SPECIAL REPORT

Crew Recovery and Contingency Planning for a Manned Stratospheric Balloon Flight – the StratEx Program

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Abbreviations:
ConOps: concept of operations
FLIGHT: flight director
NAV: mission navigator
PSA: pressure suit assembly

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Abstract

The StratEx program used a self-contained space suit and balloon system to loft pilot Alan Eustace to a record-breaking altitude and skydive from 135,897 feet (41,422 m). After releasing from the balloon and a stabilized freefall, the pilot safely landed using a parachute system based on a modified tandem parachute rig. A custom spacesuit provided life support using a similar system to NASA's (National Aeronautics and Space Administration; Washington, DC USA) Extravehicular Mobility Unit. It also provided tracking, communications, and connection to the parachute system. A recovery support team, including at least two medical personnel and two spacesuit technicians, was charged with reaching the pilot within five minutes of touch-down to extract him from the suit and provide treatment for any injuries. The team had to track the flight at all times, be prepared to respond in case of premature release, and to operate in any terrain. Crew recovery operations were planned and tailored to anticipate outcomes during this novel event in a systematic fashion, through scenario and risk analysis, in order to minimize the probability and impact of injury. This analysis, detailed here, helped the team configure recovery assets, refine navigation and tracking systems, develop procedures, and conduct training. An extensive period of testing and practice culminated in three manned flights leading to a successful mission and setting the record for exit altitude, distance of fall with stabilizing device, and vertical speed with a stabilizing device. During this mission, recovery teams reached the landing spot within one minute, extracted the pilot, and confirmed that he was not injured. This strategy is presented as an approach to prehospital planning and care for improved safety during crew recovery in novel, extreme events.

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Introduction

On October 24, 2014, Alan Eustace set a new skydiving record for the highest altitude to date when he released from a balloon at 135,897 feet in a program named StratEx. The flight went to a peak altitude of 136,410 feet (41,578 m), and after a short float period, the pilot was released from the balloon at an altitude of 135,897 feet (41,422 m). With only a small drogue shoot to stabilize his descent, the pilot reached speeds of 820 mph (1,320 km/hr; Mach 1.22) during a free fall that lasted four minutes 27 seconds and covered a vertical distance of 123,435 feet (37,623 m) before deploying his parachute. Nine minutes and 52 seconds later, he completed the flight landing 78 miles (125.2 km) east of his departure point. This altitude eclipsed that achieved by Felix Baumgartner in the Red Bull Stratos project two years earlier of 127,852 feet. Both parachutists ascended beyond physiologically critical altitude of Armstrong's line (63,000 ft) where ebullism can occur—a disease characterized by diffuse alveolar damage and tissue edema resulting from an extremely low external pressure. However, the two conveyances differed significantly in that Red Bull Stratos ascended in a pressurized capsule attached to a balloon while StratEx completed the entire journey in a pressure suit (Figure 1). StratEx's novel approach eliminated the capsule and required the pilot to conduct the entire mission in a spacesuit,

