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Review

On the Move: A Review of Mobile and Military Surgery

Colton D. Wayne [1,2,3,*], Taylor H. Jacobs [1,4], Kyle Alexander [4], Zachary Dumbauld [1], Siddharth Narayanan [1], Omar Rokayak [4] and Forrest O. Moore [2,3]

1 Department of Pediatric Surgery, Nationwide Children's Hospital, 700 Children's Drive, Columbus, OH 43205, USA; siddharth.narayanan@nationwidechildrens.org (S.N.)
2 Department of Surgery, John Peter Smith Hospital, 1500 S Main Street, Fort Worth, TX 76104, USA
3 Department of Surgery, Baylor University Medical Center, 3500 Gaston Avenue, Dallas, TX 75246, USA
4 Department of Surgery, Virginia Commonwealth University Medical Center, 1250 E Marshall Street, Richmond, VA 23298, USA
* Correspondence: colton.wayne@nationwidechildrens.org; Tel.: +1-(817)-404-9152

Abstract

The ability to provide ambulatory and mobile surgery services in rural and austere environments has seen tremendous growth in recent decades due to innovations in surgical techniques and equipment. These advances have been implemented in both civilian and military settings, increasing the capabilities of surgeons and surgical subspecialists across the globe. This review aims to briefly explore the history of ambulatory and mobile surgery and describe the recent efforts to make advancements in this field to improve global surgery opportunity and access, as well as to provide an overview of both military and civilian utilizations of mobile surgical teams and strategies.

Keywords: ambulatory surgery; mobile surgery; global surgery; military surgery; mass casualty medicine

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1. Introduction

The evolution of surgery is a long and storied road, as its history can be traced back to the Stone Age [1,2]. Archaeological discoveries have revealed human remains, as well as tools and surgical equipment, indicating that procedures such as limb amputations, cranial burr holes, and trauma care have been performed across a number of cultures over the course of human history [1–4]. Just as the use of resources and tools has advanced from stones and spears, the practice of surgery has advanced greatly since its inception. Today, the field of surgery remains an ever-changing domain, with frequent innovations and updates to improve not only surgical knowledge and techniques but also access to surgical care.

As with much of medicine, the frequent setting for early surgeries was on the battlefield, often for limb amputation. With the discovery of anesthetic medications, the breadth of surgical procedures that physicians were able to offer expanded greatly, and most surgeries, particularly elective procedures, were performed in monitored settings of hospitals [5,6]. This is the general trend that persists in the modern day, with most emergency and elective surgeries being performed in either major medical centers or surgical centers, based on the acuity and complexity of the case and situation. This is especially true in high-income, high-resource countries with much greater access to available healthcare compared to many low- and middle-income countries (LMICs) [7–10]. One solution to improve access to care in LMICs, and even in low-resource areas of well-developed countries, is the utilization of ambulatory and mobile surgery strategies.

In this review, we will explore the history of mobile and ambulatory surgery and discuss its usage based on the current literature. We will then describe utilizations and customizations of mobile surgery in the context of current-day military applications and mass casualty incidents (MCIs), and then present a discussion on the use of artificial intelligence (AI) platforms in military surgery and austere environments. This review will then highlight some of the recent innovations and advances in mobile surgery for a variety of surgical specialties, followed by a section detailing a clinical synthesis, insights, and conclusions. Articles referenced in this review were retrieved from PubMed/MEDLINE and Google Scholar, using a Boolean search string containing the following terms: "mobile surgery", "military surgery", "ambulatory surgery", "forward surgical teams", "combat trauma care", "mass casualty incidents", "REBOA", "disaster management", "single surgeon units", and "artificial intelligence in military surgery/mobile surgery". Independent searches were additionally performed on the Google webpage and via manually searched reference lists to include studies not identified by the search engines. Additionally, only studies identified in the English language were used to perform the literature review and build the library.

2. Brief History of Mobile and Ambulatory Surgery

The progression of surgery in the past two centuries is cohesive with developments in anesthetic compounds and medications. As patients were provided better sedation, paralysis, and pain control, surgeons were able to perform much longer and more complex operations in a monitored hospital setting [5,6,11,12]. With technological advancements and inventions such as electrocautery, laparoscopic and arthroscopic cameras, and laser- and robotic-assisted surgery, there has been a concomitant drive to adapt these technologies to improve efficiency and increase access to care in a variety of settings [13]. In well-developed countries, this has been observed with the advent of outpatient ambulatory surgery centers, where a high volume of elective cases are performed. In these facilities, surgical teams function with fewer surgical faculty and support staff while performing lower-risk operations that do not typically require postoperative hospital admission [14], with advances in anesthetic capabilities greatly aiding this initiative [11,13–15]. By performing appropriate surgical procedures in ambulatory surgery centers, surgical specialties such as general surgery, orthopedic surgery, otolaryngology, gynecology, and urology have been able to decrease the overall cost of surgery for patients and reduce the burden on the healthcare system by avoiding the utilization of inpatient resources for select cases [16–20].

Surgeons and other healthcare professionals have been able to adapt the principles of ambulatory surgery into mobile surgery and develop strategies to address healthcare inequities in LMICs. The overarching goal for global surgical care is the development of healthcare systems that are well equipped to provide safe, affordable, and high-quality surgical and anesthesia care to all people. Achieving this requires the development of self-sustaining healthcare systems with both robust infrastructure and trained surgical and anesthesia personnel in low-resource areas, specifically in LMICs. Metrics to achieve this goal by 2030 are well described by the Lancet Commission on Global Surgery [21] and are summarized in Figure 1. To bolster these indicators while also accounting for the barriers related to the current infrastructure, geographical landscape, and local cultures, ingenuity and innovation are necessary.

