Emergency Medical Considerations in a Space-Suited Patient

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INTRODUCTION: The Stratex Project is a high altitude balloon flight that culminated in a freefall from 41,422 m (135,890 ft), breaking the record for the highest freefall to date. Crew recovery operations required an innovative approach due to the unique nature of the event as well as the equipment involved. The parachutist donned a custom space suit similar to a NASA Extravehicular Mobility Unit (EMU), with life support system mounted to the front and a parachute on the back. This space suit had a metal structure around the torso, which, in conjunction with the parachute and life support assembly, created a significant barrier to extraction from the suit in the event of a medical emergency. For this reason the Medical Support Team coordinated with the pressure suit assembly engineer team for integration, training in suit removal, definition of a priori contingency leadership on site, creation of color-coded extraction scenarios, and extraction drills with a suit mock-up that provided insight into limitations to immediate access. This paper discusses novel extraction processes and contrasts the required medical preparation for this type of equipment with the needs of the prior record-holding jump that used a different space suit with easier immediate access.

KEYWORDS: high altitude parachute, stratosphere, sky diving, balloon, crew escape, space suit.

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On October 24, 2014, Alan Eustace broke the world record for highest altitude skydive by falling from a balloon at 135,890 ft (41,422 m) in the Paragon Stratospheric Exploration (StratEx) program. This bested the prior record set by Felix Baumgartner and the Red Bull Stratos project 2 yr earlier. While both parachutists used pressure suits to ascend to altitudes in excess of Armstrong's line (~63,000 ft—the point at which water will spontaneously boil, 'ebullism'), the approaches were radically different. The Red Bull Stratos project used a pressurized capsule for the ascent, providing a pressurized environment with independent life support, whereas the StratEx project hung the pilot in his pressure suit directly below the balloon. Multiple prior efforts to reach these altitudes have resulted in fatalities. These include Pyotyr Dolgov (1962), who suffered decompression/ebullism when his visor cracked exiting his gondola at 93,970 ft, and Nick Piantanida (1966), whose helmet depressurized at 57,000 ft. There were also several near misses, including Excelsior I (1959) by Colonel Joseph Kittinger, who lost consciousness during a flat spin of 120 rpm after his drogue parachute wrapped around his neck, and Excelsior 3 (1960), when a pressure suit leak resulted in decompression of his hand. On the Red Bull Stratos jump to 127,852 ft (2012), Felix Baumgartner went into a rapid spin for about 25 s and was briefly incapacitated.[15]

The StratEx project recognized these risks and included specialized medical crews for field support. The unique design of the StratEx project included an Extravehicular Mobility Unit (EMU) type spacesuit with an integrated life support system and a custom parachute system. This unique design created an environment where medical treatment of injuries prior to, during, and/or after the flight could be severely hampered by inadequate access to the parachutist. It also created the potential for additional injuries to would-be lay rescuers because of the complexity of the system. The donning and doffing procedures were extensive and limited access for medical interventions. This paper discusses the unique challenges faced by the StratEx project team, including design, pertinent risks, field stabilization needs, team training, and preparations for a potential in-suit medical emergency. With the growth of commercial spaceflight, emergency

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support and response to similar scenarios will be necessary; documenting early experiences in the field is critical to guide future efforts.

The Red Bull Stratos jump in 2012 used a pressure suit derived from that used by U2 pilots and astronauts in the NASA Space Shuttle program.[15] In contrast, the StratEx suit was custom designed by ILC Dover and is closer to NASA's EMU suit for extravehicular activities. The suit assembly includes a metal-framed torso, shoulder bearings and a metal waist connector ring, leg assembly, a transparent helmet 'bubble' with a double polycarbonate layer, modified mountaineering boots, and heated gloves.

The suit was covered in a blend of Gortex, Kevlar, and Nomex, designed to provide thermal and tear protection. The inner layer of the suit was made of urethane-impregnated nylon bladder to maintain pressurization at 5.4 psi (37.2 kPa, 280 mmHg, equivalent to ~8,000 m or 26,000 ft) with 100% oxygen. A neck dam isolated the head atmosphere from the rest of the body, with a small pressure differential to ensure one-way flow of oxygen and CO_2. In addition, the pilot wore a facemask for oxygen supply and breathing, eye protection for sunlight and UV-radiation exposure, and an in-suit helmet for protection and to hold the glasses and mask in place. This novel approach ensured minimal dead space, as the pilot was always inhaling pure oxygen and exhaling the CO_2 to the compartment below the neck dam, while the demand-based approach ensured efficient use of consumables. In the suit, the pilot wore thermal undergarments and a coolant system that circulated water through small tubes (**Fig. 1**).