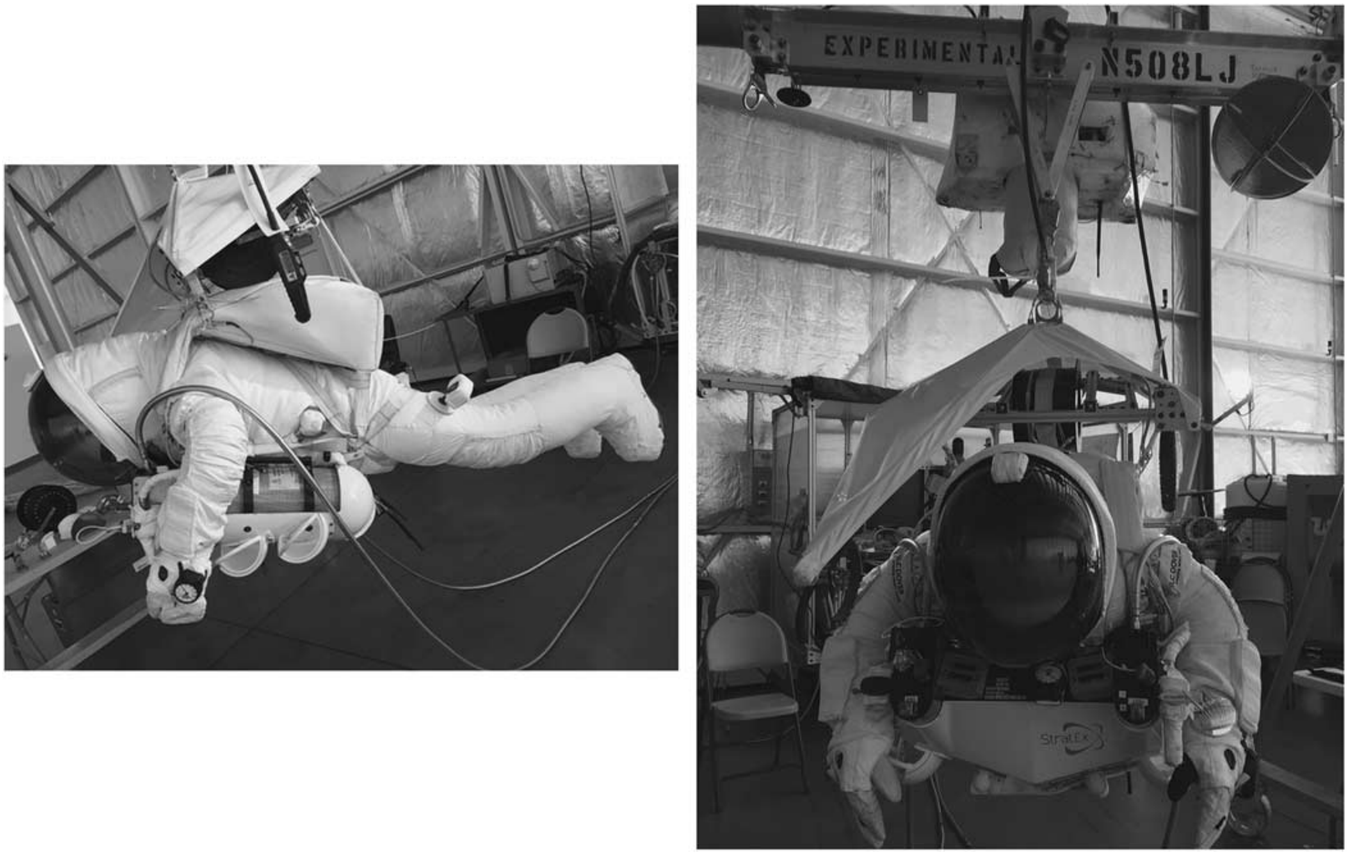

Figure 1. Alan Eustace in StratEx Suit Ascending in Pressure Suit Assembly, Which Includes the Suit, the Equipment Module, and the Parachute.

which created new medical scenarios that would need to be anticipated for contingency medical care. The emergency response efforts of prior high-altitude dives were extended by StratEx to include a risk analysis helping to drive a concept of operations (ConOps) in order to integrate the entire StratEx team.[1]

Historically, high morbidity and mortality have been associated with attempts at the altitude record.[2] Cautionary examples of mortality include Pyotyr Dolgov, who suffered decompression when his helmet cracked at 93,970 feet in 1962, and Nick Piantanida, whose facemask depressurized at 57,000 feet in 1966. Non-fatal emergencies occurred during the Excelsior program in 1959 when Joseph Kittinger lost consciousness during a spin, with a rate of 120 rpm, after early deployment of his drogue parachute, which wrapped around his neck. Later, in1960, a tear in his glove resulted in ebullism, swelling, and loss of function in his distal upper extremity, which normalized without long-term disability.[3]

Medical treatment of any injury prior to, during, or after the flight could be delayed or impeded by the distance between the pilot and the medical team and the time required for suit extraction. This report aimed to describe the process and approach to providing contingency medical care during the StratEx program as a unique event with enough generality to be extrapolated for similar extreme events in the future.

Report

Medical care rendered during the Red Bull Stratos program provided an initial background for recovery operations during the StratEx program.[4] Challenges from Red Bull Stratos included potential obstacles with communications, rapid access to the parachutist, field medical care, transfer to higher-level care, and integration of the medical team with operational teams.

Trauma, decompression illness, ebullism, and high g-forces secondary to spin were known complications of high-altitude balloon jumps, leading to a need for a broad range of diagnostic and treatment capabilities.[5] For this reason, emergency medicine physicians were integrated into the recovery teams and equipped with field medical kits capable of Advanced Life Support. Though field medical care would be provided, the potential for polytrauma and decompression illness necessitated a Level I trauma center and a hyperbaric chamber.[6] The flight launched eastward from the airport at Roswell, New Mexico (USA), so the closest hyperbaric chamber in San Antonio, Texas (USA), 500 miles away, and Level I trauma center in Lubbock, Texas (USA), 175 miles away, were identified and contacted for higher-level definitive care.

Chase and Recovery Team Strategy

The chase phase followed the parachutist or pilot while the recovery phase assessed the pilot's condition and returned him to base. Once the pilot was launched, there was no option to abort the operation if something went wrong–the pilot would have to be recovered. Because of the possibility of premature release and changes in altitude profiles leading to new trajectories, landing time and location were uncertain but were projected to be in a remote area. Additional variability was introduced through

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external factors, including weather, trajectories, timing, terrain, equipment problems, military jamming of Global Positioning Systems/GPS signal, airspace restrictions, and government and public interactions. For example, a slower than expected ascent rate could lead to a change in trajectory that might cross restricted airspace, or predict landing in a populated area, where an early or delayed release might be necessitated.

