A literature review of medical support in cave rescue and confined space medicine – implications in urban underground space development.

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Abstract. Objective: To conduct a literature review and knowledge synthesis of medical support in cave rescue and confined space medicine (CSM), thereby, extrapolating the knowledge gained from cave rescue and CSM to consequence management in Urban Underground Space (UUS) development. Methodology: A review of current medical literature was conducted. Data sources: Search engines utilized include PubMed, Medline, Cochrane Library, Science Direct and Google Scholar. Results and Recommendations: The synthesized knowledge based on available literature was extrapolated to application during consequence management in UUS development. Conclusion: As underground urbanization progresses to create sustainable habitats for the world’s increasing population, city planners need to consider the need for consequence management in UUS. The knowledge and experience gleaned a posteriori from cave rescue and CSM should be utilised to optimize the planning of emergency response in an urban underground environment.

1. Introduction

Rescue missions in cave and confined space environments are notorious for being perilous and technically challenging undertakings. Both casualty and rescuer face a high risk of mission failure and significant threats to life and limb during the rescue mission. Poor planning, inadequate training, equipment failure and reckless attitude of rescue teams have exacted the ultimate penalty – death of rescuer. Yet, there have been documentations of successful rescues when fortitude is paired with meticulous planning and cautious execution. Upon mission completion, an after-action review is conducted as part of the debriefing. While it may seem reasonable to stop at applying these ‘lessons learnt’ to future missions of similar nature, we should consider the potential benefits of taking it one step further – that of applying this knowledge in the field of UUS development.

Modern UUS planning and development has been gradually gaining momentum since the 19th century, with significant progress in the past 40 years. Multiple reasons exist to raise the strategic importance and accelerate the progress of subterranean urban development. Despite the modern progress made in UUS development, there is a paucity of data to show an adequate level of consequence management in UUS city planning. This article aims to synthesize the knowledge gained from cave rescue and CSM with the objective of applying this knowledge to optimize consequence management in UUS development.
2. Methodology
A review of existing medical literature on relevant topics was conducted. This literature review is exempt from medical ethics review.

3. Data sources
Search engines used to conduct literature search include PubMed, Medline, Cochrane Library, Science Direct and Google Scholar. Keywords used in literature search include the following: caving, cave expedition, spelunking, speleology, cave diving, cave rescue, confined space medicine, confined space rescue, urban search and rescue, structural collapse disaster, crush syndrome, underground urbanization, underground city masterplan, subterranean urban development, consequence management.

4. Results
4.1. Cave rescue
4.1.1. Background.
A cave is a naturally occurring cavity in the earth that is big enough for a person to enter. It is commonly found in the side of a hill, cliff, mountain or located underground [1]. Different geological processes give rise to a variety of cave sizes and morphology. Examples of sizeable caves include Vietnam’s Hang Son Doong cave and the Mammoth cave in U.S.A. [2]. The main types of caves include solution caves (formed in limestone), lava caves (tunnels formed by lava flow), sea caves (erosion of coastal rock), and glacier caves (excavating tunnels through ice). Humankind has a long relationship with caves. Archaeological research suggests that prehistoric humans used caves as a shelter from the elements [3] and for sacred rituals or religious practice [4].

4.1.2. Physical environment.
Terrain and climate
The interior of caves is in a natural state of complete darkness. Without an artificial illumination, navigation and movement inside a cave would be near impossible, likewise for visual assessment of the casualty’s injuries. Thus, cave rescuers need to ensure adequate light source with redundancy. The climate within caves varies from dry and dusty to wet and submerged. Most caves have a high degree of moisture. Some sections of caves may be permanently submerged or prone to flooding during periods of heavy rainfall. The temperature of subterranean caves is generally cooler than surface temperatures and less prone to fluctuations [5]. In this cold and wet environment, an injured immobile casualty risks becoming hypothermic. This worsens the risk of coagulopathy in traumatic bleeding and the shivering response increases energy expenditure. Cave rescuers need to ensure adequate thermal insulation of casualty and provide supplementary caloric support. Wet and muddy rock surfaces are slippery, increasing fall risk and wound contamination with subsequent wound infection. Intravenous cannulas must be wrapped securely to prevent dislodgement during extrication. Rescuers need to move carefully and deliberately to avoid falling and causing secondary injury to casualty.