The front of the suit included two high pressure oxygen tanks, lithium-ion battery, radios and associated equipment, parachute pull cords, and pilot gauges (including altimeter, suit and oxygen tank pressures). The back of the suit held the parachute, attached via shoulder and leg straps (**Fig. 2**). The assembly and pilot weighed just over 400 lb/180 kg. Of note, there was only one suit built for the program. This limited hands-on practice of suit extraction protocols because suit damage could compromise the mission.

Fig. 1. Undergarments, including thermal underwear, physiological monitor, and integrated cooling system. Padding (white blocks) were used to prevent pressure points.

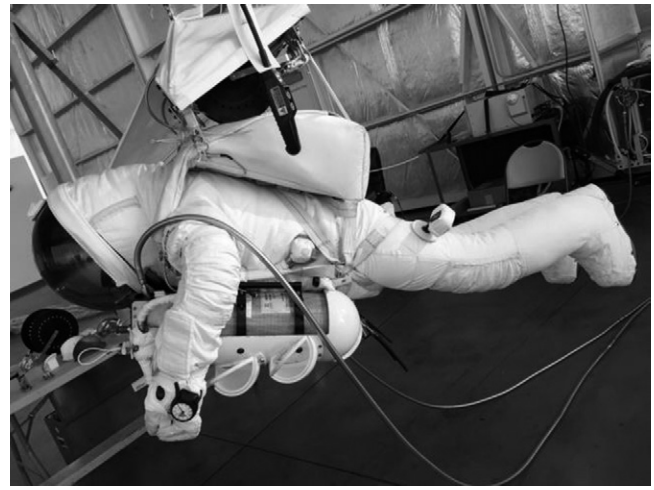

Fig. 2. Pressure suit assembly with anterior life support and posterior parachute. Two silver hoses are ground oxygen lines removed prior to flight.

Suit donning took 10 to 15 min. Similarly, removal of the suit required specific procedures to avoid damaging delicate components. The whole system then underwent checks before being reused. Because of suit design requirements, there were multiple barriers to providing care to the pilot in case of a medical emergency. First, the equipment module on the front and the parachute container on the back made it impossible to have direct access to most of the patient while suited. Second, doffing while preventing damage or contamination by a foreign object was impossible in an emergency. Third, it was impossible to expose the patient using standard trauma techniques of cutting clothing and obstructing materials. The torso had multiple metal frames and bearings, and two large high-pressure pure oxygen tanks, limiting the use of power tools. This required the pilot to be pulled from the waist opening. Cutting the shoulder assemblies facilitated this, but the materials were extremely tough, requiring special cutting techniques. The helmet, facemask, and neck dam need to be cut/removed prior to extrication. And before the waist seal could be opened, the oxygen tanks had to be manually closed and the parachute harness cut. Taken together, these limitations required modification of standard life support practices. Such modified emergency medical practices are described below.

Trauma

Although skydiving has an excellent safety record [less than 0.008 fatalities per 1000 jumps (USPA.org)], this project carried significantly higher risks. The risk of trauma was particularly high for the initial launch, when an accidental release or balloon malfunction could cause a lethal fall before the parachute opened. The potential for landing in uneven terrain magnified this risk and made tracking and access harder. Initial field interventions considered Advanced Trauma Life Support and related procedures.

High Altitude Risks

Ebullism. Decompression to an ambient pressure below 47 mmHg (which occurs above approximately 63,000 ft, "Armstrong's line") can result in ebullism: the vaporization of water contained in tissues.[17] Exposure causes bubble formation throughout the various tissues and spaces of the body, resulting in loss of preload and cardiac output,[2,16] and pulmonary tissue damage and acute respiratory distress syndrome.[12] It is important to note that bubble formation is not instantaneous and tissues can tolerate hypobaria for some period of time.[5] The length of time humans can tolerate this is unknown. Two human exposures with survival are known to have occurred.[8] This suggests that an exposure of up to 60–90 s is survivable and a protocol has been developed for ebullism management.[12] Rapid field interventions include airway management, high-frequency percussive ventilation, and potentially pneumothorax decompression. The suit is pressurized to maintain an atmosphere of 5.4 psi/280 mmHg, preventing vaporization of water.

Gas embolism. Rapid decompression can result in gas embolism through expansion of gas in the lungs and, thus, lung volumes beyond total lung capacity with a closed glottis, tearing alveolar lung tissue and tracking through tissue planes into the subcutaneous tissues, causing pneumothorax, pneumomediastinum, and embolism (arterial gas embolism).[4,7,16] Gas embolism is treated with repressurization (descent), administration of oxygen,[3] and with fluids and supportive care.[9] Rapid evacuation to a hyperbaric chamber for recompression is critical. As pneumothorax is the only hard contraindication to hyperbaric recompression, rapid identification and definitive treatment with a chest tube is critical before progressing to hyperbaric treatment.[12]

Decompression sickness. Decompression sickness (DCS) is due to formation of inert gas bubbles in tissues/blood due to supersaturation, which either by mechanical stress or secondary cellular stress cause organ dysfunction.[11] A pure oxygen prebreathe protocol is followed to decrease the likelihood of nitrogen bubble formation when exposed to a hypobaric environment. The suit is pressurized to 5.4 psi, the equivalent of ~26,000 ft. If DCS symptoms develop, treatment is immediate descent and pure oxygen. If symptoms are severe or persist, the patient is expedited to a hyperbaric treatment facility on standby.