The primary medical goal was to have two suit engineers and two medical team personnel to the pilot within five minutes of landing, to assess and treat emergent conditions, and to transport him from the landing site for further treatment, if needed. A 5-minute time frame was established because the suit was a closed system that might lead to asphyxiation if a significant life-support malfunction occurred. Medical personnel were state-licensed emergency medicine physicians. Secondary goals included equipment recovery, physiologic monitoring, and system data backup.

Planning

This primary goal drove the development of a detailed ConOps: a detailed description of the process to be followed for safe recovery of the pilot. A ConOps is used by operational teams for planning and mission development, so it helped to integrate the medical plan with non-medical participants. It included a statement of goals and objectives for the process and a description of the strategies, tactics, policies, and constraints affecting the flight. It also defined participants' organizations, activities, interactions, roles, responsibilities, and capabilities such as the engineers, mission control, fire department, and air traffic control. Most importantly, the ConOps described possible scenarios that could be practiced via a table-top exercise or drills. Development of the ConOps was an iterative process with each revision informed by practice runs or table-top exercises. A separate document, termed "flight rules," contained the detailed procedures and checklists which were developed from experience and planning.

An example of objectives aimed at safe launch and recovery included preparation of vehicles, equipment, and coordination with local landowners, police, fire departments, hospitals, and airports. The involvement and role of these important participants was discussed and integrated into practice sessions. Preparation also included a predicted flight path and knowledge of potential terrain and landing zones. Effective communication with mission control, pilot, and chase teams, as well as ancillary staff such as filmmakers, was paramount. Specifically, efficient transition of launch and pressure suit assembly (PSA) engineers from launch phase to chase phase was an important handover. Reliable monitoring was important for navigation and tracking of the pilot and equipment, as well as collecting flight data such as vital signs, recordings, logs, and imagery for real-time situational awareness. Finally, medical personnel needed a facility with the PSA system to allow for rapid doffing and emergency procedures. Repeated extraction practice allowed for improved execution of these tasks.

In order to accomplish these goals and provide backup resources, five vehicles were assigned to the chase team. A primary helicopter (CHASE 1), a Bell Long Ranger, would track the pilot and be ready to land nearby with two suit technicians and two physicians. A second helicopter (CHASE 3), a Bell Jet Ranger, would provide backup and deploy an additional suit technician and two more physicians. A fixed-wing airplane (CHASE 5), a Quest Kodiak, would provide overhead spotting and deploy a parachutist to guide the pilot to a safe landing zone and render assistance, if needed. Because of the reduced visibility permitted by the suit design, this additional parachutist was added to improve landing selection. Also, in the event of suit failure or injury, the parachutist would accelerate the doffing process. Two ground vehicles provided additional transportation resources. An all-wheel-drive truck named CHASE 2 carried the chase team coordinator and could support field communications, tracking, and mission control backup. Another named CHASE 4 backed up CHASE 2. After a nominal recovery, both vehicles could carry equipment that was too heavy to be carried on the helicopters, including the balloon carcass.

For an emergency warranting higher-level care, a commercial aeromedical evacuation helicopter followed the chase teams. Also, a truck with local fire department emergency medical technicians accompanied the ground vehicles in case of medical issues with any of the chase team members. This vehicle carried a search and rescue paramedic with extensive experience in field operations. Though not part of the recovery team, a fourth helicopter carried a film crew for documentation of the flight. The ConOps addressed how this element would operate so as not to interfere with flight safety.

A flight director (FLIGHT) in mission control maintained operational authority over these multiple teams (Figure 2) and communicated with them via the mission navigator (NAV). The NAV also directed vehicles along the best routes to support operations and provided tracking information to all elements as a backup to on-board tracking systems. In mission control, a physician was present to provide medical monitoring and guidance to FLIGHT. Other team members in mission control included a meteorologist, flight engineer, PSA engineer, communications operator, and safety monitor.

Discussion

The ConOps included a narrative scenario of nominal and off-nominal operations that could be repeated and practiced. Even though deviations were expected during flights, these scenarios helped with testing and refinement of safe practices. In order to build these scenarios, multiple outcomes were considered. A decision tree was created and assessed to determine the likelihood of each scenario. The highest probability and most dangerous outcomes were addressed through optimization and training. Though this process was limited by the uncertainty of planning for unique events, the effort of evaluating risk helped to highlight areas of concern and focus preparation.

The top-level chase and recovery scenario consisted of five events: (1) balloon was launched; (2) chase team was en route; (3) pilot released; (4) pilot landed; and (5) pilot returned to launch site.

Each point was termed a node in the decision tree, with the final event being a special node called an outcome. Each node was connected via a path. For example, a path from Node 1 to Node 2 might be a nominal launch. With each element, a complete scenario can be constructed to form a trunk, as pictured in Figure 3.