Communications
Radio communication using high-frequency radio network is severely limited when deep underground because high-frequency radio waves do not penetrate rocky terrain. Specialized rock-penetrating Very Low Frequency (VLF) radio communication equipment has been shown to work but is expensive and bulky [6]. The Cave-Link system allows data and short messages to be transmitted through several hundred meters of rock using VLF radio waves [7]. Hard-wired field telephones are still in use by cave rescuers e.g. the TP-6N [8], requiring a long cable to be laid between the points of communication. There is limited bandwidth to support telemedicine during cave rescue. Hence, rescuers must function independently.
4.1.3. Medical issues.
Emergency cave rescues involves extricating cavers who are injured or entrapped within a cave. It requires a skill mix of both caving expertise and prehospital wilderness medical management. The rescue operation necessitates a close collaboration between medical first responders and experienced cavers [9]. Medical problems encountered in caving can be classified into traumatic injuries and non-traumatic illnesses. Stella-Watts et al analysed 877 caving incident reports between 1980 and 2008 by National Speleological Society [10]. A total of 1356 individual cavers were identified in this study, with an average age of 27 years and a total of 81 cases of fatalities. Falls were noted to be the commonest incident (74%), leading to trauma and contributing to 30% of fatalities. Of these traumatic injuries, the lower extremities were most commonly injured (29%), followed by upper extremities (21%) and head injuries (15%). Fractures and soft tissue injuries constituted the majority of injuries sustained. Hypothermia was observed in 7% and drowning occurred in 3% of the casualties.

Suspension trauma is a rare but potentially lethal condition affecting cavers who are suspended passively for prolonged duration on a rope attached to their climbing harness, without other forms of significant trauma [5, 11]. The pathophysiology is believed to be due to failure of venous return from the lower extremities with decreasing central volume causing activation of the Bezold-Jarisch reflex and leading to bradycardia, vasodilation, hypotension and loss of consciousness. In extreme cases, death may occur. Rhabdomyolysis may potentially further complicate the pathophysiology and late complication of renal failure [12].

Non-traumatic illnesses associated with caving are mostly related to infectious diseases, with histoplasmosis and leptospirosis being commonly reported [13]. Histoplasma is a fungal infection by Histoplasma capsulatum excreted by infected bats in their guano. The fungal spore grows in the soil inside caves and when disrupted by cavers, the spores are aerosolised and inhaled, leading to respiratory infection [14]. Leptospirosis is caused by spirochetes of the genus Leptospira and is transmitted from animal reservoirs via urinary excretion to humans through contact with contaminated water. It is endemic in Malaysian Borneo [15].

4.1.4. Rescue process.
Non-ambulant casualties require a stretcher for extrication. Negotiating narrow crevices pose great difficulty during the extrication process [16]. Specialised stretchers, e.g. Skedco, Alp design stretcher, are purpose-designed to fulfill this function in cave rescues. A modular helmet applied and strapped together in 2 halves with a face visor protects the casualty’s head and face [17]. Casualty packaging must be carefully done to ensure splinting and immobilisation of fractures during extrication, without impeding the physical movement. The casualty is monitored for signs of clinical deterioration, dehydration, and hypoglycaemia. Airway, breathing, circulation, and disability must be periodically reassessed and managed adequately to prevent deterioration e.g. placement of airway adjuncts.

Difficult cave terrain inevitably results in prolonged extrication, during which traumatic injuries can deteriorate. Of 444 incidents with documented rescue duration between rescuers establishing contact with victim to exiting the cave entrance, 57% required longer than 2hr [10]. In a case report of a 53-year-old caver who sustained severe head injury at a depth of 1000m from the cave entrance in Bavaria, Germany, the rescue operation took 12 days in order to extricate the caver [9]. Technical competency in rigging is required to overcome terrain challenges e.g. Tyrolean traverse technique to cross wide canyons, secure placement within stretcher during long vertical lift.