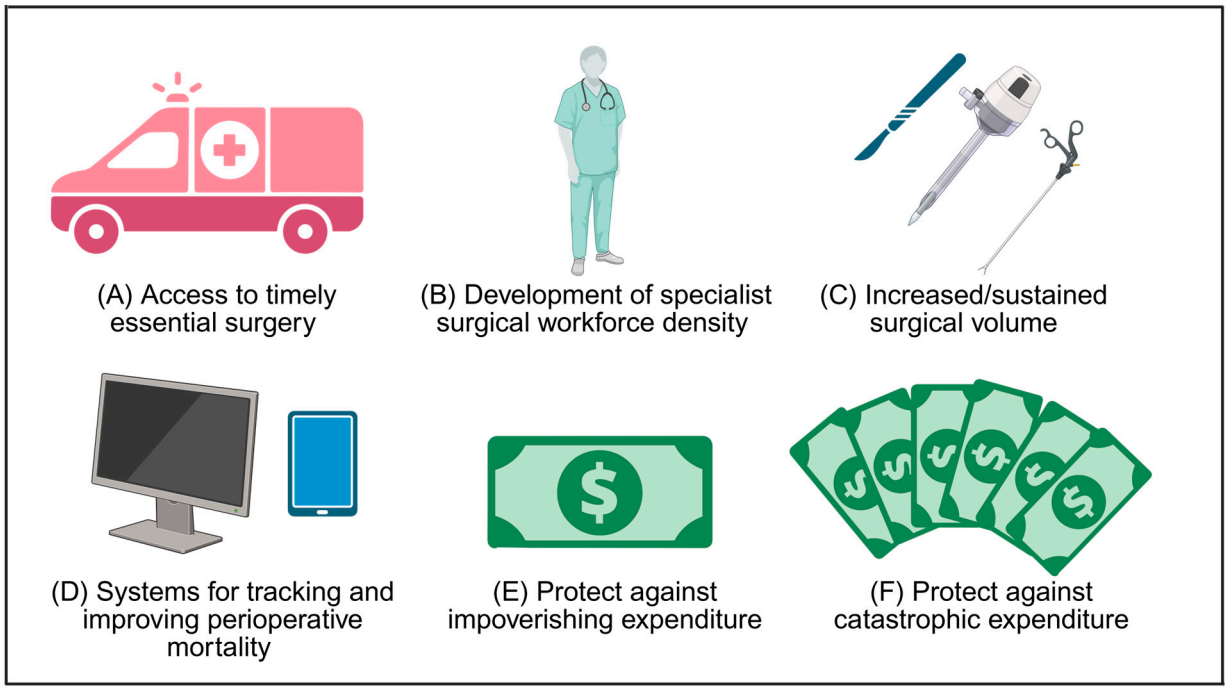

Figure 1. "Core Indicators for monitoring of universal access to safe, affordable surgical and anesthesia care when needed" adapted from The Lancet Commission on Global Surgery's publication-Global Surgery 2030: Evidence and solutions for achieving health, welfare and economic development by Meara et al. [21]. (**A**) Access to timely essential surgery, ensuring the majority of the population has access to treatment facilities, within a 2-h timeframe, capable of performing essential procedures, known as the Bellwether procedures. Specifically having access to a cesarean section, a laparotomy and treatment of an open fracture. (**B**) Development of a specialist surgical workforce density, increasing the number of surgical, obstetric, and anesthesia providers per 100,000 people within a population. (**C**) Increased/sustained surgical volume, increasing and sustaining the number of surgical cases performed per 100,000 people per year. (**D**) Systems for tracking and improving perioperative mortality, developing systems to monitor the cause of death in patients who underwent a surgical procedure and set goals for perioperative mortality rate improvement. (**E**) Protect against impoverishing expenditure and (**F**) Protect against catastrophic expenditure, preventing devastating out-of-pocket costs to patients and their family. Created in BioRender. Jacobs, T. (2025) https://BioRender.com/vgkcka4 (accessed on 16 May 2025).

Access to timely essential surgery was defined by the Lancet Commission on Global Surgery as a population having access to three essential surgical interventions, known as the Bellwether procedures, within a 2 h timeframe [21,22]. The Bellwether procedures specifically include a Cesarean delivery, a laparotomy, and the treatment of an open fracture. The ability to perform these procedures was found to be significantly associated with a facility's ability to provide essential emergency and surgical care [22]. Access to Bellwether-capable facilities within 2 h is generally met in urban areas in most countries, but rural areas, especially in LMICs, frequently experience barriers to care. These barriers can include healthcare facilities with limited capabilities, lack of transportation, and poor overall healthcare infrastructure. In the United States, efforts have been taken to address the problem of rural isolation for a large percentage of the American population, with governing bodies for residency training placing more emphasis on rural surgery, with increased opportunities for residency program flexibility to train residents to operate in rural and austere environments [23]. Mobile surgery units have also been developed, which allow for the practice of elective, acute care and emergency surgery in all manner of locations and environmental settings [24]. These "operating rooms on wheels" have revolutionized access to care both in the United States and abroad.

While these innovations have advanced the capabilities of adult surgical care, there has been a startling lack of progress in advancements for global and austere surgery for children. As with adults, studies in pediatric populations in developed countries have shown cost and efficiency benefits of performing certain procedures in outpatient ambulatory surgery centers [18]. However, it was not until the last 10–15 years that the focus in the pediatric surgery community shifted and prioritized surgical efforts in LMICs for the pediatric population, particularly since 2015 [21,25,26]. Numerous studies have since been published indicating not only health and wellness benefits provided to LMICs when surgical capabilities and access for children were increased, but also economic growth to those countries as well [21,27–30]. Technological advances, specifically those related to telemedicine, have improved access to care both in the United States and abroad [31–33]. In both adult and pediatric populations, advancements and alterations in anesthesia practices have been crucial in increasing the availability of surgical care in LMICs and austere environments [12,15,34–36]. As new technologies continue to emerge, surgeons will continue to strive to implement them in such a way to improve access to care across the globe.

3. Applications of Mobile Surgery in Military Medicine

In this section, we discuss the unique goals and challenges of military mobile surgery, the structure of the modern forward surgical team (FST) and military mobile surgical units (MSUs), their unique integration into the chain of evacuation and continuity of care, and the more recent creation of smaller, ultra-far-forward single-surgeon teams (SSTs) (Table 2). While much is published about military mobile surgery units, the following sections present an overview and updates based on the current literature.

Table 1. Comparison of select mobile and ambulatory surgery units.

