircraft in the event of fire. The use of flame-retardant gloves will provide similar protection. Some of these same protective garment issues are applicable to disaster medical response as well.

## CONCLUSIONS AND SUMMARY

The keys to an effective critical care disaster medical response that extends beyond the normal confines of a hospital ICU include both personnel and logistic issues. A large repository of knowledge and experience is not available regarding this type of "portable ICU care" in the disaster medicine literature or other sources. It seems logical that aeromedical critical care experiences may be directly applicable. In particular, the U.S. Air Force CCAT Team experience may be instructive. We have discussed these issues in detail. Clearly, the best plan is the plan that is deliberative, takes local factors into account, and is practiced before any actual disaster event. Education of healthcare professionals in clinical response protocols, teamwork, and familiarization with the portable medical equipment is the "linchpin" for success.

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