Cave rescues that involve a partially submerged cave from flooding are made more challenging by the need to include cave diving skills during extrication. Diving condition of flood water can be extremely silty with poor visibility [18]. Limited air supply, lack of familiarity with navigation and inadequate lighting equipment compound these problems. The casualty’s ability to swim and use SCUBA equipment needs to be factored in during the planning [19]. Pre-existing hypothermia may be worsened during the diving component, thus a need for insulated wet suits. Rate of ascent in deep cave systems must be controlled to prevent decompression illness, as encountered during a cave diving incident in Steinugleflaget cave, Norway, February 2014 [20].
4.2 Confined space medicine (CSM)

4.2.1. Background

The two main scenarios involving CSM are: Urban Search and Rescue (USAR) and occupational risk management. Structural collapse of man-made structures results in casualty entrapment requiring USAR. Occupational risk results from industrial exposure to confined spaces, e.g. sewage tunnels. OSHA’s definition of confined space includes these criteria: (a) It is possible to enter and work within the space. (b) The space is not intended for human occupancy. (c) Entry and exit are restricted [21].

4.2.2. Physical environment

Physical hazards arise from entrapment by heavy objects. Atmospheric hazards are caused by low oxygen level, high carbon dioxide level, toxic gases or a high level of suspended dust [22-23]. Low oxygen levels can go entirely unnoticed with rapid onset of asphyxial death. Hypoxia detection requires a high level of awareness. Safety legislations mandate that workers and rescuers entering confined spaces must monitor atmospheric levels of O2, CO2 and toxic gases, e.g. hydrogen sulphide, using hand-held monitors. A powered ventilation system is used to ensure circulation of fresh air. Supplied Air Breathing Apparatus (SABA) or Self-Contained Breathing Apparatus (SCBA) allow rescuers to breathe safely [24]. Particulate filtration masks protect against suspended dust.

4.2.3. Medical issues

Crush syndrome

Crush syndrome is a systemic manifestation induced by crush injury of muscles, resulting in rhabdomyolysis. Systemic manifestations include acute kidney injury (AKI), sepsis, acute respiratory distress syndrome, hypovolemic shock, and arrhythmias [25-26]. It occurs in casualties pinned down by heavy objects for more than 1-2 hours. Myoglobin from crushed muscle tissue leads to acute tubular necrosis and AKI. Upon extrication, the affected limb may appear to be minimally injured, with patchy areas of non-specific hypoesthesia. Subsequently, increasing compartmental pressure impairs microvascular flow and worsens muscle necrosis. Hypovolemic shock is caused by third space loss. Hyperkalemia, hypocalcaemia and a high creatine kinase level are notable features [27]. It is essential that the duration of entrapment and risk of crush syndrome is communicated to receiving staff.

The general goals of treatment are to enhance renal perfusion and increase urine output. Aggressive fluid resuscitation must start before, during and after extrication [28]. Alkalisation of urine by using a solute-alkaline diuresis may protect against the development of AKI. Solute diuresis is achieved by administering intravenous 20% mannitol with close monitoring. Early intermittent haemodialysis for established AKI is necessary to manage the effects of fluid overload, severe hyperkalemia, metabolic acidosis and uremia. Tissue ischemic necrosis requires surgical fasciotomy and radical debridement.

Asphyxia

Hypoxic asphyxia when humans enter enclosed spaces with a depleted atmospheric oxygen. Oxygen levels <10% significantly impairs the central nervous system while levels <6% are fatal, with rapid onset within minutes [21]. A similar situation occurs when atmospheric oxygen is diluted by the presence of other physiologically inert gas, e.g. nitrogen, in abnormally high concentrations. Most asphyxial cardiac arrest casualties do not survive and neurological outcome among survivors is poor [29].

Toxic gas inhalation

A wide range of toxic gas inhalation within confined spaces can occur and varies according to the incident e.g. carbon monoxide and hydrogen cyanide. The acute effects may range from minor local irritation, e.g. chlorine, to severe metabolic effects on the central nervous system, e.g. hydrogen sulphide. Personal protective equipment is essential to prevent exposure [30]. Acute medical management is tailored to the specific type of exposure.
4.2.4. Rescue process
Communication via radio waves is difficult within collapsed building structures and may require hard-line communication, e.g. wired field telephone, as a backup. Cable discipline is needed to organise a multitude of communication wires, electrical wires for power tools and ropes used for rigging.