Unit Name	Forward Surgical Team (FST)	Special Operations Surgical Team (SOST)	Mobile Surgery Truck (*Cinterandes Foundation*) [37]	Medecins Sans Frontiers, Mobile Unit Surgical Trailer (MUST) [38]	Mobile Surgical Unit (MSU), "Te Waka Hauora" by Mobile Health (New Zealand) [39,40]
Unit type	Military, conventional	Military, special operations	Civilian	Civilian/NGO	Civilian, private company funded by Ministry of Health
Setting	Conflict zone; typically 3–5 km behind frontline military units	High-threat and austere environments; embedded with special operations combat units	Rural Ecuador	Disaster and conflict zones, including Mosul, Iraq in 2017	Rural New Zealand
Personnel	20 total, including 3–4 surgeons (general/trauma, orthopedics), 2 nurse anesthetists, 3–5 surgical, critical care or general RNs, and 3 STs	6 total: surgeon (general/trauma), EM physician, nurse anesthetist or anesthesiologist, critical care RN, RT, and ST	Core team includes a surgeon, anesthetist, OR technician, medical coordinator, driver, general coordinator, and receptionist	Includes multiple surgeons and logisticians; exact staff not specified	Surgeon, anesthetist, anesthesia technician, unit driver, one permeant nurse, and four local nurses
Surgical capabilities or typical cases	2 OR tables, up to 30 trauma/damage control patients	1 OR table, 2–10 trauma/damage control patients	7641 cases over 20 years; 60% abdominal or endoscopic cases	1 OR table, reported capability of 10 surgeries per day, and 100 surgeries total without major resupply	1 OR table; endoscopy and ambulatory cases (general, gynecological, orthopedic, and dental surgery); over 34,000 surgeries performed
Setup and logistical requirements	Requires setup of 3 interconnected tents (resuscitation, OR, recovery); power from generator or vehicle-based; dependent on host/logistics unit	Highly mobile and rapidly deployable; equipment carried in backpacks; surgery can be performed in aircraft, vehicles, shipping containers, and buildings	Surgery is performed in a mobile surgery truck, and tents are used for postoperative care	Requires 40 m^2 of flat surface to set up five trailers (operating theatre, recovery room, intensive care unit, sterilization room, storeroom) and multiple adjacent tents; three portable power generators; reliable nearby water supply is a priority	Heavy truck and trailer that expands upon setup to form operating room, waiting area, and recovery; schedule and procedures planned, with MSU traveling on a rotating schedule

Table 2. Comparison of select mobile and ambulatory surgery units.

Unit Name	Forward Surgical Team (FST)	Special Operations Surgical Team (SOST)	Mobile Surgery Truck (*Cinterandes Foundation*) [37]	Medecins Sans Frontiers, Mobile Unit Surgical Trailer (MUST) [38]	Mobile Surgical Unit (MSU), "Te Waka Hauora" by Mobile Health (New Zealand) [39,40]
Perioperative support	Typical recovery tent with capacity for 6 patients; can hold for 6 h prior to evacuation	Limited holding capability; ideally supported by rapid evacuation	Tent complex near surgical unit	Multiple adjacent tent structures for surgical evaluation and triage; autoclave and water treatment systems included	Robust patient preoperative and postoperative education; follow-up phone call on postoperative day one; primary care and local hospital support
Follow-up care	Evacuation to Role 3 or higher-level facility	Evacuation to Role 3 or higher-level facility	Local healthcare providers and telemedicine for follow-up with surgical team	Not specified	Close partnership with local hospitals
Strengths	Multiple surgeons allow for concurrent cases; robust damage control capacity; proximity to front lines	High mobility, autonomy, minimal footprint; able to reach otherwise inaccessible or denied areas	Highly mobile, coordinated with local health resources; low cost	Ability to rapidly deploy to a location within 16 days and, once there, set up within hours; strong focus on maintaining surgical sterility	Wide variety of surgical services available; also provides education for local healthcare staff; long history of continued operations and accreditation from regular quality reviews
Limitations	Less mobile due to size, tent-based infrastructure, and logistical support needs	Limited surgical capacity (single surgeon); fatigue risk in prolonged missions; minimal holding and postoperative care capability	Limited resources, space, and postoperative care after the unit leaves	Requires significant logistical support, and limited space in single OR	Restricted to ASA I and II patients with BMI < 35

ASA—American Society of Anesthesiologists; BMI—body mass index; EM—emergency medicine; NGO—non-governmental organization; OR—operating room; RN—registered nurse; RT—respiratory therapist; ST—surgical technician.

3.1. Operational Goals of Military Mobile Surgery

Military mobile surgery is a unique facet of mobile surgery and has fundamentally different goals as compared to humanitarian surgery. The primary goal of military mobile surgery is damage control and reducing the time to lifesaving surgical intervention for the combat casualty to less than 60 min, which has clear evidence of lowering combat mortality rates [41]. While this is a goal shared by other military surgical assets, mobile units attempt to further reduce the time to care through greater mobility, closer proximity to the point of injury, and a smaller logistical footprint than typical of larger military surgical teams. With this proximity to the point of injury comes proximity to threats and the need for these MSUs to integrate with forward conventional or special operations military combat units [41]. The mobility of these surgical units enables them to accompany these combat units and rapidly set up surgical damage control capability in austere and often hostile environments.

Damage control surgical procedures conducted by MSUs focus on stopping hemorrhage and contamination. These include procedures such as closure of gastrointestinal perforations or resection without re-anastomosis, abdominal packing for solid organ injuries, vascular ligation or shunting, limited external fixation for major orthopedic injuries, and burr holes or bone flaps for suspected extradural or subdural hematomas [42].

Damage control surgery is accompanied by damage control resuscitation, which aims to combat the lethal diamond of death resulting from coagulopathy, hypothermia, acidosis, and hypocalcemia that occur in acute hemorrhagic trauma [43]. Damage control resuscitation focuses on active warming strategies, transfusion of whole blood or components in 1:1:1 ratios, and permissive hypotension [44]. Military MSUs can provide this type of major surgery and resuscitation for a limited number of casualties, given their finite resources, and often cannot conduct more than two concurrent surgeries. After providing limited damage control and initiating resuscitation, the goal of the military MSU is to rapidly evacuate the casualty to a higher echelon of care for definitive management, ideally a nearby semi-permanent military hospital [44].