At each node, several off-nominal scenario elements were identified. For example, at Node 1, the launch could have been delayed or canceled. More seriously, an aborted launch could have threatened pilot safety or initiated an alternative chase scenario. Three important deviations were considered from the baseline scenario: (1) a launch abort, or a significant deviation from the predicted balloon track, requiring the operational timeline to be extended; (2) a casualty to the pilot; and (3) a casualty to one of the primary chase elements.

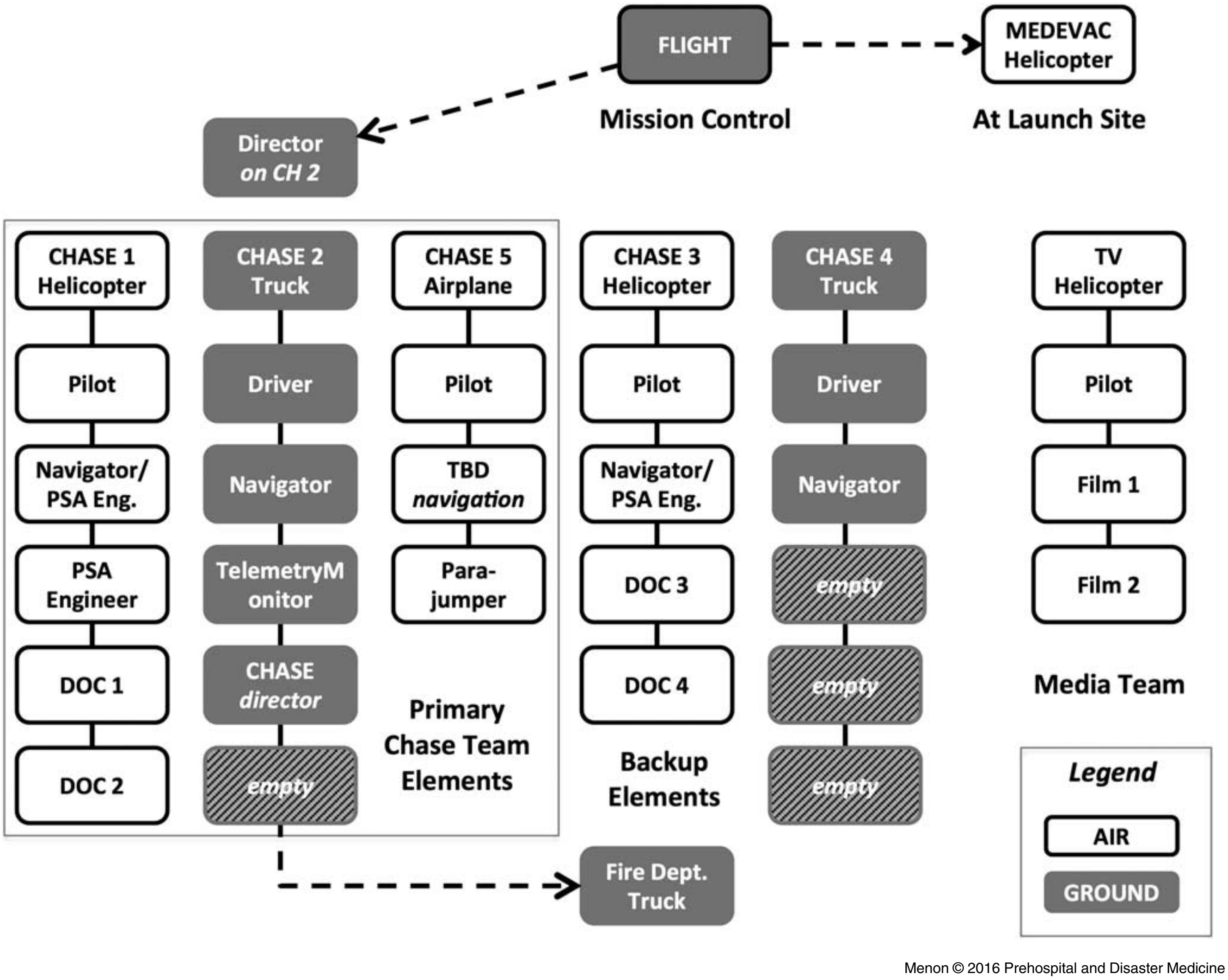

Figure 2. StratEx Chase Team Organization.

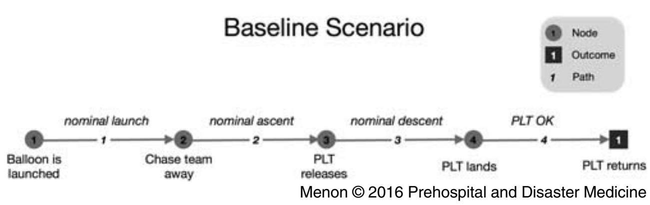

Figure 3. Baseline Nominal Chase Scenario.
Abbreviation: PLT, pilot.

