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Exploring the Impact of 3D Printing on Medical Logistics for Class Viii(A) In Operational Environments and Distributed Maritime Operations

December 2020

LT Elena V. Williams, USN

Thesis Advisors: Bryan J. Hudgens, Lecturer
Dr. Kathryn J. Aten, Associate Professor

Graduate School of Defense Management

Naval Postgraduate School

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ABSTRACT

The study answers the following research questions: does 3D printing have the potential to positively affect medical logistics operations for operational and distributed maritime operations (DMO) environments? And if so, which Class VIII(a) consumable medical supplies show high potential? The qualitative cases analysis investigates the challenges of medical logistics in austere, deployed environments, particularly in mass casualty scenarios, and the implications of additive manufacturing (AM) to medical logistics operations for selected Class VIII(a) consumable items in one simulated distributed maritime operations (DMO) environment. The analysis and findings suggest that some Class VIII(a) medical supplies are not good candidates for 3D printing. However, interviews with subject matter experts revealed other potential Class VIII(a) consumable medical supplies that meet characteristic requirements to be 3D printed in operational environments. The study results in initial insights, propositions, and recommendations on how to proceed with 3D printing to support medical logistics operations for operational and distributed maritime operations (DMO) environments.

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ABOUT THE AUTHOR

LT Elena Williams enlisted in the United States Navy in December 2003 as a Master of Arms and cross rated to Hospital Corpsman. She excelled through the ranks to First Class Petty Officer in 2012. While enlisted, she attended college independently and earned her Bachelor of Science in Healthcare Administration from Kaplan University and her Master of Business in Healthcare Management from University of Texas. In July 2016, she commissioned as a Lieutenant Junior Grade in the Medical Service Corps. After graduating Officer Development School, she received ordered to her first command as a Naval Officer. In September 2016, Lieutenant Williams reported to Naval Hospital Twentynine Palms assigned as Assistant Department Head of Materials Management. She was recognized with, "Best Innovative Award" for the Radio Frequency Identification Program. In March 2017, she attended Financial and Material Management Training Course and graduated with Honors. In July 2017, she was assigned as Department Head of Operations Management. She initiated Operations Security Program, recognized during MEDIG/JC inspection. Lieutenant Williams is a member of the American College of Healthcare Executives. In 2017 she received Executive Medicine AQD (67A) and in 2018 she received Command Fitness Leader ADQ (2PT). She is Surface Warfare qualified and has maintained her certification as Certified Nuclear Medicine Technician and Master Training Specialist. In July 2018, she received Individual Augmentee orders to Train Assist Advise Command-South/NATO Role 3 Hospital in Kandahar, Afghanistan as the Logistics and Operations Officer. After graduating Naval Postgraduate School, she will be reporting to Naval Medicine Readiness and Training Command Camp Lejeune as Department Head Materials Management.

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LIST OF ACRONYMS AND ABBREVIATIONS

AD	Additive Manufacturing
ANA	Afghan National Army
ANP	Afghanistan National Police
ASL	Authorized Stock List
BAF	Bagram Airfield
BUMED	Navy Bureau of Medicine and Surgery
CNO	Chief of Naval Operations
COCOM	Combatant Command
CONUS	Continental United States
CJTH	Craig Joint Theater Hospital
CT	Computed Tomography
DAPA	Distribution and Placing Agreement
DARPA	Defense Advanced Research Projects Agency
DLA	Defense Logistics Agency
DMAM	Distributed Medical Architecture Model
DMLSS	Defense Medical Logistics Standard Support
DMO	Distributed Maritime Operations
DoD	Department of Defense
ECAT	Electronic Catalogue
GSA	General Services Administration
GSW	Gunshot Wounds
IA	Individual Augmentees
ICU	Intensive Care Unit
ISAF	International Security Assistance Force
JHU/APL	Johns Hopkins University Applied Physics Laboratory
KAF	Kandahar Airfield
LBS	Logistics Business System
LSD	Dock Landing Ship
MASCAL	Mass Casualty
MEDLOG	Medical Logistics

MTF	Military Treatment Facility
MMC	Materials Master Catalog
MMU	Multination Medical Unit
NMLC	Navy Medical Logistics Command
NATO	North Atlantic Treaty Organization
NAVSUP	Naval Supply Systems Command
OCONUS	Overseas Continental United States
OML	Operational Medical Logistics
OR	Operating Room
PAR	Periodic Automatic Replenishment
PPE	Personal Protective Equipment
PV	Prime Vendor
PVM	Prime Vendor Medical
TAAC-S	Train Advise Assist Command South
TEWLS	Theater Enterprise-Wide Logistics System
TLAMM	Theater Lead Agent for Medical Materiel
USAMMCE	United States Army Medical Material Center Europe
USAMMC-SWA	United States Army Medical Material Center-South West Asia
USCENTCOM	United States Central Command
USEUCOM	United States Europe Command
USNORTHCOM	United States Northern Command
USN	United States Navy
USU	Uniformed Services University
WRNMMC	Walter Reed National Military Medical Center

I. INTRODUCTION

> USCENTCOM is far and away the most complicated theater for final delivery of medical materiel. There are many locations where operational units consume medical materiel, that are distant from an MTF; only a few locations in USCENTCOM are included in the PV contract, and they are logistics hubs; and the active conflict on this theater creates an uncertain planning environment with dynamically challenging demands, and potentially high demand for medical material (Resnick, A. C., Wesler, W., & Yoho, K. D., 2014, p. 54).

This study is motivated by the shortages in medical supplies that can occur during mass casualty events in operational environments. Prolonged patient stays can result in drastic shortages of medical supplies. These shortages often result in nonstandard workarounds by medical professionals in forward-deployed medical units. Inventories of Class VIII(a) consumable medical supplies can rapidly deplete in a single event. Class VIII(a) consumables not ordered routinely run out and currently must be acquired through prime vendors (PV) located in the United States, resulting in fulfillment lead-times that can negatively influence patient survivability and quality of life. This study reveals the potential for a 3D printer on-site in forward-deployed medical units to provide readily available consumables when depleted during mass casualty events while ordered items are in transit.

NATO Role 3 Multinational Medical Units (MMU) like the one in Kandahar, Afghanistan, provide medical care to coalition forces and warfighters. Medical logistics in austere and operational environments face challenges very different from those faced in supporting a stateside hospital or medical treatment facility (MTF). It is challenging to get medical supplies and equipment quickly during unpredictable operational conditions, such as armed conflicts.

In anticipated distributed maritime operations environments (DMO) resupply and networks are limited, "In a genuine DMO environment concept, fleet forces may be required to operate independently for periods of time" (Eyer & McJessy, 2019, para 13). It is possible that U.S. adversaries will build a fleet that can challenge the U.S. Navy fleet in open water combat. This will likely be remote and offshore with significant challenges in resupply. This is important as reports have found that resupply of Class VIII(a) will encounter time and distance constraints with a DMO environment.

Manufacturing healthcare products on-site to treat battlefield injuries and medical conditions is a potential solution to this challenge. 3D printing has the potential to allow this. This study focuses on the potential of 3D printing and its impact on the logistics of Class VIII(a) consumables. Class VIII(a) consumable items are medical materiel (equipment and consumables) used in military medical communities and include repair parts peculiar to medical equipment. For this study, the term *Class VIII(a) consumable* is used interchangeably with *medical supplies*. This study provides the Navy with an empirically based answer to the question, “Can 3D printing positively affect medical logistics operations for existing austere operational environments and/or projected future DMO environments?” and identifies Class VIII(a) medical supplies at high risk for short-notice depletion and with high potential for 3D printing.

Transportation and location are significant constraints for operational environments that are not typically faced in stateside environments. Deployed medical units in operational environments use Class VIII(a) consumables, which are critical to survivability and quality-of-life outcomes. In operational environments, many weeks can pass with no trauma activations. Then, with no notice, multiple activations for mass casualties can occur in a single week. The unpredictable environment of a war zone can deplete existing stock rapidly and can make resupply challenging.