Beyond casualty care, military MSUs can play significant roles providing surgical and medical support to local populations or in humanitarian missions. In one example, a French FST in Chad cared for 358 patients in an almost exclusively humanitarian role, providing surgical care that was 92.7% elective and postoperative care with a median follow-up of 30 days [45]. As part of a broader effort to strengthen international relations in Latin America and the Caribbean, the United States military has reported success in performing elective, low-risk ambulatory surgery using rapidly deployable tent-based facilities [46]. Higher volumes and complexity of mobile surgical interventions have also been conducted on larger military hospital ships such as the USNS Comfort, a hospital ship with a 1000-patient bed capacity and 12 operating rooms [47].

3.2. Forward Surgical Teams (FSTs) and Their Role in Combat Casualty Care

Perhaps the most common and most well-represented mobile military surgical team in the current literature is the FST. The first FST described in the modern literature was developed by the surgeon Charles Rob to support British airborne units in World War II [48]. Within the United States military, the surgeon Robert Zollinger developed similar units consisting of one truck with tents, equipment, and enough supplies to conduct 100 major operations [49]. At least 17 variants of the FST are described in the published literature among the US, UK, French, and Australian militaries, with most of these reports originating from the US military experience. The reported team size is variable, ranging from 8 to approximately 20 medical staff [50].

The conventional US Army FST consists of twenty personnel, including two to three general surgeons, one orthopedic surgeon, two nurse anesthetists, and supporting nursing,

operating room, and medical technician staff. These teams can set up surgical capability within several hours in three interconnected tents to form a small emergency room, operating room, and recovery room. Once set up, an FST can independently manage a combined total of up to 30 major surgical cases and trauma resuscitations over 72 h [50,51]. While FSTs use portable equipment (power generators, portable anesthesia machines) and are typically transported to their operational locations by high-mobility vehicles, aircraft, or amphibious platforms, these surgical units remain stationary once deployed and are not designed to deliver care while in motion [50,52].

Much has been published about the experiences of US military FSTs in recent conflicts. An analysis of 10,992 patients treated from 2008 to 2014 by US military FSTs in Afghanistan showed that the most common surgical procedures were exploratory laparotomy, vascular procedures other than the head and neck, and external fixator placement [53]. Notably, in addition to surgical capability, FSTs provided a high number of non-operative interventions, including wound care, ultrasounds, and X-rays [53]. Injuries treated by FSTs in Afghanistan most commonly involved the lower extremity/pelvis/buttocks (23.3%), matching improvised explosive devices as a prevalent mechanism of injury throughout that conflict. Although 80% of all injuries treated by FSTs were classified as either minor or moderate in abbreviated injury scale severity, severe injuries were most commonly to the head [54]. Compared to patients treated at larger, non-mobile combat support hospitals (CSHs), patients initially managed by FSTs experience equivalent [55] or superior [56] outcomes, a benefit attributed to the FSTs' ability to deliver timely damage control surgery and resuscitation close to the point of injury.

3.3. Integration with Evacuation and Continuity of Care

The conventional US Army FST can typically provide up to six hours of postoperative care before patients require evacuation to a higher level of care, typically a CSH. Within the well-described NATO and US military medical structure, care for the injured combatant is classified according to progressive echelons ("Roles") of care, in which MSUs (including FSTs) represent the second-level medical care (Role 2), after initial level one buddy or unit-level medic care (Role 1). The CSH (or equivalent Navy fleet hospital, Navy Expeditionary Medical Facility, or Air Force Theater Hospital) represents third-level care (Role 3) and provides robust and semi-permanent trauma care, including surgical subspecialty care (neurosurgery, radiology, and otolaryngology), CT imaging, and full laboratory services. Definitive care for combat casualties in this system typically occurs at the highest level of care, or standing hospitals in the US or Germany (Role 4) [48,57].

Depending on the distance between Role 2 FSTs and Role 3 hospitals, casualties can be evacuated by ground, helicopter, or fixed-wing transport. Casualty evacuation to definitive care is often provided by mobile Aeromedical Evacuation (AE) or critical care units such as US Air Force Critical Care Air Transport Teams (CCATTs) [48]. AE teams, composed of flight nurses and medical technicians, are trained to deliver in-flight medical care and ensure continuity of care from the delivering surgeon to the receiving medical facility. While they do not routinely include a physician, AE teams are prepared to manage medical emergencies and other postoperative issues that may arise during transport [58]. CCATTs are deployed when a higher level of care is required, as they include a critical care physician, a critical care nurse, and a respiratory therapist. These specialized teams can simultaneously care for up to six patients on an aircraft, including three who require mechanical ventilation. CCATTs have shown significant flexibility in their ability to directly offload casualties from FSTs during mass casualty events [59].

The recent conflict in Ukraine has underscored the limitations of the NATO model relying on MSUs. Faced with the realities of large-scale warfare on home territory, similar

Ukrainian MSUs have at times been replaced by pre-existing civilian hospitals located near the front lines. These standing facilities can serve as the initial point of surgical care, receiving casualties directly from first responders and providing damage control surgery before transferring patients to a larger, more distant hospital for definitive treatment [60].

3.4. Development of Single-Surgeon Teams (SSTs)

More recent efforts have focused on developing even smaller, more agile surgical teams given the needs for increased operational flexibility, closer proximity to injury in austere terrain, and high-threat combat operations that cannot support the logistical footprint of a larger surgical unit. US Army FSTs have traditionally adapted to this by dividing into two 10-person elements, each including two surgeons and a nurse anesthetist, with acceptable outcomes [61]. This concept of modular 10-person teams has since evolved into the formalized Forward Resuscitative Surgical Detachment (FRSD) [62,63].