Casualty for a chase team was defined as an impairment of operation, such as a flat tire, accident, or engine failure. Further differentiation was important to delineate the absence of personnel injury (OK) from the presence of injury (not OK), which might require medical support from one of the other chase teams. An example in Figure 4 shows a decision tree branching at Node 1. The squares represent outcomes where the scenario ends, and the open circle represents a continuation to the scenario on that branch.

Challenging scenarios that were considered included accidents involving a chase team member resulting in an injury. In such a case, medical assets would need to allocated between the primary goal of pilot recovery and treating team member's immediate medical needs. For this purpose, the ConOps included redundant medical assets like the local fire department and Emergency Medical Services teams with a plan to use them in these scenarios.

The StratEx ConOps decision tree resulted in 59 separate outcomes that allowed for further scenario analysis. Most outcomes represented similar variations on a few nodes. For example, a casualty to CHASE 1 could occur at many different stages in the tree, and each had a similar likelihood. The same probabilities would apply to CHASE 3 casualties. Thus, the likelihood of multiple paths was assessed with a few unique probability assessments.

Abort on Ground—This would occur at the moment of launch, but before ascent. For example, the wind might exceed limits and cause balloon failure. Statistics from the NASA (National Aeronautics and Space Administration; Washington, DC USA) Scientific Balloon Flight Facility at Fort Sumner, New Mexico (USA) suggested that this is a rare occurrence, three out of 242 listed launches, approximately 1.0%.[7] It is not likely to result in

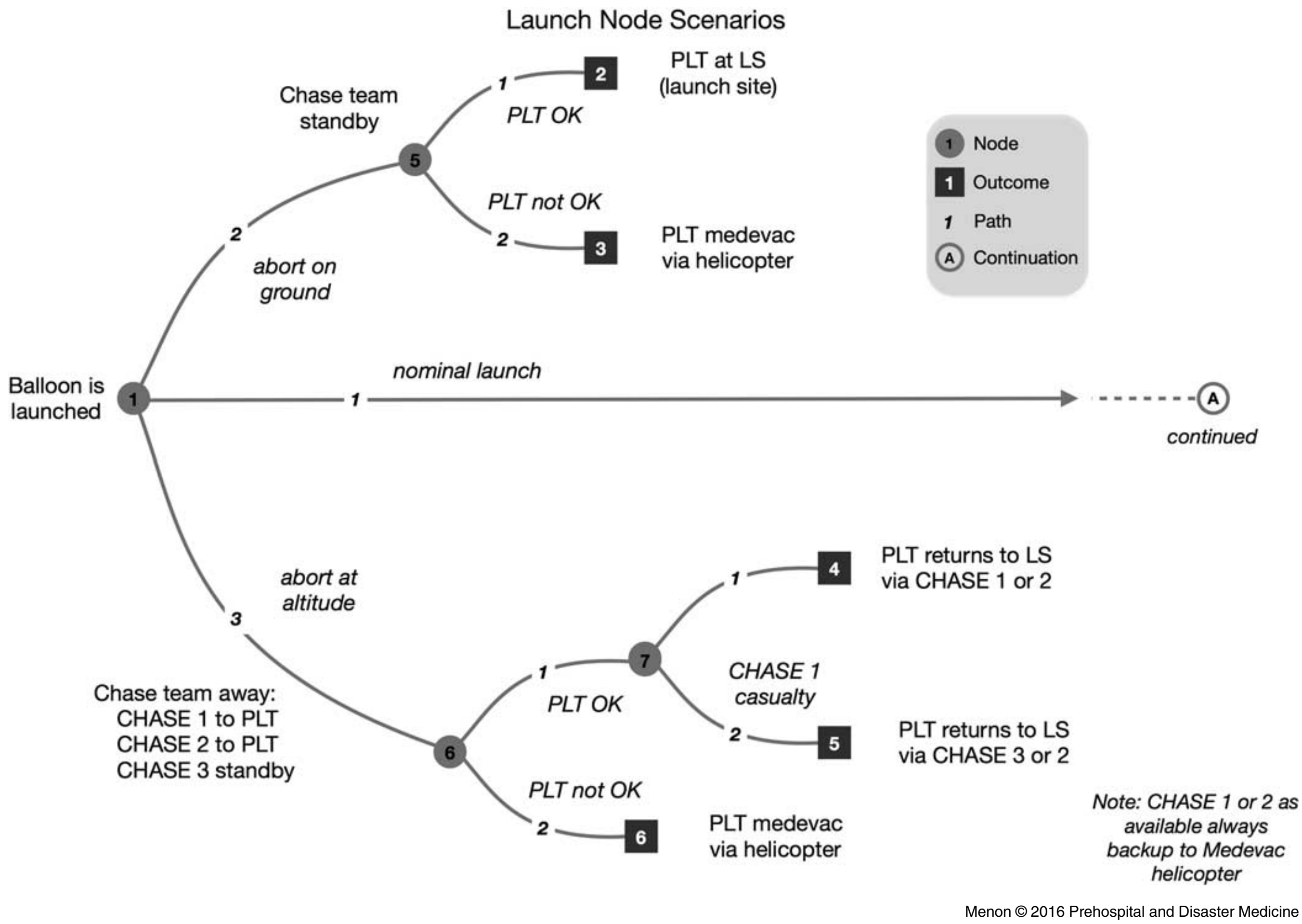

Figure 4. Launch Node Scenarios.
Abbreviations: LS, launch site; PLT, pilot.