The Navy is currently using 3D printing to meet warfighting needs. The chief of naval operations (CNO) recently acknowledged the benefits to the Navy of 3D printing capabilities in support of maintenance and repair consumable parts for planes and ships (Chief of Naval Operations [CNO], 2020). Further, the CNO acknowledged that 3D printing can improve timeline efficiencies and supports integration with existing supply and maintenance processes. The Navy has used 3D printing to produce and provide to the fleet items ranging from repair parts to consumable supplies. The CNO noted that Navy 3D printing capability currently produces parts made from polymer, composite materials, and metal for consumables (CNO, 2020).

This success suggests that 3D printing can provide similar benefits with respect to medical supplies. Shortages of medical supplies can occur in operational environments, including DMO environments, and 3D printing has the potential to alleviate, at least partially, shortages experienced during resupply transit and delivery. If 3D printing has successfully produced maintenance and repair parts, it also offers the potential value for producing medical equipment repair parts (CNO, 2020).

The Department of the Navy's Bureau of Medicine and Surgery (BUMED) M42 Expeditionary Medical Logistics program office requested support to understand how 3D printing could affect the logistics of medical consumables in operational or DMO environments. In support of this need, this study investigates the challenges of medical logistics in austere, deployed environments and the potential of 3D printing to address those challenges.

A. RESEARCH QUESTIONS

Primary Question

- Does 3D printing have the potential to positively affect medical logistics operations for operational environments, including DMO environments?
- If so, which Class VIII(a) consumables show high potential?

Secondary Questions

- How does the resupply process for Class VIII(a) consumables differ from the processes for other classes of materials?
- How does a shortage of Class VIII(a) medical supplies affect an MMU during a mass casualty event?
- What does recent research suggest about the potential of 3D printing for Class VIII(a) consumable items?

B. RESEARCH METHOD

This study explores the potential of 3D printing to positively affect medical logistics operations for Class VIII(a) consumables in operational and DMO environments through a qualitative, embedded case analysis (Yin, 2003). Both the overarching and embedded cases are extreme, and thus the processes that influenced events and outcomes are likely to be transparently observable (Pettigrew, 1990). Because of the nature of combat situations, however, the cases represent similar extreme situations. The overarching case presented in this exploratory research is a single case focused on three mass casualty events. The embedded case analyzes shortages of six critical class VIII(a) consumable medical supplies during the mass casualty events: syringes, IV tubing, central lines, cranial kits, suction valves, and canisters.

This qualitative, exploratory research focuses on how logistics processes for Class VIII(a) consumables differ from the processes for other classes of materials. Class VIII(a) consumables are mandated to use PV located within the United States (Cardinal Health, 2020). This study's focus on Class VIII(a) medical supplies is derived from my observations from field experience, where constraints with resupply strained the medical care system. Class VIII(a) supplies are important because these consumables have a unique purpose: to save lives.

In order to understand how a shortage of medical supplies affects a Role 3 MMU during a mass casualty event, as well as the resupply process for Class VIII(a) consumables, I conducted interviews with two intensive care unit (ICU) nurses with roles at the Kandahar NATO Role 3 MMU. The interviewed medical professionals identified Class VIII(a) items that were rapidly depleted during mass casualties. These items informed subsequent interviews of 3D subject matter experts. To gather information on the potential of 3D printing for Class VIII(a) consumable items and to identify high potential consumables, I reviewed documents and conducted interviews with experts from Uniformed Services University (USU) and Walter Reed National Military Medical Center (WRNMMC) who have successfully researched and tested 3D printing medical supplies.

This research provides analysis and findings that support the potential to 3D print Class VIII(a) consumables. The potential has been demonstrated through usage cases in the field with simulated clinical settings and through real-time use in WRNMMC.

C. CONTRIBUTIONS AND SCOPE

This study's findings are exploratory, based on a single setting, and are not generalizable to all settings. However, by providing deep understanding of the implications of additive manufacturing (AM) on medical logistics operations for selected Class VIII(a) consumable items in one DMO environment, the study provides initial insights, propositions, and recommendations on how to proceed. The analysis and findings suggest that some Class VIII(a) medical supplies are not good candidates for 3D printing. However, interviews with subject matter experts revealed other potential Class VIII(a) consumables that meet characteristic requirements to be 3D printed in operational environments.

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II. BACKGROUND: MEDICAL LOGISTICS

The purpose of this chapter is to provide information needed to understand medical logistics in operational and DMO environments. Medical treatment facilities (MTF) in operational environments face challenges very different from those faced in stateside civilian or military MTFs. The continental United States (CONUS) MTFs receive Class VIII(a) medical supplies from CONUS-based PVs, whereas outside the continental United States (OCONUS) MTFs receive Class VIII(a) supplies either direct from CONUS PV or through OCONUS intermediate distribution centers called Theater Lead Agent for Medical Materiel (TLAMM) (Resnick, et al., 2014). Understanding the contrast between different medical logistics environments reveals the gaps that occur when applying a model from one environment to another with different characteristics. The current medical logistics supply chain operates within an unconstrained environment and typically does not experience unpredictable demand, constraints on capacity to treat patients, constraints on ability to transport, and limited storage capacity.

This chapter first describes an overview of the current state of medical logistics. It is necessary to understand current logistic elements such as policies, procedures and vendors that are consistent across all environments. This section introduces important logistic terminology that will appear throughout this capstone.

Next, the chapter presents a close analysis to reveal how applying general logistics processes for medical supplies in an operational environment creates gaps due to remote locations separated by time and distance. The rights of logistics frameworks are used to review current logistics process models against different environments, resulting in identified problems. The unpredictable demand within this environment challenges the current process.

Finally, this chapter examines the similarities between the current operational environment and a future projected DMO environment. This is an important comparison for anticipating and preparing for future operating environments. This comparison reveals the ways that time and distance are and will be more significant logistics constraints in both current austere operational environments and projected future environments.

A. OVERVIEW OF CURRENT STATE MEDICAL LOGISTICS

This section provides an overview of medical logistics and how it operates in a current unconstrained environment. It is important to understand medical logistics elements and terminology that are consistent across all environments.

There are processes within medical logistics similar for all facilities and classes of supply. The Defense Logistics Agency (DLA), Naval Supply Systems Command (NAVSUP), and Naval Medical Logistics Command (NMLC) provide total logistic support to facilities (Defense Logistics Agency [DLA], 2020). It is important to understand that "DLA maintains centralized inventory management and physical distribution of vendor medical materiel to medical facilities around the world" (DLA, 2020). Similarly, it is important to mention that DLA manages all the classes of supply: "DLA manages the following commodities: Class I subsistence; Class II clothing and textile; Class III energy; Class IV/VII construction and equipment; Class VIII(a) and (b) medical; Class IX repair parts for aviation, maritime and land systems" (Resnick et al., 2014, pp. 2–3).

The resupply process for Class VIII(a) differs from the other classes because Navy Medicine is mandated to acquisition medical materials from PV (Cardinal Health, 2020). PV is a single distributor of brand-specific medical supplies and provides next-day delivery to CONUS-based MTFs. A PV contract is 10 years for pharmaceuticals, medical/surgical supplies, and equipment. Medical facilities within Department of Defense "(DoD) must first place an order with their Primary [PV] (Cardinal Health, 2020). If the Primary [PV] is unable to supply the item, or if the item is on backorder and the DoD facility needs it sooner than the expected delivery date, the order with the [Primary PV] can be canceled and then placed with the Back-up [PV]" (Cardinal Health, 2020).

Contracts have been awarded to two DoD PVs. Electronic Catalog (ECAT) and Cardinal Health are U.S. manufacturers that ship from CONUS to OCONUS (Cardinal Health, 2020). ECAT is an online ordering system developed and supported by DLA Medical Supply Chain Division (DLA, 2020). It facilitates ordering and payment of medical supplies and distributers through a single portal. ECAT is one of the mandated tools for procurement of Class VIII(a) medical supplies under the PV contract (DLA, 2020). The medical PV to DoD facilities is Cardinal Health (Cardinal Health, 2020).