Within the last decade, even smaller, ultra-mobile single-surgeon teams (SSTs) of four to ten personnel have developed out of the same demand by the US military for far-forward surgical care with smaller logistical footprints and even more mobility. These units are often called to support small unit deployments or special operations missions in especially austere and hostile environments, where surgical care would otherwise be impossible. Examples of these SSTs include Special Operations Surgical Teams (SOSTs, US Air Force Special Operations Command), Golden Hour Offset Surgical Teams (GHOSTs, US Army), Expeditionary Resuscitation Surgical Teams (ERSTs, US Army), Expeditionary Resuscitative Surgical Systems (ERSSs, US Navy), and Surgical Resuscitation Teams (SRTs, US Special Operations Command) [64–67]. Published literature describing similar French SOSTs [68] and a NATO course dedicated towards training allied personnel on developing and refining similar teams also exist [69]. Each SST typically contains a general or trauma surgeon, nurse anesthetist or anesthesiologist, emergency medicine physician, surgical technologist, and a critical care and/or emergency nurse; in some cases, a respiratory therapist or paramedic-level provider(s) are also included. Uniquely, some of these SSTs are trained to perform mobile surgery on land-, air-, and sea-based platforms, including buildings of opportunity, aircraft, ships, and moving vehicles; however, this capability and overall team composition vary depending on the unit and mission. Collectively, these smaller teams that provide surgical care in more extreme conditions have been termed Austere Resuscitative Surgical Care teams [64,70].

Given the rapid development and wide variety of SSTs, along with the variability in their staffing, equipment, and training, several efforts have been and remain underway towards increased standardization and clearer delineation of their capabilities, limitations, and appropriate utilization [71]. These include their limited capacity to manage multiple severely injured patients simultaneously, a reduced capability for prolonged casualty care in the event of evacuation delays, heightened risk of provider fatigue due to reliance on a single surgeon, and a lack of redundancy among team roles [71].

Despite these limitations, SSTs have displayed success, with reported survival rates of 97% (SRT; analysis of 190 casualties) [72] and 98.7% (SOST; analysis of 5113 patients including 468 surgeries) [73]. Notably, five military mobile surgical teams and SSTs, including a US Army FRSD, US SOST, and other US and NATO assets, successfully managed over 60 injured patients during the 26 August 2021 bombing and mass casualty event at Hamid Karzai International Airport amid the US withdrawal from Afghanistan. The surgical teams used an existing NATO medical facility at the airport—except for the FRSD, which established two operating rooms, two trauma bays, and two ICU beds at a distinct location on the airport's grounds [74]. This dispersion of surgical resources was noted to improve access to care during the incident. Combined, the surgical teams performed 15

major damage control surgical procedures (including thoracotomies, laparotomies, and vascular shunting) and evacuated 37 casualties by aeromedical transport within 15 h of the attack. Sustained additional operations continued for more than 40 continuous hours. This event publicly highlighted the adaptability, effectiveness, and value of these teams [63,74].

From conventional FSTs to ultra-mobile SSTs, these military units demonstrate how mobile surgery is used to meet the demands of modern combat casualty care and is adapting to meet requirements for even greater mobility and flexibility. While extremely effective in providing immediate lifesaving care through proximity to the point of injury and operational flexibility, the success of military MSUs depends on a broader system of casualty evacuation, as well as recognition of their appropriate operational utilization.

4. Ambulatory Surgery in Mass Casualty Incidents and Disaster Medicine

Mass casualty incidents (MCIs) and disasters are events that can rapidly overwhelm emergency resources and health systems within a community or region. These incidents have been prevalent in the United States in recent years. In 2024, there were over 500 mass shootings in the United States [75]. Domestic terrorism remains concerning following the 11 September 2001 attacks, Boston Marathon bombings, and the 2025 New Orleans truck attack. Natural disasters such as hurricanes, tornadoes, and wildfires disrupt infrastructure and produce countless victims [76]. While rare, these events demonstrate the importance of innovation in the management of MCIs and disaster scenarios.

Immediately following an MCI, appropriate triage is critical to ensure that limited resources are utilized for the greatest impact [77]. While there are numerous MCI triage algorithms, only a handful have been validated in the field [77]. Despite variety in algorithms, Suda et al. recommended exercises or virtual training to improve triage quality with verified triage algorithms [77]. The utilization of virtual reality programs has improved methods in training for MCI triage. Way and colleagues utilized a VR platform to simulate an MCI and train first responders on the Sort, Assess, Lifesaving Interventions, and Treatment and or Transport (SALT) triage algorithm; 95% and 91% of participants rated the simulation and virtual patients, respectively, as realistic [78]. In a similar study, other authors concluded that virtual reality programs are valuable in assessing performance in MCIs [79].

As with effective triage in disaster and MCI scenarios, early surgical care is another critical need. Given the chaotic and sometimes austere nature of these scenarios, surgical intervention is difficult to perform either on the scene of an MCI or in the hospital when resources are limited. As with military surgery, damage control surgery and resuscitation are critical in MCI scenarios. Technological advances have aided in these efforts—one such example is resuscitative endovascular balloon occlusion (REBOA), a minimally invasive procedure to temporarily control non-compressible hemorrhage [80–82].

4.1. REBOA: In-Depth Analysis and Assessments of Long-Term Effectiveness

Various medical evacuation training platforms, such as the American College of Surgeons Basic Endovascular Skills for Trauma (BEST) and Endovascular Skills for Trauma and Resuscitative Surgery (ESTARS) courses, consider REBOA to be a bridge treatment for endovascular hemorrhage control until definitive surgical intervention is feasible. REBOA has been tested and approved for various trauma-related and surgical pathologies, including abdominal and/or pelvic trauma, post-partum hemorrhage, and aortic rupture [82,83].

Improvements in endovascular technology have facilitated the use of REBOA in forward-deployed settings [84]. In both the operational military and austere environments, the overall process of managing resources and transport capabilities often becomes a

limiting factor for trauma patients. Space and supplies are equally limited in such settings to what a provider can carry in a backpack, vehicle, or makeshift clinic. REBOA has been successfully utilized in austere operational settings and military medicine based on increased utilization and ongoing technical advancements of both the device/equipment and deployment practices [83,85–87].