pilot injury because of low altitudes and surrounding staff—a conservative estimate of less than 0.1 pilot "not OK" was used.

Abort at Altitude—In this case, there is a failure just after launch so that the pilot will descend near the launch site. NASA Scientific Balloon Flight Facility statistics included 20 out of 242 launches—conservatively estimated to be less than a 0.1 rate. The likelihood of pilot injury in this event must be considered higher than a ground abort—estimated to be 0.2, which is addressed further in *Pilot Landing* discussion.

Helicopter Casualty—Many paths involved a casualty to CHASE 1 or CHASE 3. This could be a mechanical problem grounding the helicopter, or an accident that may or may not lead to serious injury. The Bell helicopters are known for reliability and the National Transportation Safety Board (NTSB; Washington, DC USA) collects data on specific aircraft. Accident rates are low, excepting ferrying of passengers, accidents occur at a rate of eight per 100,000 hours with 1.5 fatalities.[8] For a typical StratEx flight profile of approximately five hours, this works out to a 0.004 rate (0.000075 for fatality rate). To be conservative, it was assumed that a major accident leading to serious injury might occur in one-half of the accidents (0.002).

Truck Casualty—A failure or accident might occur to CHASE 2. It is assumed that reliability of the chase truck will approach 100% after careful maintenance and preparation. The accident rate over rural highways was approximated to be 60 per 100 million miles.[9] The rate of fatalities in trucks was estimated to be 1.5 per 100 million miles traveled.[10] It was assumed that a typical launch would entail approximately 100 miles of travel for each vehicle, based on typical distances covered by the balloon and the need to follow roads rather than a straight-line path. This yields an accident rate of 0.00006 and a fatality rate of 0.000002. The vehicles were manned by a dedicated, experienced driver supported by a navigator, and remained on maintained roads. For analysis, a conservative estimate of accident rate was used at 0.00002.

Tracking Deviation—This was a variation in the scenario where the balloon tracked so far off the predicted path that the CHASE 1 and CHASE 3 helicopters would have switched roles for multiple refueling. During initial ConOps development, the team did not know how well the meteorologists could predict winds at different altitudes, and hence, track projections. With experience, this proved to be reliable. However, a failure of the release system, inability to vent the balloon, or some other problem could force the balloon and pilot to stay aloft for longer than expected, and thus

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deviate from the projected track. The probability of a significant deviation was estimated to be low, based on expert practice experience, so a rate of 0.1 was used. However, consideration of this prospect forced the team to work out procedures to coordinate helicopter refueling operations that became helpful in practice.

Pilot Landing—This factor estimated whether the pilot would land uninjured, with minor injuries that could be treated on site, or with serious injuries that required medical evacuation. These rates were hard to estimate due to the unique nature of the suit design. The extra weight and bulk of the life-support system, as well as the pressurization of the suit, restricted extremity movement extremely and did not permit waist movement. This restricted his ability to completely flare the canopy and made it impossible for him to land on his feet. Attempts to execute a half turn and land on his back were unsuccessful during low-altitude jump tests in the suit–a face plant and flip was the common outcome. During these jumps, the suit provided adequate protection and the pilot was not injured, but given the momentum involved, traumatic injury seemed like a possible outcome. There was no statistical basis for estimation, so for the purposes of calculation, rates were estimated to be 0.2 for an injury and 0.1 for serious injury.

Using these scenario probabilities, the likelihood of events represented in the decision tree was computed. The technique was to combine the probabilities at each path along a branch to yield the probability of that particular outcome. This was done for each branch in the tree yielding 59 different outcomes. Then, similar outcomes were combined into related scenarios. For example, all scenarios that led to the pilot returning to base unharmed via CHASE 1 were considered to be related and the probabilities were added together. A summary of all of these calculations is shown below.

The analysis in Figure 5 was encouraging to see that 89% of the time the pilot returns safely to the launch site. On the other hand, there was a significant probability (11%) of some kind of injury involving medical evacuation. The results were sensitive to the scenario probabilities for "pilot not OK," which was set conservatively high to see how the system would handle a serious emergency.