“Prime Vendor Medical (PVM) is a mandatory program for all DoD hospitals for the distribution of healthcare products on Distribution and Placing Agreement (DAPA)”. “Cardinal Health is [Primary PV] to DoD facilities in the Global North and Global West Regions and is Back-up [PV] in the Global South Region” (Cardinal Health, 2020).

To initiate an order through a PV, Class VIII(a) medical supplies are acquisitioned through Defense Medical Logistics Standard Support (DMLSS). DMLSS is an “automated system that manages medical material, equipment, war reserves material, and facilities management” functions to support Navy Medicine (Naval Medical Logistics Command [NMLC], 2020). It is the primary ordering system for medical supplies and is used universally by medical facilities CONUS and OCONUS. Class VIII(a) medical supplies “are added to stock based upon the demand for the” material (United States Navy [USN], 2010). Medical logistics environment demands are categorized as recurring or nonrecurring, and “a logistics manager uses recurring demands to identify Class VIII(a) medical supplies to stock by determining how much of the item to keep and when to reorder” (USN, 2010).

Most medical treatment facilities rely on medical logistics distribution centers called MEDLOG. These distribution centers are either virtual or physical and are located within the facility. A MEDLOG account is required to distribute from the PV to the customer. For example, if 10 customers require 100 boxes of Band-Aids, and 1,000 boxes equals a case, MEDLOG will order one case of 1,000 boxes and distribute to the 10 customers. If MEDLOG is operating correctly and sets its reorder point at 200 boxes, that will automatically trigger the PV to ship another case within 1 to 2 business days to replenish what was distributed.

Everything discussed so far is designed for all environments. However, there are common features specific to CONUS. It is important to note the features of PV for medical logistics that are not consistent across all environments. Several features are specific to CONUS MTFs and medical logistics operations, including next-day business delivery for recurring items based on a set reorder point or periodic automatic replenishment (PAR) level and for nonrecurring items required to be filled within 7 days. CONUS facilities will experience the 7-day delivery that is written within the PV contract. However, clauses within the contract allude to the fact that OCONUS will not experience the same requirement (Resnick et al., 2014). Another common feature specific to CONUS is that customers can define delivery options to set specific days or times convenient for the end users (Cardinal Health, 2020).

B. CLASS VIII(A) MEDICAL LOGISTICS IN OPERATIONAL ENVIRONMENTS

This section provides an analysis of medical logistics in an austere operational environment. A subsection discusses the application of the rights of logistics frameworks to illuminate inefficiencies and reveal gaps that occur when applying a model designed for stateside environments to an austere operational environment with different characteristics related to time, distance, and demand. The operational environment experiences unpredictable demand, limited storage, and connectivity issues, making tracking orders and identifying appropriate levels of stock challenging.

Globally, the U.S. military MTFs are stretched across the continents of Europe and Asia. A study by RAND (Resnick, et al., 2014) provided useful analysis of the operational environment and its challenges receiving Class VIII(a) medical supplies with a thorough examination of the medical logistics supply chain to United States Central Command (USCENTCOM). Within the study is a map featured in Figure 1. Figure 1 shows the geographic combatant commands (COCOMs). Staying within the focus of USCENTCOM, an operational environment currently involved in the most conflicts, the map marks red dots to “represent OCONUS MTFs and yellow stars” to identify two “locations of the OCONUS” TLAMMs (Resnick, et al., 2014, p. 10, Figure 1). MTFs are often situated in combat areas or hostile environments.

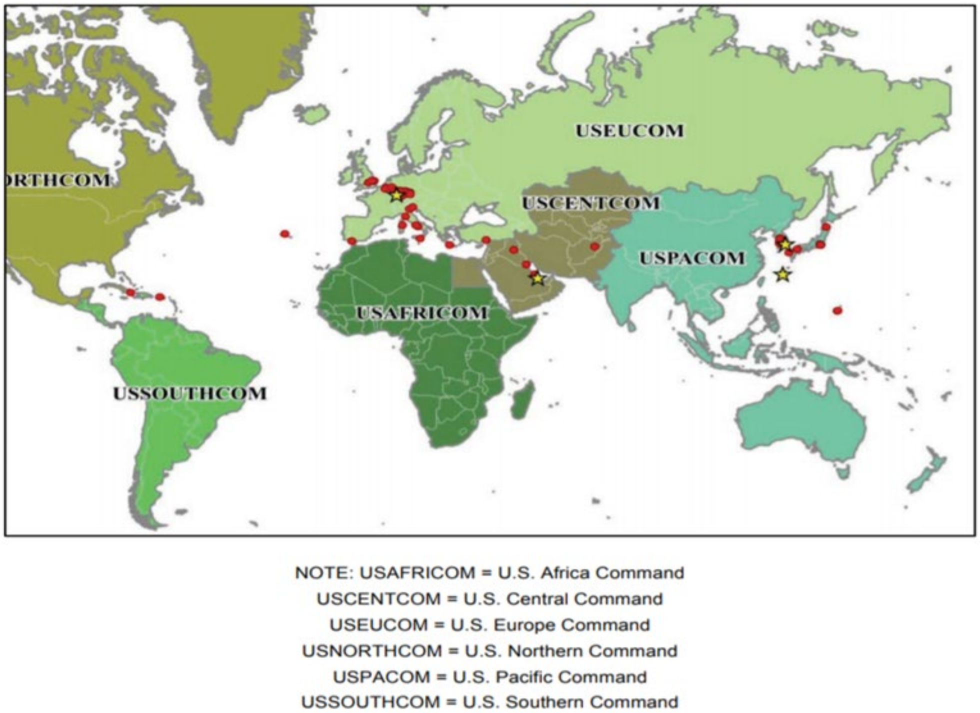
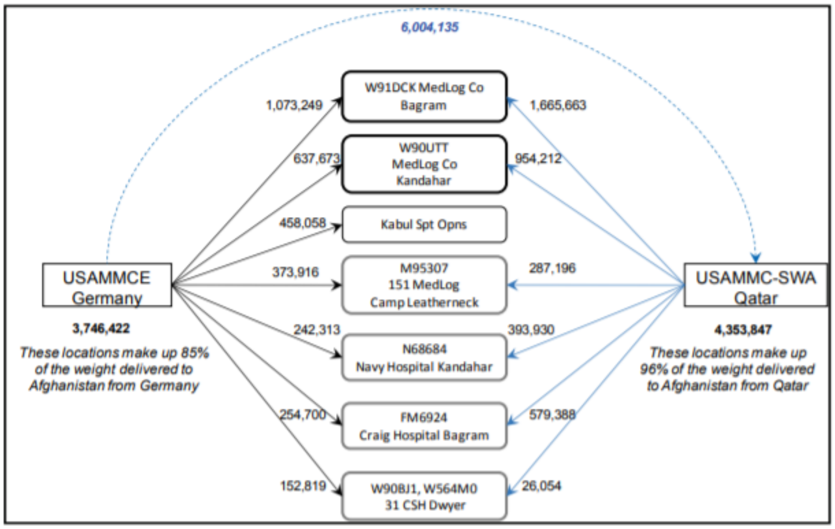


Figure 1. Map of Geographic COCOMs, OCONUS MTFs, and TLAMMs.
Source: Resnick et al. (2014, p. 10).

It is important to understand the general medical supplies logistics process in an operational environment. Time and distance constraints are visible within Figure 2. PVs are located within United States Northern Command (USNORTHCOM) in a distant fixed ashore facility, making receipt of Class VIII(a) medical supplies challenging. DLA receives classes of supply from manufacturers and PVs within CONUS and ships to OCONUS TLAMMs. These TLAMMs serve as MEDLOGs for the surrounding MTFs within their area of operations. The TLAMMs receive medical materiel from the United States, and their goal is to buffer for unexpected surges in demand (Resnick et al., 2014). Class VIII tenders and commercial flights get the supplies from CONUS to OCONUS. The first point of delivery from DLA to OCONUS is United States Europe Command (USEUCOM), where U.S. Army Medical Materiel Center Europe (USAMMCE) is located (Resnick, et al., 2014). USAMMCE ships Class VIII(a) medical supplies directly to Afghanistan or via U. S. Army Medical Materiel Southwest Asia (USAMMC-SWA) in Qatar (Resnick, et al., 2014).