Despite its efficacy, REBOA's application in its current state is limited in duration, as it induces distal ischemia during occlusion and can lead to reperfusion injury upon balloon deflation [88]. Severe physiological derangements and irreversible end-organ ischemic injury have been observed in animal models when subjected to periods of aortic occlusion longer than 20–40 min [82]. Several approaches (including intermittent REBOA and partial REBOA) are being investigated to overcome the negative effects of its prolonged use, and these have previously been covered in depth [82,89]. Other challenges include the limitation in obtaining reliable, accurate blood pressure measurements, which has formed the basis of several ongoing research studies. For example, the accuracy and reliability of a disposable vascular pressure device for arterial pressure monitoring in critical care transport was evaluated and was shown to provide a reasonable estimate of the mean arterial pressure, with recommendations to perform future trials validating its efficacy under different environments, including austere locations [90]. Several novel pre-clinical studies using swine models indicate that REBOA, when used in conjunction with a small portable arterial pressure-sensing device, may potentially augment the former's safety and functionality in trauma patients both at the point of injury and in the hospital [91,92]. A recent study utilizing a swine model obtained accurate and precise arterial pressure measurements using a miniature portable device during standard and partial REBOA in both uninjured and shock conditions, highlighting extended and enhanced capabilities in any low-resource/battlefield settings. This study suggested the likelihood of eliminating the need for standard invasive pressure monitoring and external setups [93]. In another recently published swine model of hemorrhagic shock with ongoing venous bleeding, hemodynamics and survival were improved when the REBOA balloon catheter was introduced into the descending aorta in a specific occlusion region (transitioning from zone 3 to zone 1), enabling hemorrhage control adjunct with resuscitative support [94].

While clinical data on the long-term efficacy and validity of REBOA are scant, some studies have demonstrated the successful use of partial REBOA in prehospital settings, as demonstrated by the London Air Ambulance, a helicopter emergency medical service [95]. Femoral artery access was successful in 13/16 patients. Of the 11 patients who underwent balloon inflation, 8 survived to 24 h after injury. However, only 2/11 patients survived to 30 days and hospital discharge, with many dying of multiple organ failure due to the nature and extent of their injuries [95]. While long-term survival was poor, this study demonstrates the feasibility of an invasive surgical procedure performed in austere and dynamic prehospital environments. Another recent single-center, single-arm, early feasibility trial used REBOA as an adjunct to advanced cardiac life support in out-of-hospital cardiac arrest patients, deeming it viable, with improvements in end-tidal carbon dioxide levels [96]. Unfortunately, none of the individuals survived to hospital admission, with the authors instead suggesting the utilization of partial REBOA to prevent re-arrest after the return of spontaneous circulation.

Innovation in this technique has allowed its application in combat; REBOA can be deployed without fluoroscopy, and improved balloon design improves efficiency [82]. Such advancements are in tandem with ongoing novel laboratory research, where a group has developed a balloon inflation guidance algorithm for the REBOA catheter, employing a simple disposable vascular pressure device in the absence of fluoroscopic guidance [97].

While several proof-of-concept studies on REBOA-related device/equipment development point towards its efficacy in severe operational settings and military medicine, there are reports that indicate otherwise. The UK-REBOA Trial showed that REBOA did not reduce—and on the contrary, might have increased—mortality compared to trauma patients in the emergency department who received standard care [81]. Evidence for the use of REBOA in MCI scenarios is quite limited; however, a case report demonstrated the use of REBOA in the emergency department as surgical resources were being utilized for other patients involved in the MCI [98]. While this case report shows promising results, further research is necessary to elucidate the role of REBOA within MCIs and disaster events.

4.2. Other Factors Affecting Ambulatory Care in MCIs

Given potential disruptions in infrastructure and emergency resources in a civilian MCI, patients at casualty collection points (CCPs) may face delays in transport to definitive surgical care. This issue has also been of concern in the military health system (MHS) when caring for combat casualties. In recent conflicts in the Middle East, combat casualties were rapidly evacuated via helicopter [99]. However, if helicopter evacuation is compromised, casualties face significant delays to definitive care. Thus, in 2018, Leasiolagi et al. described a mobile operating room and CCP to accompany soldiers in far-forward environments [99]. In the civilian setting, emergency prehospital surgery is prevalent but limited. For example, a 1996 study investigated the experience of emergency medical services (EMS) directors with in-field extremity amputations [100]. This study had limited power due to a low incidence of in-field amputation; only 18 of the 143 survey respondents had direct experience with the procedure, and 96% of respondents lacked formal training within their EMS system on the procedure [100]. In this study, the majority of injuries indicating in-field amputation were motor vehicle accidents [100]. While it is more common to have a general or trauma surgeon performing these operations in the hospital, in MCIs and disaster scenarios, surgeons and prehospital providers may work in tandem to provide more advanced care to patients facing extended extrication or transport times. The literature on this topic is limited; future research is necessary to elucidate the incidence and success of in-field surgery in disaster and MCI scenarios.

5. Innovation for Surgery and Anesthesia in Low-Resource Areas

As previously discussed, both urban and rural communities in LMICs often face extreme barriers to care. Technology and innovation have been critical to mitigating some of these health inequities across the globe. To identify the needs of communities in LMICs, geospatial mapping of countries has been implemented to identify which areas are in need and what barriers are in place that the country may be able to address. Esquival et al. performed a geospatial mapping study in 2016, evaluating disparities in essential surgical care in Zambia, and found that approximately 80% of the population was more than 2 h from a capable healthcare facility [101]. With the increasing popularity and significant utility of these analyses, similar studies have been performed in numerous countries [102–115]. These studies provide an objective analysis to identify disparities and help accurately guide infrastructure improvement in the respective country.

To further address surgical access disparities, MSUs have been developed to bring surgical care directly to these patients. These units are generally modified box trucks, tractor-trailers, or ships, known as "Mercy Ships", which have been equipped with all of the necessities for a functioning surgical theatre and anesthesia care [116,117]. Many organizations have employed these MSUs (Table 2), such as the non-profit organization Cinterandes, who perform surgical procedures in a fully functional mobile operating theatre in rural Ecuador [37]. Over a 20-year time period, the group has performed 7641 operations,

with 60% being abdominal or endoscopic procedures, and the cost per procedure has been maintained at less than USD 100 [37,118]. The team provides immediate postoperative care in a tent complex established near the surgical unit. A local healthcare provider team is available for longer-term postoperative care, and telemedicine systems are used to facilitate follow-up with the surgical team [118]. In follow-up studies evaluating outcomes for 4545 procedures performed, there were no deaths, three instances of minor surgical complications, and four instances of major complications [118]. Similar organizations with MSUs provide care in low-resource areas in multiple countries in sub-Saharan Africa [116]. These units not only address barriers to access to surgical care in LMICs but also have infrastructure in place to minimize perioperative mortality and provide overall affordable care [38–40].