This approach was also used for sensitivity analysis, which could determine the effects of eliminating specific scenarios. For example, if the nominal scenario was eliminated and the probabilities recalculated, it became more clear what were the most likely risks, which could be better addressed. For example, it became apparent that a second helicopter (to back up the primary recovery helicopter, CHASE 1), would significantly reduce the risk to the pilot because of a helicopter casualty. The TV helicopter was a potential backup and might be incorporated into the ConOps. Since the TV helicopter already had its own purpose, special equipment, and operators, there would have been additional requirements, training, and personnel. This increased the risk of some scenarios since there would have been more failure points, more assets to coordinate, and would spread the medical assets more thinly. Likewise, the medical team could have deployed from an airplane via parachute. The ConOps and the decision tree analysis indicated that this added additional risk and complexity, including injury to personnel and more widely dispersed medical personnel. A single expert jumper would avoid extra training and responsibilities for medical personnel. The ConOps and decision tree analysis were useful evaluation tools in

Related Scenarios

Related scenario		Outcomes	Total Probability
1	PLT at LS (Launch Site)	1 outcome	0.91%
2	PLT to LS via CH 1	9 outcomes	79.48%
3	PLT to LS via CH 1 or 2	1 outcome	8.07%
4	PLT to LS via CH 1 or 3	2 outcomes	0.00%
5	PLT to LS via CH 2	3 outcomes	0.00%
6	PLT to LS via CH 2 or 3	1 outcome	0.03%
7	PLT to LS via CH 3	13 outcomes	0.42%
8	PLT to LS via EMT 1 (Fire Dept. EMT truck)	4 outcomes	0.04%
9	PLT medevac via MED helicopter	14 outcomes	11.02%
10	PLT medevac via CH 1	1 outcome	0.00%
11	PLT medevac via CH 2	1 outcome	0.00%
12	PLT medevac via CH 3	2 outcomes	0.01%
13	PLT medevac via EMT 1	1 outcome	0.00%
14	1 though 8 (PLT to LS)		88.96%
15	9 through 13 (PLT medevac)		11.04%
16	PLT to LS or medevac via CH 1	14 outcomes	83.52%
17	PLT to LS or medevac via CH 2	6 outcomes	4.06%
18	PLT to LS or medevac via CH 3	18 oucomes	0.46%
19	PLT to LS or medevac via EMT1	8 outcomes	0.04%
20	PLT medevac via MED helicopter	14 outcomes	11.02%

Figure 5. Probabilities of Decision Tree Scenarios.
Abbreviations: EMT, emergency medical technician; LS, launch site; PLT, pilot.

these assessments and helped inform medical preparation by focusing on important scenarios and narrating how those scenarios would unfold operationally.

Training and Operations

One of the challenges facing the medical team was the overlapping responsibilities. Chase and recovery members were also part of launch operations or PSA teams. Also, engineering schedules slipped significantly throughout the years of preparation so medical team members could not de-conflict their clinical practice in order to be available for all training or test launches. Therefore, medical team members were asked to fill multiple roles and cross-train in order to assure that positions could be filled regardless of availability. This also provided backup for roles during operations, and helped team members better appreciate their colleagues' duties and contribute to the ConOps development.

Over the course of StratEx system development, many small balloon launches were conducted to test equipment, practice launch procedures, and conduct experiments. Each of these launches was an opportunity for medical team training. Also, tabletop exercises were conducted to prepare for major launches. Each of these events allowed the team to test, practice, and refine procedures and equipment. Operations began in May 2013 with sounding balloon tests, an airplane jump test, several tabletop exercises, and an October 2013 launch of a 90,000 cubic meter balloon. Flight rules and the ConOps were further focused after these early activities. In particular, the program needed to continue to integrate the interaction between helicopters, the primary chase asset.

Early summer of 2014 saw the program resume operations after an extended period of equipment redesign and testing. By late summer, the chase team was conducting two training operations a week, working with helicopters, chasing small balloons used for