NOTE: Kabul Spt Opns = Kabul Support Operations

SOURCE: USTRANSCOM, Class VIII tender actuals data.

Figure 2. Consignee Receiving Class VIII Materiel (in [Pounds]) from both USAMMCE and USAMMC-SWA Using the Commercial Tender. Source: Resnick et al. (2014, p. 60).

Two main ordering systems are used to manage the acquisition of Class VIII(a) medical supplies: DMLSS and Theater Enterprise Wide Logistics System (TEWLS) (Resnick et al., 2014). DMLSS is the primary ordering system, but TEWLS provides tracking information based on commercial stock numbers that give real-time data on where the item is in transit, whether the item is backordered, or if the order was cancelled due to the item being unavailable. The medical logistician or end user replenishes all Class VIII(a) items first in DMLSS, and the logistician or MEDLOG staff track the item in TEWLS. Access to TEWLS must be requested by the medical logistician or MEDLOG staff to receive access (Resnick et al., 2014).

Featured on the map in Figure 1 are red dots indicating MTFs. One of those MTFs is NATO Role 3 MMU in Kandahar, Afghanistan. For two decades military troops have been in Afghanistan. When injured in combat, troops are transported to a Role 1, 2, or 3 level of care MTF. NATO Role 3 MMU is one of seven MTFs in USCENTCOM requesting medical supplies from two TLAMMs, as seen in Figure 1 (Resnick et al., 2014).

NATO Role 3 MMU is far removed from PVs in the United States and therefore, relies heavily on the two TLAMMs. NATO Role 3 MMU acquisitions and tracks Class VIII(a) medical supplies through DMLSS and TEWLS. NATO Role 3 MMU has a MEDLOG physically within its facility. The medical logistician or end user replenishes Class VIII(a) in DMLSS. The request is first sent to MEDLOG, where recurring orders are stocked and immediately delivered to the end user. Nonrecurring orders are typically not stocked within MEDLOG, and the request is sent to USAMMC-SWA to fill. Recurring orders that are out of stock are also sent to USAMMC-SWA to fill. Recurring and nonrecurring orders are sent forward to USAMMCE if USAMMC-SWA is out of stock. If USAMMCE is out of stock for that recurring or nonrecurring item, the request is sent to PV in the United States. The request is not complete until the end user receives the Class VIII(a) medical supply items ordered or the order is cancelled. Backorder items can be cancelled by the logistician or MEDLOG staff and an alternative item with similar characteristics can be researched within USAMMCE's virtual MEDLOG.

Applying general logistics processes for medical supplies in an operational environment creates gaps due to remote locations separated by time and distance. Unpredictable demand makes it difficult to be effective in identifying recurring orders to manage inventory levels, set reorder points, or have stock of all the right products in the right quantity. Critical items required may not be established as recurring orders due to the inconsistent frequency of need. A critical item may be used one month and not used again for several months or used four times in 3 days. Storing large amounts of inventory to buffer against delivery times is challenging due to the varying shelf lives of Class VIII(a) medical supplies, the limited storage capacity with MEDLOG, and the erratic nature of demand. Varying shelf lives create issues because an item can arrive expired or can expire before being used. Patient influx occurs from the erratic operational environment, resulting in prolonged patient care that rapidly depletes MEDLOG inventory, and buffers can be exhausted during a single event.

1. Rights of Logistics

Logistics is the process to supply end users with resources. The "seven rights of logistics" is a framework for assessing effectiveness. In 2000, the "seven rights of logistics were coined and publicized" (Swamidass, 2000). "The seven rights are to deliver the **right** product, in the **right** quantity and the **right** condition, to the **right** place at the **right** time for the **right** customer at the **right** price" (Swamidass, 2000) (see Figure 3). It is important to receive medical supplies timely due to storing requirements (temperature control items), expiration dates and to deliver patient care.

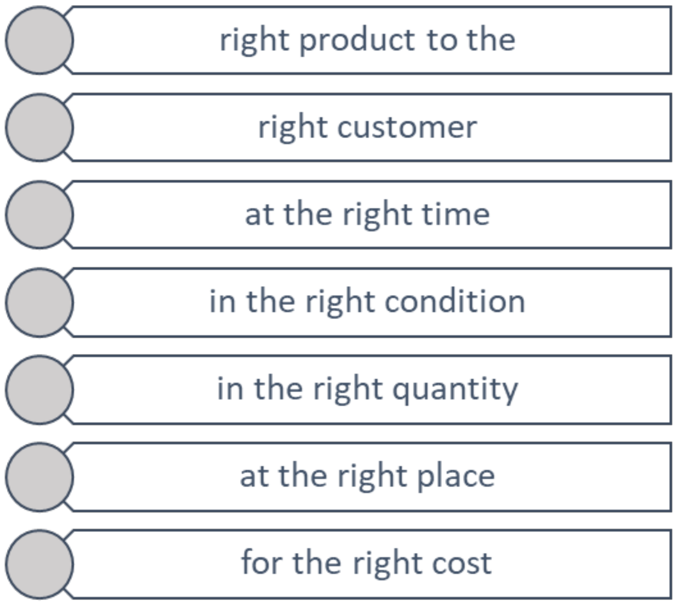


Figure 3. The Seven Rights of Logistics Framework. Source: Swamidass (2000).

Though there are seven rights, only four are discussed in this section: "right product, right place, right time, and right quantity" (Swamidass, 2000). These four rights reveal constraints most relevant to this study's research findings within the operational environment. The other rights, while important to the framework, do not provide value-added contributions to this study. With respect to the issue of cost specifically, while logistics and 3D printing experts would argue that it is more cost effective to ship in bulk, this study places more emphasis on having the right product at the right time. This study is not intended to find cost-effective ways to improve medical logistics processes but to find solutions with potential to provide the right medical supply "at the right time, in the right quantity" for unpredictable demand environments (Swamidass, 2000).

a. Right Product

The concept is understanding the right product that the end user requires and the originator (manufacturer) transports (Swamidass, 2000). This concept is to ensure that the right product arrives to the end user who ordered it. When the right product is available, patient care is delivered, and the mission continues.

When the right product concept is applied to the operational environment, it reveals inefficiencies. The TLAMMs manage many locations with inventory buffers: "USAMMC fills 65 percent of the orders and must maintain a buffer against lead times that are longer than usual when ordered direct from PV" (Resnick et al., 2014, p. 60). Having a supply buffer to manage against long delivery times is good in theory. However, having a buffer of one item is insufficient if it is not the "right" item. Items are arriving within USCENTCOM, even if arrival times are irregular; however, the item is not always the most critical right item to meet the end users' needs.

b. Right Place

The right product must be delivered "to the right place" (Swamidass, 2000). Having the right product in the right place is crucial to delivering patient care. Class VIII(a) medical supplies are transported from the United States to TLAMMS to reach the end user who ordered the item. The environment characteristics can affect how and when that end user will receive the item.

In operational environments, even when the right product has been ordered, medical material is regularly delayed and not where it needs to be. Requested orders have been lost or delivered to the wrong unit. Class VIII tenders and commercial flights experience delays (Resnick et al., 2014). If transported on a container ship it will take 3 to 6 months to arrive within USCENTOM (Resnick et al., 2014). According to the RAND study, "All shipments from PV intended for USCENTCOM end users are first delivered to USAMMCE" (Resnick et al., 2014). USAMMCE either "ships Class VIII(a) medical supplies directly to locations in Afghanistan [or] supplies the forward TLAMM, USAMMCE-SWA" (Resnick et al., 2014, p.60). USAMMCE supports 300 locations within 38 countries across USEUCOM (Resnick et al., 2014).