Resource limitations and a lack of modern surgical technology in low-resource areas also create the potential for disparate surgical care. To address these limitations, physicians have collaborated with innovators and local stakeholders to adapt available resources to meet surgical needs and develop novel technology to minimize health inequities. One major innovation in surgical care has been the evolution of minimally invasive surgical techniques, especially laparoscopic surgery. While laparoscopic surgery has improved patient outcomes and recovery, it is difficult to implement in low-resource areas where there is limited access to (and high costs for) necessary equipment, including insufflation gas, laparoscopic energy devices, camera systems, and lighting capabilities. This has led to lower rates of laparoscopic procedures, like laparoscopic appendectomy, compared to open surgery in LMICs [119]. Despite lower rates of implementation, the rates of minor and major complications and surgical-site infections were lower than with open procedures and at similar rates as seen in high-income countries [119]. To circumnavigate resource hurdles and increase the utilization of laparoscopic approaches, multiple innovations have been devised for low-resource settings. To increase familiarity with the technique, low-cost and easily portable laparoscopic training simulators have been developed to train local healthcare providers [120]. These low-cost training systems are approximately one-fourth the cost of high-end training systems but have comparable, if not better, reviews by providers trained using both systems [121].

To perform abdominal laparoscopic surgery safely, a potential (or working) space needs to be created within the intra-abdominal cavity. This is generally performed through insufflation of carbon dioxide gas. Reliable access to carbon dioxide gas can therefore be a limitation in austere settings. Provider groups in LMICs have worked with local businesses, specifically soft drink companies, to obtain a sustainable source of carbon dioxide tanks for use in laparoscopic procedures [122]. Providers can also perform laparoscopy without insufflation gas using a technique called gasless lift laparoscopic surgery, in which instruments are used to lift the abdominal wall and mechanically create a potential space [123,124]. Laparoscopy systems that utilize mobile telephones as the camera-recording device for laparoscopes negate the necessity of large camera towers with specialized cameras [125,126]. This technology has been implemented in both laparoscopic and endoscopic procedures, with both having similar visualization and diagnostic capabilities to their traditional laparoscopic counterparts [125,127]. Companies have continued to build on these technologies and make further advances, generating low-cost compact laparoscope systems with built-in cameras and light sources [128]. Increasing access to and training with such technologies and surgical techniques at affordable costs in LMICs and low-resource areas may increase the surgical capabilities in the community, improve perioperative outcomes, expand the surgical workforce, and provide affordable care.

In order to bolster the number of surgical, anesthesia, and obstetric healthcare providers to adequately care for a population, the concept of task shifting has been increas-

ingly adopted around the world [129]. This is defined by the World Health Organization (WHO) as follows:

"Task shifting involves the rational redistribution of tasks among health workforce teams. Specific tasks are moved and, where appropriate, from highly qualified health workers to health workers with shorter training and fewer qualifications in order to make more efficient use of the available human resources for health [130]."

These healthcare providers assist in the management of patients with varying degrees of supervision by a qualified physician. This practice expands the surgical workforce density, thereby increasing access to care. This practice is implemented most commonly in the United Kingdom, the United States, and sub-Saharan Africa, with anesthesiology being the most frequent specialty to implement task shifting [129]. Multiple outcome analyses in different countries and in different specialties have demonstrated no significant difference in patient outcomes between those who received care from non-physician providers compared to those treated by physicians in certain settings [131–137]. While certain outcomes are comparable between non-physician providers and physicians, this practice continues to be marred by controversy, with concerns of variable oversight and the potential for suboptimal care [129]. Stronger studies, like the randomized control trial by Gajewski et al. [137], are needed to definitively quell concerns of suboptimal care in the practice of task shifting.

6. Role of Artificial Intelligence (AI) in Mobile Military and Single-Surgeon Units

Artificial intelligence (AI) and machine learning describe a broad range of algorithms that are reliant on datasets to make predictions and, while still nascent, have been transformative in different aspects of trauma care [138]. By leveraging lessons learned from civilian systems, MHSs also have designed, adopted, and implemented AI solutions to improve care for service members in both domestic and deployed contexts, including their beneficiaries [139]. Several avenues of support and benefit utilizing AI have been identified for MHSs, including more precise allocation of medical personnel and resources, improved operations of military treatment facilities, and early detection of emerging threats to health [139]. It is likely that the incorporation of AI platforms will have positive outcomes on the function and efficacy of military mobile units and SSUs, but this requires robust clinical validations.

The adoption of AI, including generative models, has been a high priority for the US Department of Defense (DoD), a federal agency that cares for more than 9.5 million patients [140]. A detailed consolidation of AI tools offering potential benefits for both disaster relief and combat casualty care in conflict zones has recently been published [140]. In 2022, the US Army Futures Command generated a roadmap on how it plans to incorporate AI assistance with decision-making in military medicine [141]. Furthermore, several DoD-sponsored projects to develop novel AI-based technologies have also been summarized [140]. All of these AI modules aim to meet similar goals in austere environments by providing a virtual medic on any battlefield to help with the triage of wounded patients [142]. Similar AI medic models are also being developed to be able to detect early symptoms of shock [143], tension pneumothorax [144], and even hemorrhage/traumatic brain injury [145–147]. While there is no direct evidence yet on the efficacy of utilizing AI platforms under FST and SSU settings, it is highly likely that using AI platforms would be highly advantageous for on-site medics by quickly providing the much-needed specialized patient care guidance to enable prompt decision-making and improve patient outcomes.