Barotrauma. Rapid pressure changes can result in injury to the lungs and tympanic membranes, with potential pneumothorax and tympanic rupture. Diffusion due to pure oxygen use can also cause sinus "squeeze." While typically not fatal, "squeezes" or tympanic membrane perforation can be incapacitating. The most concerning manifestation is pneumothorax. Initial field treatment may include pain control or needle decompression.

G_z exposure. A flat spin during descent may cause a rush of blood to the lower extremities, resulting in decreased perfusion of the brain and loss of consciousness,[1] or to the upper extremities and head, resulting in increased blood flow, ocular hemorrhaging, and cerebral hemorrhaging, depending on the axis about which the body is spinning. Intracranial hemorrhaging has the potential to lead to neurological injury and death.[14] The parachute system used a drogue to prevent a spin; if a significant spin exposure was suspected, this would be managed by supportive/neurosurgical care in a tertiary care facility.[13]

Hypoxia. Insufficient oxygen delivery (partial pressure of oxygen below 100 mmHg) could result in impaired performance, anoxic injury, and death. The suit is pressurized at 5.4 psi (280 mmHg) with 100% oxygen, yielding an oxygen partial pressure higher than air at sea level (21% oxygen, 160 mmHg). Treatment of an exposure would include immediate descent, early resuscitation, and airway management.[10]

Other Risks

Other risks include electrical injury or shock from equipment malfunction, in-suit fire from Li-ion batteries, toxicological exposure in the case of combustion or over-heated components, and thermal injury such as frostbite in the event of a failure of the thermal protection systems at high altitude. Given the remote location of operations and the possibility of communications and tracking failure, there is a potential for extended recovery time of an injured pilot. This would increase the odds of heat illness, dehydration, and other environmental exposures.

The most urgent scenarios include pneumothorax, cardiac dysrhythmia, or traumatic arrest, which would necessitate rapid access to the chest for decompression, defibrillation, and CPR. Rapid resuscitation efforts on site by experienced providers improve survival and complete neurological recovery.[6] Shorter overall scene time does seem to improve mortality in patients who require early critical resources and penetrating trauma.[10] We therefore developed protocols and practiced with specially trained engineers and medical providers who were deployed to the field.

Medical Emergency Extrication and Stabilization Procedures

It was determined early on in the program that the most important first step, from the standpoint of medical support, was rapid recovery of the pilot. The suit was designed so that the pilot was able to remove his own face bubble. However, this proved to be difficult at times due to pilot fatigue and impossible if he was unconscious. It was estimated that he could have as little as 10 min of oxygen left in his life support system. Coupled with the fact that studies have demonstrated improved outcomes if advanced life support procedures are initiated within 7 min of cardiac arrest,[6,10] the goal was set for the support team to reach the pilot within 5 min of landing. Because of the difficult terrain where this mission took place, we could not guarantee to meet that goal with ground transportation. Thus, helicopters were used to track the pilot and deliver the support team and supplies rapidly to provide care if needed. In addition, because of the complexity of the suit, dedicated suit engineers and medical providers trained as an integrated team.

Early simulation indicated a minimum of four people required to extract an unresponsive pilot from the suit and provide initial medical care. The team took an innovative approach and used the concept of a role-based approach that has been used in other situations, including Advanced Trauma Life Support and in IndyCar extrication teams. The roles were critical in doffing: one person pulled at the pilot's waist, one person stabilized the head and neck, and one made sure the arms did not get stuck at the shoulder joints. For redundancy, two four-person teams were created and deployed in separate helicopters. Teams practiced mock extraction emergencies at each test and jump to ensure preparation and continued competency. Practice sessions helped to facilitate medical team familiarity with suit design and extrication procedures, as well as engineering team familiarity with medical protocols and requirements. Team members were rotated through the different roles so all team members had a good understanding of what the other team members would be doing.

Our extraction protocols centered on four-person teams composed of two physicians and two suit engineers. The suit engineer's initial action was to remove the helmet bubble and flight mask for medical assessment. In case of medical concern the lead physician would declare a color-coded extraction procedure and set in motion medical emergency plans for specific severity of injuries, as follows:

Green extraction. Pilot appears well, speaking, and denies any pain or dyspnea. Nominal extraction, emphasizing care to protect the pilot and suit.