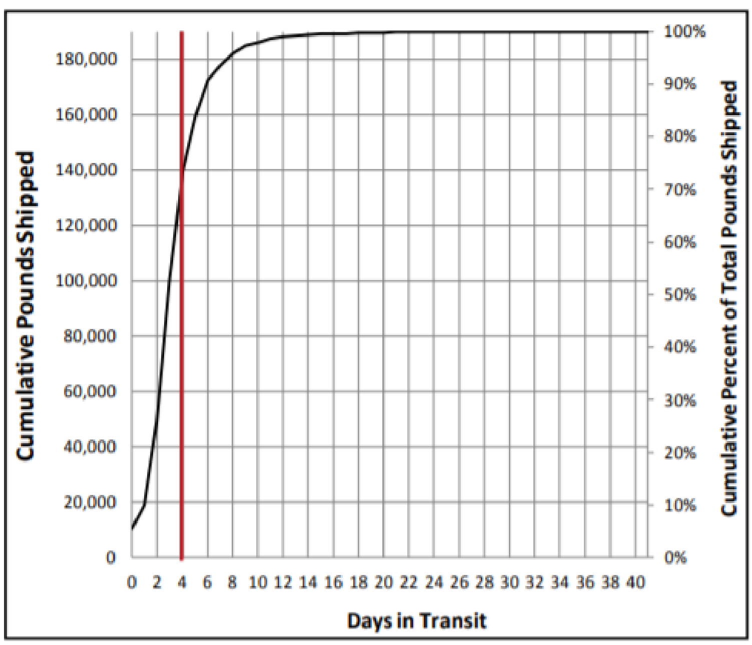
According to the RAND study, "Current medical logistics platforms for Class VIII(a) resupply systems are inadequate for forward resupply in a distributed, contested environment" (Resnick et al., 2014, p. 60). After PV ships the material to USAMMCE, it is "shipped to USAMMC-SWA, where it sits in inventory" until it can be delivered or until a stocked item is requested (Resnick et al., 2014). "Over 18 months USAMMCE shipped 4.3 million pounds of material to Afghanistan via USAMMC-SWA. When medical material arrived in Afghanistan, more than half of the shipments by weight had still not reached their end users" (Resnick et al., 2014, p. 60). Medical logisticians in theater are faced with large numbers of requests due to the operational tempo environment.

c. Right Time

Recurring orders must "be delivered to the" end user "at the right time", in advance of the user needing the product (Swamidass, 2000). The end users and logisticians identify recurring orders based on demand and set reorder points. The challenge for operational environments is that the end user and logistician deal with unpredictable demand. It is not logical to identify all Class VIII(a) medical supplies as recurring because of varying shelf lives and inconsistency in item demand. It is often one nonrecurring item required for a patient that could mean life or death.

The significant distance between medical units in operational environments and PV in the United States shapes the time frame for delivery of products. PV delivers consumables to USAMMCE within 7 to 37 days; if not backordered or a new item, PV requires 90 days to fill per contract (Resnick, et al., 2014, pp. 18–19). Clauses within the PV contract restrict aspects of the 7-day delivery requirement in operational environments (Resnick et al., 2014). For example, new item requests (NIR) include a 90-day period prior to filling, causing significant constraints for operational medical units requiring an item not within the DMLSS catalog (Resnick et al., 2014, p. xvi). NIRs take an extremely long time to process and deliver to an operational environment.

The challenge here is that "USCENTCOM experiences longer lead times than any other COCOM" (Resnick et al., 2014, p. 60). USCENTCOM does not receive items directly from PV and relies on nearby TLAMMs, USAMMCE, and USAMMC-SWA (Resnick et al., 2014). Class VIII tenders deliver to USAMMCE as the first line of logistics resupply to USCENTCOM. According to the RAND report, Resnick (2014) observed that "shipments paid for under this tender were frequently late and that 37 percent of all shipments were in transit more than four days" (Resnick, et al., 2014, p.57). Figure 4 illustrates shipments were frequently late. Once at USAMMCE, consumables can be delivered in 4 to 5 days but are likely to be to USAMMC-SWA prior to Afghanistan (Resnick et al., 2014). This extended transport chain delays receipt of supplies needed in operational environments. Class VIII(a) consumable medical supplies have unique characteristics such as shelf lives and can expire prior to arrival. The flow of PV Class VIII(a) medical supplies is via Class VIII tender to USAMMCE, then to USAMMC-SWA, or direct from USAMMCE to Afghanistan.



SOURCE: USTRANSCOM, Class VIII tender actuals data.

Figure 4. Shipment Durations with Class VIII Tender. Source: Resnick et al. (2014, p. 58).

d. Right Quantity

The right quantity concept ensures the end user has the right amount of the product they need to complete the task (Swamidass, 2000). Stocking in bulk or having a buffer ensures the right quantity will be available to meet recurring demand.

According to the RAND report, "USAMMC-SWA's mission is to provide resupply to units in USCENTCOM and hold inventory that would buffer against a surge in demand from USCENTCOM units or an interruption in the supply chain delivering medical materiel from USEUCOM to USCENTCOM" (Resnick et al., 2014, p. 26). This is a challenge for unpredictable demand environments. Inconsistency in demand makes it difficult to identify appropriate stock levels to maintain in inventory or to have a significant buffer against surges. A surge in demand can deplete buffered stock during a single event experienced in Afghanistan. Due to the type of environment, "commercial air delivery of medical supplies accounts for > 90% of OCONUS resupply, may be unavailable or limited during hostilities at a time when greater demand on medical supplies is dictated" (Resnick et al., 2014). During transit of a recurring order, a mass casualty can occur, and the right quantity may not be available.

C. CLASS VIII(A) MEDICAL LOGISTICS IN A DISTRIBUTED MARITIME OPERATIONS ENVIRONMENT

While the main focus of this research is on existing austere operational environments, projected future environments in DMOs are likely to present related or similar challenges. The "DoD provides medical care to its service members whether they are at their home station or deployed" (Resnick et. al., 2014, page 1) through a full range of operational environments. This section discusses how the limitations of applying the general medical supplies logistics process in an operational environment might also be relevant for future projected operational environments, specifically DMOs.

A 2019 study by researchers at John Hopkins University (JHU) analyzed the effects of an attack on an afloat vessel's ability to receive resupply to treat mass casualties (John Hopkins University Applied Laboratory [JHU/APL], 2019). The report examined this in a simulated DMO environment with a model that demonstrated how distance affects a ship's capability to transport patients and receive resupply. This section describes the model and the simulation findings. The model results and findings are relevant to both DMO and operational environments, which can experience the same constraints of time, distance, and network outages. What the report found regarding Class VIII(a) is pertinent to the impact a single attack can have on a forward operating unit.

In the simulated model, the JHU analysts used assumptions of a DMO environment. One assumption is that a DMO environment will have limited network capabilities, impacting the ability to use computer systems to resupply (JHU/APL, 2019, p. 11). Network issues and distance from land based TLAMMs further isolate units from resupply. Replenishment and acquisition of Class VIII(a) supplies are accomplished via email, web access, or even teleconference (JHU/APL, 2019, p. 9). The study suggests that "in DMO, standard communication may be unavailable due to communications blackouts or even cyber-attacks" (JHU/APL, 2019, p. 9). The unreliability of communications networks in a DMO environment can significantly delay or even prevent replenishment orders and increase the likelihood of shortages or depletion of critical Class VIII(a) supplies.

The current resupply process for operational environments relies on two computer systems: DMLSS and TEWLS. Communication systems in an operational environment experience blackout when an adversary or insurgent attacks locals or units or when units are out on patrol and encounter an improvised explosive device. This affects the ability to use computer systems. Computer issues caused by communication blackouts and distance from TLAMMs further isolate medical units from resupply in austere operational environments.

USCENTCOM relies heavily on nearby TLAMMs that the study identified as high-risk facilities in a DMO environment, vulnerable to attack from an adversary. "Dependency on TLAMMS and other shore-based distribution centers may be precluded as these facilities may be at risk of attack" (JHU/APL, 2019, p. ES-3). NATO Role 3 MMU is in an operational environment, remote in USCENTCOM, and dependent on the nearby TLAMMs. Like a DMO environment, TLAMMs are at risk of attack within the existing operational environment. If attacked, the delays currently experienced in receiving Class VIII(a) medical supplies would be significantly longer.