Locating survivors under structural collapse is a constant challenge in USAR. A multi-prong approach comprising search and rescue dogs, fibreoptic scopes and chemical detection of survivors is commonly used. While the majority of casualties rescued from collapsed buildings are extricated by uninjured bystanders at the incident site, the specialised skill and equipment of USAR personnel are needed to rescue survivors deep under the rubble. The instability of partially collapsed structures can endanger both entrapped survivors and rescuers, hence a need for structural engineers to create shoring structures for stabilization [31-32].

Limited access to entrapped casualties during confined space rescue and awkward body postures of rescuers are similar problems faced by cave rescuers [33]. Thus, options are limited to basic medical interventions and most USAR teams focus on extrication of casualties in the shortest possible time. It is significant to note that previous mining accidents showed improved survival if miners were able to escape into underground mining refuge chambers built as part of the underground mining tunnels. Such emergency shelter systems provide breathable air and limited supplies of water, food, & first aid supplies. The Chilean mine rescue of 33 miners entrapped for 70 days is a fortuitous example [34].

4.3. Urban Underground Space (UUS) development

4.3.1. Background
Global population increase has created a need for a sustainable approach in urbanization. Demands for surface land utilization to build liveable space competes with infrastructure that supports city dwellers. These driving forces have led city planners to turn to the underground space to meet these demands [35]. As far back as 2500 B.C., humans had used underground spaces for shelter, storage, and defensive purposes [36]. Historical examples that were discovered include the Nushabad underground city in Iran and the Derinkuyu underground city in Cappadocia, Turkey [37-38].

4.3.2. Recent development
The advantages of subterranean thermal stability and shelter from extreme climate changes remain relevant in modern times, as exemplified by Montreal underground city, Canada, built in the 1970s [39]. Moving forward, land-scarce cities such as Helsinki, Hong Kong and Singapore are pushing ahead to design and build UUS in an effort to achieve urban resilience [40-41]. Singapore is an archetypal land-starved city that is reaching its limits of using high-rise buildings and land reclamation as solutions to ever-increasing demand for land use. Hence, Singapore’s government saw the need to develop an Underground Master Plan task force in 2007 with the main objective of identifying potential types of underground land usage and determining potential locations for such usage [42]. In 2010, the Economic Strategies Committee under the Prime Minister’s office made a key recommendation to invest in creating and using underground space [43]. In line with this strategy, the Jurong rock cavern for the storage of hydrocarbon products and the Underground Ammunition Facility for storage of military ammunition have been created. In the international arena, organizations such as International Tunnelling and Underground Space Association (ITACUS) and Associated research Centers for the Urban Underground Space (ACUUS) are actively promoting progress and collaboration in UUS development [44]. This has generated collaborative research e.g. underground freight transport system which utilises electrical propulsion to operate a dedicated underground freight transportation network [45].

4.3.3. Hazard vulnerability assessment in UUS
City planning must include hazard vulnerability assessment as part of the prevention and mitigation components of disaster risk management. The design and construction of UUS is no exception. With ambitious plans to maximise the utilisation of underground space, the number of people working and
living in the subterranean environment is expected to increase sharply in the near future. Thus, it is important to consider the potential risks that human populations in UUS may face and incorporate a high degree of resiliency into the system [41, 46].

Whilst subterranean constructions are generally more resistant to earthquakes compared to surface buildings [47], underground infrastructure is still susceptible to engineering failure and deliberate terrorist attack. Fires and explosions may occur due to accidents, e.g. gas/fuel pipe leakages, or may be caused by acts of terrorism. Blast waves from bomb explosions in a subterranean enclosed environment cause greater damage than an explosion of the same magnitude in an open-air surface environment [48], leading to significant damage of structural integrity. A fire outbreak which is not expediently managed will produce huge amounts of smoke and toxic fumes that remain confined within the subterranean space, resulting in severe contamination of the breathable air [49].