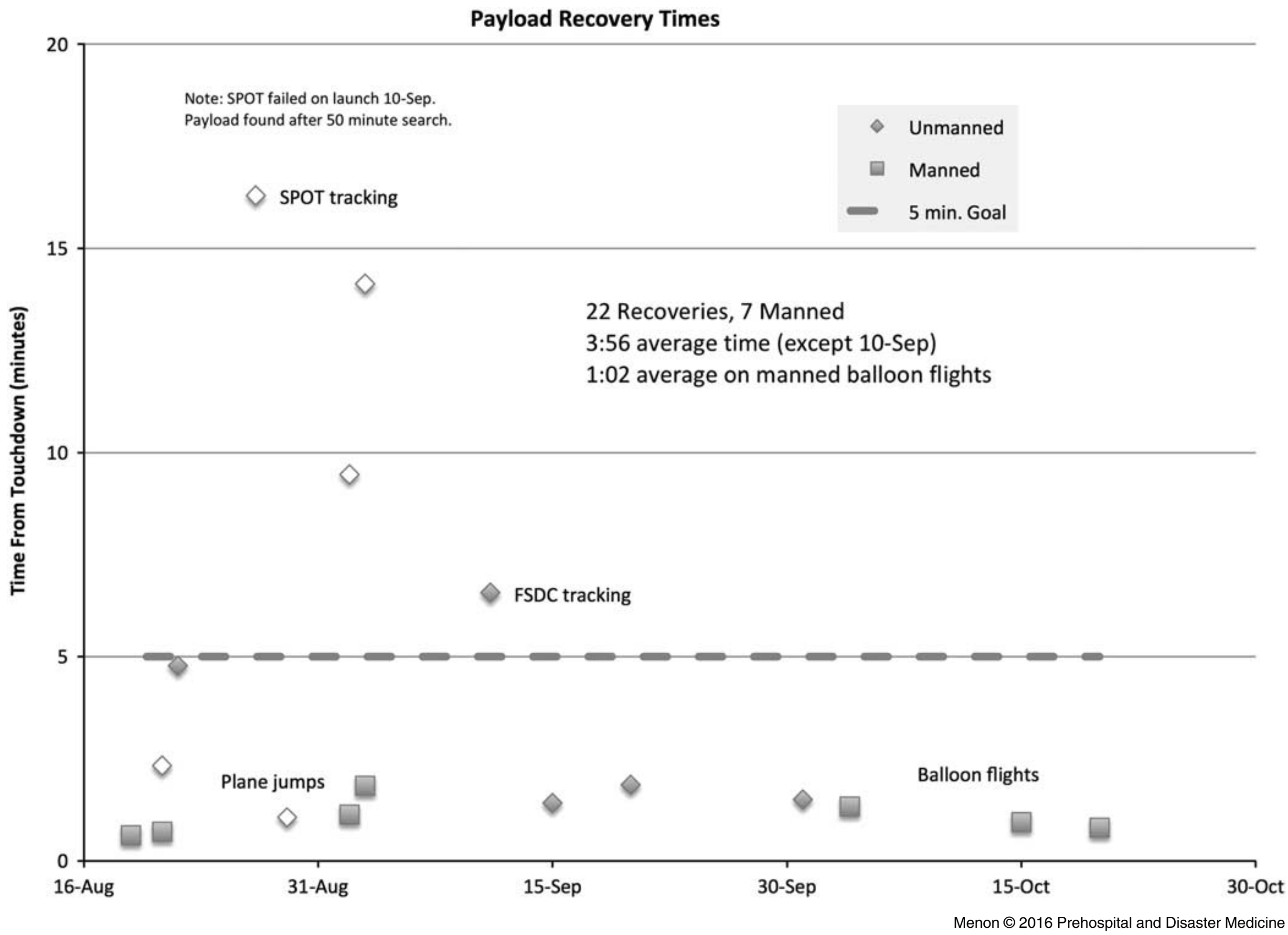

Figure 6. Chase Team Performance Showing Response Times.
Practice balloon flights, plane flights, an internally developed Flight Service Data Comlink (FSDC) tracking system, and commercial SPOT GPS tracking (SPOT LLC; Covington, Louisiana USA).

equipment tests, and supporting airplane jump training. Helicopter pilots became integrated into the team, provided valuable input to the process, and practiced rescue operations such as long-line operations to extract the PSA from a lake or ravine. Several navigators developed proficiency and refined techniques, and available personnel flew as spotters and communicators. During that time, communications systems were still a work in progress, so the team became accustomed to working with different methods of communication (line-of-sight radio, radio repeaters, satellite phones, cell phones, and text messaging), often with degraded or spotty reception. This was valuable from a training standpoint, since the team did not have to rely on a perfect system and had experience working with backup methods. Likewise, tracking systems were still developing, and the exercise of following a small balloon through the sky with marginal tracking was a valuable experience.

In all, 10 training events were conducted in August 2014 and 17 in September 2014, with two more in early October 2014, leading to manned flight operations beginning on October 4, 2014. As seen from the chart (Figure 6), the time from payload touchdown to arrival of the recovery team to the landing point steadily decreased until midway through September when the team could reliably respond below the 5-minute criteria.

During the three manned flights in October, the chase team averaged approximately one minute until a member of the medical team arrived at the pilot—the final flight logging a best time of 49 seconds.

Conclusion

The StratEx program was an example of an extreme event that pushed the boundaries of knowledge, engineering, and medicine simultaneously. The success of the mission depended on prehospital planning and preparation. Though there have been a few prior high-altitude jumps, the StratEx project presented new challenges for medical response. A scenario and probability-based analysis helped to plan for potential outcomes by estimating the risk of possible scenarios. These scenarios were mapped through the ConOps, which also served to integrate the medical team with the engineering and operational teams. Iterative feedback after practice jumps and from engineers helped refine the ConOps and prepare medical assets with the best possible risk posture. Similar analysis and preparation can help approach medical care of similarly novel events that carry significant risk and require a coordinated prehospital response.

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