Two other assumptions were built into the model. One was that the current Class VIII(a) resupply system is “inadequate for forward resupply in a contested environment and extended casualty care at a Role 2 level and the second was that significant casualty rates will overwhelm medical resources” (JHU/APL, 2019, p. 11). The JHU analysts built the model to incorporate uncertainty or stochasticity. The uncertainty of DMO or operational environments make them different: “It is not known when or where an event such as a missile strike will generate casualties or how many they will generate” (JHU/APL, 2019, p. 17).

The analysts used the Distributed Medical Architecture Model (DMAM) to simulate naval medical operations during combat (JHU/APL, 2019). The study focused on constraints of afloat requirements for resupply such as helicopters, connecting vessels, and distance between ships (JHU/APL, 2019). The model simulated one day, and “the full run of the simulation included hundreds of attacks across 46 ships” (JHU/APL, 2019, p. 27). A missile strike resulted in 67 casualties, 75 urgent casualties, and 58 deaths (JHU/APL, 2019). During several iterations of the simulation, Class VIII(a) supplies were brought to the ship that was hit. For the last iterations of the model, there were no Class VIII(a) supplies remaining onboard. Another model was conducted to evaluate the distance between ships, which greatly impacts a ship’s ability to get close enough to resupply the vessel in need. During an attack, supply ships will be limited to conduct resupply operations. The results of increased distance were casualties taking longer to be evacuated as well as delays in delivering Class VIII(a) supplies. In a DMO environment, seen within the study, mass casualty events deplete Class VIII(a) medical supplies, greatly impacting mission readiness. This is relevant to existing challenges faced by deployed medical units within operational environments.

The JHU researchers argued that “the current Class VIII(a) processes are designed to support peace-time operations” (JHU/APL, 2019, p. 9). The current Class VIII(a) medical logistics supply process involves specific characteristics that are not applicable to a constrained environment, such as DMOs or operational environments.

In a DMO or operational environment, medical units cannot sufficiently predict the necessary supplies to treat medical conditions that emerge, traditionally requiring access to large amounts of Class VIII(a) supplies to be readily available on hand. Operational environments experience unpredictable demand from sudden increases in patients with uncertain medical conditions. For this reason, the supply chain in a DMO or operational environment must be viewed differently. As seen within the JHU study, mass casualties deplete Class VIII(a) supplies. Within operational environments, mass casualties are frequent or nonexistent, making planning for additional volume difficult. Accumulating large inventory stores of Class VIII(a) medical supplies in an operational environment or DMO is challenging due to unpredictable demand, uncertainty of patients, and varying shelf lives. This further makes identification of "the right product, in the right quantity, at the right time" more challenging to appropriately stock and maintain buffers (Swamidass, 2000).

D. CONCLUSION

The time an order spends in transit is long enough for unpredictable demand to cause shortages in Class VIII(a) consumable medical supplies. It is not reasonable to ship individual items across the ocean daily; therefore, bulk orders are placed, and shipments are sent in batches. It is more cost effective to continue to order items in bulk and maintain inventory buffers within warehouses. However, recurring orders spend time in transit, experiencing long lead-times from U.S. PVs to intermediate warehouses prior to arrival within Kandahar. It is not guaranteed the right item will be readily available for a medical condition that arises from combat during a mass casualty.

The NATO Role 3 MMU in Kandahar has limited storage capacity and tends to not stock enough of what is needed and to stock too much of what is not. While inventory buffers identified by recurring orders are maintained at nearby TLAMMs, the unpredictable demand of an operational environment creates challenges for logistics managers seeking to identify all the required Class VIII(a) supplies and have them available, not expired, and in the right quantity.

Taking time to review the different environments against a model that works within unconstrained environments shows the challenges and reveals the gaps. The reality is that there will always be time and distance constraints during any existing or future operational environment. The challenges presented by time and distance can be mitigated by 3D printing medical supplies on the spot, thereby ensuring "the delivery of the right product, in the right quantity, to the right place, at the right time" (Swamidass, 2000).

III. METHODS

The primary goal of this research is to identify logistics problems in operational environments and explore causes for shortages, challenges in resupply, and potential benefits of 3D printing in medical logistics in an operational environment. This qualitative, exploratory case study focuses on medical logistics in a deployed military trauma facility in Afghanistan during mass casualty events from October 2018 to April 2019. This approach is appropriate because 3D printing is an emerging technology and extant research is largely focused on repair parts. The analysis of this case reveals the potential for a 3D printer on-site in forward-deployed medical units to provide readily available consumables that have been depleted during mass casualty events while ordered items are in transit.

The study relies on a single, embedded case design (Yin, 2003). The overarching, focal case is comprised of the response of NATO Role 3 MMUs in Kandahar, Afghanistan to three mass casualty events that occurred in Afghanistan between October 2018 and April 2019. Critical shortages that occurred during the events comprise six embedded cases. Since 2010, NATO Role 3 MMU, a 70,000 sq ft trauma care facility, has been the primary trauma receiving center for all combat casualties and inpatient care in Southern Afghanistan. It is a rocket-proof structure, staffed by the U.S. Navy and Army, the Romanian Army, and contractors. Conceived in 2005 "as part of the International Security Assistance Force (ISAF)" mission, it has since been supported by the U.S. Navy Individual Augmentees (IA) medical units (Brisebois et al., 2011). I served for 9 months as the department head of logistics operations at NATO Role 3 MMU and draw on guides and documentation that I collected during that time.

A. DATA COLLECTION AND SOURCES

I collected and analyzed data in two phases. Phase 1 focused on the case. Phase 2 focused on recent developments in 3D printing. Interviews were the principal data source for each phase of analysis. I also collected operational documentation from the NATO MMU and reports of research on 3D printing of medical supplies.

I selected interviewees based on their role within NATO Role 3 MMU and their roles in 3D printing specific to medical supplies and devices. I conducted semi structured interviews via telephone and video conference. Interviews lasted 1 to 3 hours. I took extensive notes during interviews, which I compiled in an interview database organized by date and time the interview occurred. I also conducted several follow-up interviews by phone or email. Follow-on interviews ranged from 30 minutes to 2 hours.

1. Phase 1: Case Data

In Phase 1, to develop the case, I interviewed deployed medical professionals from NATO Role 3 MMU. Interviewees included two critical care nurses and one trauma surgeon. I also collected the Logistics and Operations Management Department Head Turnover Guide from NATO Role 3 MMU and my documented daily operations.

I asked medical professionals to describe their experience during October 2018 to April 2019, including how shortages of medical supplies affected the Role 3 MMU during the mass casualty events. Interviewees described the patient medical conditions the MMU received, the number of patients received, and the effects on Class VIII(a) medical supplies. They described insufficiencies in the resupply chain of Class VIII(a) and improvised actions taken to supplement shortages during long order fulfillment lead-times between acquisition and receipt.

The Logistics and Operations Management Department Head Turnover Guide is drafted by each department head rotation through NATO Role 3 S4. It contains documents pertinent to daily operations and gives details on how to run the S4 department. This provides documented history to ensure critical information is passed on to the incoming department head. It ensures continuity of operations, situational awareness, and roles to function as the S4 logistics and operations department head. It contains detailed information regarding duties and responsibilities, chain of command, and key elements of the environment such as nearby partnerships, intermediate distribution centers, supply ordering processes, lead-times, services, contracts, collateral duties, financial reporting guidance, letters of appointment, points of contact, and each division description with the S4 department.

During my time as department head of logistics operations, I recorded data obtained during my 9-month deployment in the Logistics and Operations Management Department

Head Turnover Guide to pass down to my replacement. For this research, I used the turnover guide and my documented daily operations to provide context surrounding exact dates when mass casualties occurred. I started documenting my daily experiences in a logbook to track information, points of contact, rocket attacks, mass casualties, supply issues, equipment issues, number of patients, and types of medical conditions. Daily accounts of my deployment were important to incorporate experience into the Department Head Turnover Guide. Table 1 summarizes the case data collection and sources.