Inundation by stormwater can occur when the UUS’s drainage system is overwhelmed by extreme weather [50]. In flood prone cities such as Tokyo and Yokohama in Japan, deep underground cisterns were built in Kasukabe as part of a comprehensive plan to provide a massive surge capacity against this risk of inundation [51]. Without a robust drainage system, rapid accumulation of stormwater in the underground can endanger human lives. Past incidents involving flooding of subterranean mining tunnels had resulted in drowning of entrapped miners [52].

Ventilation control is critical to maintain a liveable underground atmosphere by ensuring safe levels of O₂, CO₂ and removal of potentially flammable or toxic gas. A failure of air ventilation system led to methane accumulation and explosion in the Pike River mine disaster, New Zealand in 2010 [53]. In underground sewage treatment facilities, an air quality monitoring system must be in place to ensure that toxic gases, e.g. hydrogen sulphide, do not accumulate.

4.3.4. Consequence management
Consequence management is defined as essential services and activities required to manage and mitigate problems resulting from disasters and catastrophes. Such services and activities may include transportation, communications, public works and engineering, fire-fighting, information planning, mass care, resources support, health and medical services, urban search and rescue, hazardous materials, food, and energy [54]. In a densely-populated city, a large-scale disaster has severe impact on many lives. It paralyzes the critical infrastructure, resulting in destabilization of the country’s socio-political and economic development [55]. The progressive usage of UUS for future growth of cities is no exception to the need for an emergency operations plan on consequence management.

5. Recommendations
The knowledge and experience gained from cave rescue and CSM can be extrapolated to consequence management of UUS development in 3 main areas: prevention, mitigation, and response.

5.1. Prevention
Preventive measures must be incorporated during the early stages of planning and construction of UUS to include the capability of detecting threats and reacting accordingly. An auto-regulating system that maintains a safe and habitable subterranean environment in a state of homeostasis must be paired with a robust multi-layered security system.

The monitoring of atmospheric air quality cannot be overemphasized in CSM. Human senses have no means of detecting hypoxic or hypercapnic air – a major contributing factor to rescuer death in CSM [56]. An automated system that analyses O₂ and CO₂ levels and detects toxic gases must be built into all areas with human activities to provide early warning of atmospheric dangers. Unlike individual portable monitoring equipment used in confined space rescues, the atmospheric monitoring system in UUS must be integrated with a public warning system to inform and update the masses. The heating, ventilation, and air conditioning (HVAC) system of modern urban buildings must be modified from that of surface buildings to suit the needs of UUS facilities. While the indoor air quality is the main concern during normal routine for the comfort of human occupants, when emergency situations occur, the priority is
that of a ventilation system that will continue to function using an emergency backup power source. In subterranean locations which are not able to have a guaranteed ventilation outlet linked to the surface, high-efficiency carbon dioxide scrubbers are required to remove exhaled carbon dioxide from occupants. An emergency source of compressed oxygen is also necessary to maintain compatible levels of oxygen in the air. A high-efficiency ventilation and filtration system will also be able to reduce the level of entrapped smoke or toxic gas build-up.

Cave rescue stresses the importance of backup light sources [5]. A caver’s ability to orientate himself relies heavily on visual cues of the terrain or landmark features. Emergency lighting is a common feature of modern buildings’ interiors and provides backup illumination during electrical supply interruptions. This function is critical for fire exits of the building to remain visible in dark, smoky interiors. Likewise, UUS must be designed with backup lighting. Illuminated signages indicating directions of evacuation or location of refuge chamber will reduce confusion and disorientation during emergency situations. To reduce reliance on electrical lighting and minimize fire risks, bioluminescence can be potentially used for this emergency purpose [57].

Building an underground facility with adequate structural resistance against both static and dynamic loads requires close collaboration between rock engineering and architectural teams. Geotechnical engineering of the underground structure needs to consider how the geological characteristics and ground behaviour type will interact with the structural design [58]. The construction of UUS must aim to achieve maximal sustainability and resilience for the underground infrastructure [59].