Yellow extraction. Pilot appears well, but complains of focal pain and can explain the injury. In this scenario, the medical team works with suit technicians to extract the pilot in a controlled manner, protecting the suit as much as possible while managing the injury. The medical team does a full evaluation on site and the Field Medical Director determines the need for further intervention or transport to higher level of care. This scenario was designed specifically because the most likely injuries to occur during this program were nonlife-threatening injuries such as trauma (sprains, broken bones, contusions, penetrating wounds), electrical injuries from within the suit, or cold exposure.

Orange extraction. Pilot is responsive, but has a neurological deficit. Precautions are taken to protect the cervical spine and minimize twisting and traction on the lower spine. The patient is stabilized and subsequently transported with the Field Medical Director to the standby Level 1 Trauma Center.

This was developed for the concern of possible spinal injury either through trauma or DCS with a cooperative pilot. Early mock-ups showed it is not possible to place a backboard or other extraction device within the suit to stabilize lower spinal injuries, only a C-collar. Extracting the pilot from the suit torso requires pulling on the hips through the waist opening, effectively placing traction on the spinal column. Priority is given to spinal stabilization and rapid transport to definitive care with the understanding that lower spinal injuries may be exacerbated. The pressurized suit design ended up affording unexpected protection against injury during landings. Despite many off-nominal orientations (on his back, head, and sides), he had no injuries.

Red extraction. Pilot is unresponsive or has a compromised airway. In this scenario, the medical team directs a rapid extrication of the pilot with cutaway of the parachute and suit components as needed. Once the pilot is removed from the suit, the medical team assumes preassigned roles for advanced life support care with the goal of rapid stabilization and transport to the nearest Level 1 Trauma Center, accompanied by the Field Medical Director.

Early mock-ups and practice attempts showed it was infeasible to provide standard advanced life support measures or to perform appropriate trauma assessments while the patient was suited. Priority was given to rapid suit extraction followed by definitive airway management—ventilation with BVM would be possible, but an ET tube would likely be dislodged during extraction. This also ensured that access to the chest and limbs was available as quickly as possible.

The only emergency scenario that strayed from this color-coded algorithm was the event of a suit fire. Because the equipment module housed lithium batteries, there was some concern that a fire could ignite with exposure of this lithium or other electrical equipment to the pure oxygen environment of the suit. Fire extinguishers were readily accessible for all testing and launch activities (including copper-based powder extinguishers to smother a lithium fire). Because of the risk to surrounding crew, the plan for managing a suit fire involved first putting the fire out, both on the outside of the suit and the inside through the head and neck opening, before attempting any extraction, to prevent additional injury to support staff, which would only serve to compound the medical emergency. Once the fire was extinguished, further care would be administered per the color-coded extraction algorithms.

The medical support team's goal on site was to find, extract, stabilize, and ensure rapid transport to a tertiary care facility in the event of injury. A medical evacuation helicopter carried a flight nurse/paramedic, blood, and oxygen in addition to trauma equipment. Multiple tertiary care facilities, including Level 1 Trauma Centers and hyperbaric facilities, were placed on standby in advance of testing or mission operations.

The medical team on site carried equipment to care for minor trauma and burns, as well as airway, advanced cardiac, and trauma life support in the event of more serious injuries. On-site imaging consisted of a hand-held ultrasound. Two high-frequency percussive ventilators were carried for ventilation and oxygenation in case of pulmonary damage related to exposure to vacuum and ebullism, based on previously published protocols.[12]

The StratEx project consisted of two altitude chamber flights (25,000 and 90,000 ft equivalent), five airplane drops from 18,000 ft, and three balloon jumps from 57,000 ft, 106,000 ft, and 135,890 ft. Risk recognition spurred early integration of the medical and engineering teams. These procedures built on the experience of earlier programs such as Red Bull Stratos and the jumps that Col. Joseph Kittinger performed. Projects like these involve unique medical risks that are often outside the realm of experience of standard prehospital providers. This is complicated by the use of high-tech equipment such as the space-suit and attached life support systems that can hinder medical access and pose risks to would-be providers. This has ramifications for the burgeoning commercial spaceflight industry. High altitude flight profiles assume many of the same risks to passengers—they will be operating in remote areas and equipment such as spacesuits may provide similar barriers to rescue teams in the event of a mishap. Traditional emergency medical procedures must be modified to accommodate unique characteristics of the suit and flight profiles on a case-by-case basis. The cross-training of the medical and engineering teams were key to optimize extraction, early diagnosis and stabilization, and access to care. Development of medical support protocols specific to mission risks and rehearsal of medical contingency scenarios can decrease confusion, and optimize team coordination and clinical effectiveness in these unique endeavors.

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