Table 1. Case Data Sources Summary

Interview Type	Semi-structured (9 questions)
Interviewees	2 critical care nurses 1 trauma surgeon
Interview Duration	1 - 3 hours Follow-on interviews were 30 minutes to 2 hours
Interview Records	Detailed notes (15 pages) Follow-on emails (4 pages) Appendix C: Commonly Used Class VIII(a) medical supplies
Operational Documents	Department Head Turnover Guide (17 pages) Documented daily operations (4 pages)

2. Phase 2: 3D printing

In Phase 2, I interviewed 3D printing subject matter experts and collected documents and articles relating to medical logistics and 3D printing. Interviewees included four subject matter experts from Uniformed Services University (USU). The interviewees served in various roles at USU, including

- Director, 4D Bio3
- Director of Strategic Partnerships
- Senior Manager for Education and Training, 4D Bio3
- Senior Research Scientist, 4D Bio3

Additionally, one subject matter expert from the WRNMMC, 3D Medical Applications Center, Department of Radiology participated in an interview. The interviewees have conducted extensive research and testing and have successfully 3D printed medical supplies. I also collected reports of research on 3D printing of medical supplies.

For these interviews, I focused on how 3D printing can impact logistics in an operational environment remote from intermediate warehouses and PVs. My initial analysis of the case data informed the interviews. The medical professional interviewees identified Class VIII(a) consumables that were rapidly depleted during mass casualties. I shared this information with the 3D printing subject matter experts to solicit their expertise on the potential of 3D printing Class VIII(a) medical supplies and to get their recommendations on which Class VIII(a) medical supplies show the highest potential. Interviewees described the characteristics of 3D printing materials and types of printers with potential to print Class VIII(a) medical supplies in an operational environment and shared their thoughts on the feasibility of 3D printing Class VIII(a) medical supplies in an operational or DMO environment. Interviewees also shared their knowledge of field tests of specific medical supplies. Table 2 summarizes the 3D printing data collection and sources.

Table 2. 3D Printing Data Summary

Interview Type	Semi structured
Interviewees	4 subject matter experts from USU • Director, 4D Bio3 • Director of Strategic Partnerships • Senior Manager for Education and Training, 4D Bio3 • Senior Research Scientist, 4D Bio3 1 subject matter expert from WRNMMC • 3D Medical Applications Center, Department of Radiology
Interview Duration	1 - 3 hours Follow-on interviews were 30 minutes to 2 hours
Interview Records	Detailed notes (6 pages)
Research Reports (see Appendix A for complete list)	18 reports 2010 to 2020 Total 327 pages

B. DATA ANALYSIS APPROACH

The seven rights of logistics framework (Swamidass, 2000) provided an overall framework to guide my analysis. I analyzed the data in phases. First, I analyzed the case data to develop an understanding of the challenges of medical logistics in operational environments. Next, I drew on my initial findings and the seven rights of logistics framework and analyzed the 3D printing data to develop an understanding of the current state of the art in 3D printing related to medical supplies. Finally, I integrated these analyses to answer the study's research questions.

I began my analysis by developing a 24-page case narrative. I identified key events from the interviews and operational documents and arranged the events in chronological order. I then annotated and coded the narrative. I coded segments of text indicating identified problems, constraints, outcomes, and critical events. I also coded for problems using the following codes derived from the "seven rights of logistics" framework: right product, right quantity, right time, right place (Swamidass, 2000). My analysis resulted in a detailed description of daily operations, identification of key shortages and constraints in resupply, and characterization of Class VIII(a) medical supplies.

Next, I coded the 3D printing experts' interviews, noting new developments, findings, research, testing, potential, limitations, and challenges. I reviewed usage cases, research reports, and documents and articles regarding 3D printing types, functions, and capabilities to identify current and future potential, and limitations of 3D printing of medical supplies.

Finally, I integrated the analyses. I compared across the key shortage events and ranked key shortage items on criticality. I then compared the characteristics of the critical Class VIII(a) medical supplies with the capabilities and limitations of 3D printing of medical supplies. This integration identified Class VIII consumables with a high potential to be 3D printed and to provide benefit in operational environments. Concepts, themes, and implications are provided in Appendix B.

C. CONCLUSION

This study analyzes data focused principally on a single case and experts' assessments. This design, although appropriate for a study of an emerging technology to be potentially deployed in an extreme context, does pose some limitations. The study is exploratory and, as such, provides direction for future study rather than results that generalize, definitively, to other situations.

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IV. CASE ANALYSIS AND FINDINGS

This chapter presents an analysis of events experienced at NATO Role 3 MMU over a 9-month period. The chapter includes both an analysis of the overall case and an analysis of specific critical incidents that occurred during the nine months. The analysis of the overall case resulted in a characterization of the unique logistics challenges in the context of operational environments and mass casualty events. Analysis of the critical incidents within the cases identified drivers and outcomes of the critical incidents. An integration of the analyses summarizes key findings, the causes and consequences of shortages and the effect on the "rights" of logistics (as discussed in Chapter II Background). These findings informed the subsequent chapter which presents analysis and findings that answer the question of whether 3D printing could alleviate some of the shortages or mitigate their effects.

A. THE SITUATION AND LOGISTICS PROCESSES AT NATO ROLE 3 MMU

The overarching, focal case (as described in Chapter III Methods) is an analysis based on my field notes in response to three mass casualty events at NATO Role 3 MMU in Kandahar, Afghanistan, between October 2018 and April 2019. The overarching case is an extreme situation due to the location and distance from CONUS where "mandated sources of supplies are located" (Cardinal Health, 2020). The analysis of the overall case resulted in a characterization of the unique logistics challenges of operational environments and mass casualty events. The overarching case is divided into two sections to provide the setting and logistics process for NATO Role 3 MMU.

1. The Setting of NATO Role 3 MMU

From October 2018 to April 2019, I maintained a daily operations log while stationed at NATO Role 3 MMU that provides the basis for discussion in this section as the overarching case. Since 2010, NATO Role 3 MMU, a 70,000 square foot trauma care facility, has been the primary trauma care facility for all combat casualties and inpatient care in Southern Afghanistan. It is a rocket proof structure staffed by United States Navy individual augmentees (IA), the U.S. Army, the Romanian Army, and contractors. Navy Medical units were deployed as IA throughout the operational environment to support Role 1, 2, or 3 level care facilities. The overarching case is divided by themes: location, patients treated, drill events, mass casualties and space.

The MMU experienced unpredictable demand during the period in question. Calibrating demand based on the ground conditions was challenging. The unpredictability of demand, number of patients, and unknown patient lengths of stay made identification of recurring ordered items challenging and setting reorder points more challenging. MEDLOG within the operational environment faced many uncertainties in demand compounded by time, distance, and space. It was challenging to identify items as recurring or non-recurring because of limited storage, obsolete consumables, stockpiling, the local populace, and the varying shelf lives of Class VIII(a) medical supplies. Time and distance compounded by rotational deployments further complicated projecting logistic requirements. While overall, there were 158 trauma activations during the period of the case, this analysis focused on six critical events that strained logistics and medical operations.

Heightened tensions and increased hostilities were anticipated from October to November and closer to the upcoming Afghan election period. The presidential elections were taking place in April 2019. Parliamentary polls were scheduled for October 20, 2018. It was difficult to predict attacks during a new year of elections. However, rotations could plan by looking at past precedent and anticipated spikes in demand around elections. Prior to 2018, in November 2017, "areas surrounding Kandahar had had a 31% chance of attack once in three months and a 20% chance of attack at least 3 times a month" (British Broadcasting Corporation [BBC], 2018). The timeline in Figure 5 provides a "what and when" chronological timeline of IA rotations including date of arrival and significant events.

October 12, 2018

- Nato Role 3 MMU supported by military IA serving nine-month deployment. Next rotation of IA Navy personnel assumed responsibility.

October 17, 2018

- Five days after arrival a base-wide mass casualty drill was conducted to train for anticipated increase in hostile acts with upcoming election.