Security screening of all entrants to UUS is necessary to minimize the risk of terrorist attack on critical underground infrastructure by means of arson and explosive bomb attacks. The London suicide bombing attacks in July 2005 had shown the devastating effects of blast-related thermal injuries when improvised explosive devices were detonated in an underground confined space [60]. The inconveniences of security screening at entrances to UUS must be weighed against the potential harm of such saboteurs infiltrating deep within an UUS and gaining access to critical infrastructure. Such threats must be detected and neutralized at the point of entry.

5.2. Mitigation

Mitigation refers to the act of reducing the severity of impact from a major incident. It is an essential component of social resilience [61]. Just as fire escape routes are mandated by fire safety legislatures, hardened underground escape tunnels and large-scale refuge chambers can provide a temporary but critical shelter for large number of casualties. These underground escape tunnels should be constructed to withstand significantly higher dynamic loads than those of the main underground facility e.g. massive shear stress exerted by movement of landmasses, thus allowing ambulant survivors to ‘self-rescue’ themselves by moving to the nearest refuge chamber. Conversely, it facilitates the access to entrapped casualties by USAR first responders. Previous incidents of mining accidents had attested to the survival value of underground refuge chambers [62-63]. In the UUS context, these refuge chambers need to accommodate at least 100 casualties per chamber and remain self-sufficient in the atmospheric air control, water, food, medication, electrical supply, and communication links with rescue service [64]. Their pre-determined locations help to expedite access during the rescue phase.

It is also noted that the mission-specific training of USAR rescue teams and close collaboration between experienced cavers and rescue medics both contribute to team effectiveness. Likewise, setting up specially-trained UUS emergency response teams with simulation-based training exercises in UUS evacuation and rescue scenarios is likely to improve effectiveness of response in times of crisis.

Both cave rescues and CSM still face challenges in establishing an effective communication network among the rescuers. In extreme situation, ‘human runners’ are used to relay verbal messages - a tedious and inefficient method. In the design of UUS, this can be prevented by pre-establishing a wired communication network that is hardened to withstand impact. Integration with Indoor Positioning System (utilizing Bluetooth, Visible Light Communication, and smartphone sensors) and Real Time Location Service (using Radio Frequency Identification) technology can further enhance the clarity of casualty location.
5.3. Response

5.3.1. Physical environment
The depth of UUS facilities is comparable with that of natural caves, and potentially deeper. In both cases, the terrain encountered can vary widely, as with the physical dimensions of the movement routes. Intact passageways with standing room in the UUS facility permit fast movement during evacuation whereas collapsed structures may only allow crawl space within tight crevices. This is a common experience among cave rescuers and influences the access path planning during USAR.

However, underground facilities designed for the purposes of petrochemical or hazardous material storage may add to the complexity of the terrain in UUS rescue if their structural integrity is compromised. Hydrocarbon leakage may pose a fire risk, while industrial chemical storage or sewage treatment plants may face leakage of hazardous chemicals e.g. hydrogen sulphide. Such environments will require the usage of Hazmat protective suits and SABA equipment by rescuers, in turn limiting their mobility within confined spaces and increasing their risk of heat injuries. Their operational time is also greatly limited, as observed in CSM rescue missions. Damage to high voltage underground electrical cables placed within common service tunnels or electrical substations may multiply the risk of fire hazards.

When subterranean water reservoirs are affected, resulting in uncontrolled egress of stored water from damaged pipes or storage facilities, the adjacent underground units will face the problems of partial or complete submergence. Any survivors of the deluge will require rescue divers for extrication from a complex and dangerous environment. Previous cave rescue missions involving the need for diving had shown the extremely high risks of such rescue missions [18].

5.3.2. Medical issues
Although suspension trauma is mostly of concern during cave rescues, this can become a potential problem if narrow confines of access routes to a casualty results in prolonged vertical extrication, i.e., an upright posture is maintained for a long time. Lack of awareness may result in preventable morbidity and mortality of the casualty immobilised within a stretcher with limited physiological monitoring during the extrication process. An effective management strategy is to use anti-shock trousers to overcome the problem of poor venous return from the casualty’s lower limbs [16].

Dust inhalation is a major problem for both rescuers and casualties during CSM rescue from collapsed buildings. Similar cranio-facial trauma can be sustained by the casualty during cave rescue. Protection of the casualty’s head and face, e.g. the modular helmet used in cave rescue, and particulate filtration mask are effective countermeasures.