AI tools can also provide critical knowledge on the anticipated outcomes (typically the "golden hour", or 60 min into the future) to facilitate proper triage on a single patient, but also to streamline the distribution of critical resources in cases of MCIs [140]. AI systems

can also help predict the need for hospitalization or emergency surgical procedures. For example, with the aid of the anticipated golden hour period, AI platforms can potentially mitigate many of the associated comorbid outcomes by evaluating the need for immediate limb amputation [148] and, additionally, can help predict limb revascularization recovery outcomes [149]. It is indeed remarkable that, by evaluating clinical characteristics that are readily available on presentation, military surgeons in combat zones were able to teach a computer to calculate the likelihood of a vascular reconstruction, which would result in limb salvage [149,150]. The casualty spectrum in this study included those with penetrating injuries, as well as blunt and blast traumas.

Critical decision-making is pivotal to evacuations. Since 2009, the DoD has made evacuations a clear priority, and it achieved a highly favorable 44% drop related to military fatality rates by 2014 [41], with studies offering sufficient justification to claim that learning-based AI holds immense promise as a fundamental tool for future military operations including evacuations [151]. The applications and feasibility of AI technology in austere environments are likely to have far-reaching benefits. It is plausible that AI tools, once developed and trained in clinical settings within the US (such as the MySurgeryRisk model), may be adapted and transferred for use in field hospitals or to more remote settings [152], and therefore, may potentially offer immense benefits to FSUs and SSUs.

This rapidly evolving and highly tangible technology also presents challenges in the military context, such as additional firewalls of privacy and security, more robust integration with purpose-built secure systems, and synchrony with mandatory regulatory obligations. A three-tier approach to advance AI in the MHS has been proposed [139]. A new study on adopting AI in healthcare suggests that generative AI tools for clinical documentation are rapidly advancing in US healthcare systems and demonstrating early success. Other AI use cases show varying degrees of adoption and success, interspersed by barriers such as immature AI tools, financial concerns, and regulatory uncertainty [153]. Another stark limitation is that the AI network is only as good as the dataset it is trained on and is still reliant on subject matter experts during algorithm development, and this is potentially affected by human error [140]. Biased, limited, or inconsistent datasets can direct AI to make poor decisions or overly simplify outcomes.

For all the benefits associated with utilizing AI platforms in healthcare settings, final decisions regarding patient care and management rely on human input, ensuring holistic ethical implementation and standardized appraisals and surveillance under critical events. The DoD and the NATO nations aim to base the ethical principles for AI on five core principles: governable, reliable, traceable, equitable, and responsible [140]. These moral codes must be continually updated to keep up with the ever-growing AI development dynamics. Military medicine and surgery in areas of conflict differ from civilian settings in that there is a core emphasis on higher trauma volumes with different mechanisms of injury, as well as the potential to operate in austere conditions with minimal staff and supplies [154]. Genuine collaborative and concerted efforts are mandated to ensure that AI systems emulate the decision-making of military physicians and contribute to bettering medical care in austere environments.

7. Critical Evaluation and Associated Challenges

The Peacetime Effect, or Walker Dip, has been well described as the negative impact on military medical readiness secondary to periods of low combat intensity, ultimately leading to higher fatality rates at the start of the next major conflict [155]. Initiatives are currently underway to fortify MHSs and curb the erosion of relevant surgical skills and knowledge during such periods [155]. Augmentation of public policies and laws, such as those advocating for the integration of military and civilian national trauma care systems,

including the Mission Zero and the 2017 National Defense Authorization Acts, has led to a small (albeit consistent) progress in mitigating this issue through formalized Military–Civilian Partnerships (MCPs) [155]. Furthermore, strategic partnerships such as those formed between the American College of Surgeons and the MHS are aimed to improve surgical educational opportunities, system-based practices, and research capabilities [155]. Such partnerships are critical in maintaining surgical readiness [156], with several of these permitting entire military surgical teams (including FSUs and SSUs) to permanently embed within level 1 trauma centers. Such planned alliances offer several benefits, where wartime experiences can be implemented and sustained in peacetime.

While military hospitals continue their tremendous work to manage patient volume and insight, conflict or war principles can be promoted and carefully integrated in civilian trauma centers. Such reciprocity facilitates improved general preparedness while also driving the sustainment of a military medical cohort that is ready to deploy. Whether such concerted efforts have a direct long-term influence on SSUs and or FSUs is yet to be evaluated. Deployment of surgical teams from other nations (UK) in small, low-resource, remote mobile facilities to provide damage control resuscitation and surgery for combat casualties has resulted in the Shader model, characterized by a low volume of surgical workload but a requirement for high readiness and competency in major trauma surgery [157].

Furthermore, there are multiple additional challenges to overcome, such as surgeons integral to combat medical care leaving active duty, budget cuts, low clinical volumes, and case complexity at the military treatment facilities [155,158]. Such challenges can hamper the clinical practice of any of the military surgery units and can threaten to disrupt recruitment and retention [159]. Other constraints that pose challenges to military medical capabilities and capacities include the approved use of unmanned gadgets and vehicles, nuclear armaments, chemical and biological weaponry, large-scale assaults, and decreased air superiority in comparison to prior conflicts [155]. Natural calamities and pandemics also continue to threaten resources and manpower reserves; therefore, continuous improvements and ongoing research and development are pivotal to further consolidate the prowess of single-surgeon and mobile military units.

8. Conclusions

Optimizing surgical and anesthesia care in low-resource areas, in both military and civilian settings, is a daunting and ever-changing endeavor. Catastrophic injuries and complex pathology make surgical management challenging, even in situations where the most advanced equipment and ample resources are at a surgeon's disposal. To meet these challenges, military and civilian surgical teams have adapted technology and optimized the deployment of trained surgical personnel to bring surgical care to the patients in need. While the surgical capacity in low-resource settings has increased with advances in modern mobile surgical teams, future progress should be focused on increasing both the breadth of operative procedures and the surgical volume. In rural areas, outside of conflict, the generation of self-sustaining and robust healthcare systems is of the utmost importance. Development of these care systems requires the collaborative efforts of innovators, the local and national government, and the people within the community. Access to surgical care can be a lifesaving and life-changing entity; therefore, we should continue to push the boundaries of what is possible and strive to optimize surgical care, even in the most challenging of settings.

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