Crush syndrome and its management has been discussed in detail in the CSM section. The severe consequences of crush syndrome can be ameliorated by a high level of awareness and early management initiated in the field during the rescue process, e.g. aggressive fluid management. In addition, tertiary medical facilities must be prepared to ramp up their surge capacity to manage a large influx of entrapped casualties who will require urgent dialysis to overcome acute kidney injuries secondary to crush syndrome. This is concurrent with an enhanced surgical capacity to manage the traumatic injuries.

For survivors inside refuge chambers, psychological support and telemedicine consultation may be needed. Lessons learnt from psychobehavioral management of humans in prolonged isolation or confined spaces, e.g. Antarctica expeditions, naval submarine crew, and astronauts, can be applied to ameliorate psychological deterioration of survivors [65]. Acute stress reaction, if poorly managed, may impair human judgement and lead to irrational behaviour. During the Thai cave rescue, meditation was used a means to calm the trapped boys and a carefully selected amount of sedation was administered to allow the boys to attempt the diving component of extrication without panicking.
5.3.3. Rescue process
In both cave rescue and CSM, the challenges encountered in radio communication and adequate lighting are similar. Rescue personnel must strive for self-sufficiency in these two aspects. Lighting equipment that might be used in explosive atmospheres have to be ATEX / HAZLOC certified [66]. Radio communication equipment must be deployable deep underground while maintaining a portable and rugged form.

The ideal skill mix of a rescue team in UUS comprises rescue personnel, paramedics, and doctors. While the rescue personnel focus on the technical aspects of extrication (which requires various shoring and reinforcement techniques), the paramedic or doctor attends to the medical care of the casualty. A close parallel to this is the highly-specialised roles of team leaders, riggers, stretcher bearers and medics in cave rescues. Members of the rescue team need adequate training and appropriate equipment to function in this dangerous environment. In lieu of the prolonged and difficult extrication process, forward deployment of medical staff to initiate medical resuscitation or perform emergency surgical procedures, e.g. amputation of an entrapped mangled limb, may be necessary.

The medical equipment brought by rescue teams is limited to the bare essentials and must fit through a narrow manoeuvring space. This includes the stretchers used to extricate the casualties. Experience from cave rescue and CSM shows that these stretchers need to be compact, lightweight, and durable [5]. Similarly, basic resuscitation procedures are no longer as straightforward when medical personnel are forced to perform them within narrow spaces with an awkward posture or limited physical access, e.g. the potential need to perform an inverted tracheal intubation [67]. Prehospital trauma care can become unusually prolonged under such circumstances [68]. Massive transfusion protocol or anti-thrombolytic medications e.g. intravenous tranexamic acid may need to be initiated in the field. When casualties with severe trauma are brought up to the surface, immediate damage-control surgery in field hospitals deployed onsite may need to be weighed against prolonged evacuation to hospitals for definitive surgery.

6. Limitations of study
The findings of this article should be regarded as a framework to facilitate further research and promote active inclusion of consequence management in UUS planning. Small to moderate population group of casualties are affected in caving accidents or confined space rescues. The difficulties encountered provide valuable insight into managing similar situations in UUS. However, the affected population in UUS may be on a much larger scale and could present operational or logistical challenges that exceed this extrapolation. This potential limiting factor has to be considered during response planning.

7. Future research
A specialized training program that addresses the unique challenges of consequence management in UUS should be established to better prepare rescue personnel who may be involved in emergency response in UUS. This training should incorporate best practices from USAR and cave rescue. Future designs of casualty monitoring device which are compact, ruggedized, lightweight, has a long battery life and able to monitor all vital physiological parameters will greatly benefit deployment under such challenging environment. Improvements can also be made in subterranean radio communication systems, e.g. wireless mesh network technology. Further development of this technology can enhance communication among first responders.

8. Conclusions
As underground urbanisation pulls ahead with increasing momentum to create more sustainable habitats for the world’s increasing population, city planners need to pause and consider the need for CM in UUS. The knowledge and experience gleaned a posteriori from cave rescue and CSM should be utilised to optimize the planning of emergency response in an urban underground environment.
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