October 18, 2018

- **Mass casualty event**
  - High ranking military officials with local high ranking government officials attacked by insider threat. Mass casualty activation occured and NATO Role 3 MMU received sixteen patients, U.S. military and Afghan partners.
  - Problem: NATO Role 3 MMU is not set up to care for patients outside of the initial 24-48 period post injury. It is set up for a 72 hour stay, this caused depletion of medical supplies. needed to care for them. Mass casualties cause an patient influx, prolonged patient stays and limit bed capacity.
- **Unpredictable Demand**
  - MEDLOG contained a lot of what wasn't needed and less of what was. Rotations are challenged with planning inventory around varying conditions of demand. With a precedent set by awareness of upcoming elections it is not a guarantee attacks will occur. Setting the wrong amount to arrive can impact the next rotation negatively. There is insufficient time to correct stockpiling, correct what isn't needed and identify what is needed to ensure recurring order history.

October 25, 2018

- **Medical Equipment**
  - Medical equipment required replacements. Medical equipment was past life expectancy, strained during mass casualty events and repair parts on backorder.
  - Multiple surgeries, patient immobilizations, patient interventions required a lot of medical equipment to support patient care.

October 30, 2018

- **Network Outage**
- Makes ordering, tracking and receiving medical supplies difficult. Relevant to future operating environment such as DMO.

November 10, 2018

- **Mass casualty event**
  - Election hostilites increased. Mass casualty activation and seven patients, all Afghan partners arrived at NATO Role 3 MMU. One patient diagnosed with contagious infection. Required isolation, PPE and Decon protocols.

December 21, 2018

- **Medical Equipment**
  - Medical equipment replacements for sterilizers installed incorrectly. Field sterilizer required long hours to trouble shoot and bring online. Surgeries were still being performed on patients from previous mass casualty and new patients arriving. This overloaded the field sterilizers.
  - Medical equipment was American voltage being plugged into European outlets. All medical equipment required a transformer (converter) in order to deliver patient care.

January 2019

- **Mass casualty event**
  - Unprecedent event occured, mass casualty activation resulted in NATO Role 3 MMU receiving five patients with GSWs to the head within a few days of each other.
  - Unpredictable demand for cranial kits typically a non-recurring ordered item. There was only one stocked within MEDLOG.

Figure 5. Timeline of Events

a. The Location of the Facility

NATO Role 3 MMU is in an underdeveloped nation constantly under threat, with rotating contractor and military personnel. It is far away from the United States, and regularly deals with unpredictable demand. Within an operational environment Class VIII(a) medical supplies face logistical challenges such as varying shelf lives which impact capabilities to use medical supplies upon arrival. Resupply experiences long lead times from Prime Vendor (PV) suppliers causing delays in receiving items. Varying shelf lives of Class VIII(a) are a significant challenge for operational environments far from PV in the United States. Another location challenge is that NATO Role 3 MMU is "not a direct delivery from PV and ordered items must stop at TLAMMs", which delays receiving resupply (Resnick, et al., 2014).

IA Navy medical professionals support NATO Role 3 MMU during a 9-month rotational deployment in Kandahar, Afghanistan. If the previous rotation does not anticipate or project demand, the new rotation faces logistical challenges. Accurately predicting demand is even more challenging in operational environments where rotations receive messages to draw down while still being expected to conceptualize demand for anticipated hostile periods.

Each rotation experienced different types of medical conditions, patient demographics and number of patients from the previous rotation. The next rotation of IA Navy personnel assumed responsibility for NATO Role 3 MMU on October 12, 2018, relieving the previous unit. The arriving rotation walked through MEDLOG and storage spaces to evaluate available resources. MEDLOG was stocked with obsolete consumables, bulk ordered items, and boxes of oral rehydration salts that never expire, were covered in dust, and would never be used. It is likely that previous rotations anticipated increasing hostilities and ordered in bulk to prevent shortages during surges of attacks. This resulted in stockpiling if the bulk ordered items were never used. Several orders had been placed by previous rotation to arrive in October 2018, but the ordered items either were obsolete, arrived expired, or were in the wrong quantity (cases instead of boxes), which further constrained already limited storage space issues.

To supplement the long delivery times and distance from PV, NATO Role 3 MMU relied on partnerships within the same geographical area. Craig Joint Theater Hospital (CJTH) Bagram Airfield is an hour away by air. CJTH and NATO Role 3 MMU established a partnership for resource sharing on recurring and non-recurring items when they depleted. However, CJTH experienced similar long lead time constraints and mass casualties as NATO Role 3 MMU which made resource sharing difficult. CJTH needed the supplies as gravely as NATO Role 3 MMU. Time, distance and space caused shortages in Class VIII(a) medical supplies because of varying shelf lives, limited bed capacity, long patient stays, limited storage to fill right products, long lead times, intermediate shipping stops, and delayed receipt in resupply.

When medical equipment needed to be replaced or needed repair parts that were backordered, the regional biomedical technician reported delayed parts were a theater-wide issue. The radiology department experienced imaging reconciliation issues with the Computed Tomography (CT) system. The portable radiographic machine was producing poor quality images, making it difficult to diagnose patients' conditions. Machine failures caused delays in diagnosis that led to delayed discharge and longer patient stays, in turn increasing Class VIII(a) supply use. Medical equipment repair parts were ordered numerous times but canceled due to backorders. This created incredible anxiety and stress for the nurses and providers who were trying to perform the necessary tests and interventions to properly diagnose and treat patients. Network outages occurred throughout the 9-month deployment, impacting the medical unit's ability to scan patients and, order, track, or receive medical supplies.

Personnel from previous rotations shared that the local hospital, Kandahar Regional Medical Center, had limited capacity and inadequate quality of life outcomes compared to the quality of care received at NATO Role 3 MMU. This caused NATO Role 3 MMU to face more patient demand than had been anticipated at this time; it is unethical to transport patients to a local hospital known to have poor outcomes. This heavily influenced demand and provider decisions and caused longer patient stays.

b. The Patients Treated

Both NATO coalition forces and Afghan partnered forces shaped the demand in the operational environment. In addition to the U.S. military, NATO coalition forces include troops from Albania, Bulgaria, Canada, France, Lithuania, Netherlands, Poland, Romani, Slovakia, and the United Kingdom. Military units referred to the base limits as "the wire." Train Advice Assist Command South security patrols took place "outside the wire" and Mine-Resistant Ambush Protected vehicles drove past Taliban's Last Stand (see Figure 6) and NATO Role 3 MMU daily. The security patrol is primarily Afghan partners from the 205th Corps of the Afghan National Army (ANA) and the 404th Zone Police Corps. If injured outside the wire the Afghan partners and coalition forces received care at NATO Role 3 MMU. The needs of the Afghan partnered forces were not adequately reflected in the available supplies, creating challenges in providing care.

Figure 6. Taliban's Last Stand. Source: author's field notes

With the operational tempo and increase in Afghan partnered forces, the longer times that patients spent within the facility led to an increase in demand for medical supplies. NATO Role 3 MMU was set up for 72-hour medical care, not long stays, or rehabilitation. The Afghan-partnered forces such as ANA, police, or linguists are not transported to Landstuhl Regional Medical Center in Germany like U.S. military or NATO coalition forces. When these patients must remain in NATO Role 3 MMU for long periods of time, it depletes medical supplies and other resources such as linen. Long patient stays require excessive use of Class VIII(a) medical supplies such as syringes to deliver medicine, IV tubing, IV fluids, needles, bandages, and any surgical interventions that are used to treat battle injuries, adding to the strain on Class VIII(a) stocked medical supplies and medical equipment.

The increase in care to partnered Afghan forces meant more patients arriving to NATO Role 3 MMU would have similar height and weight to the local populace. This created problems caring for ANA partnered forces and linguists, who were typically thinner and smaller in stature then the average American. MEDLOG was stocked with expired pediatric medical supplies because it had not treated a child in 5 years, so some of those supplies could be used for smaller Afghan partnered patients. However, NATO Role 3 MMU was not established for rehabilitation of patients as it was set for 72-hour trauma care. Therefore, there were no assistive devices identified in order history as recurring except for large crutches. There were no other sizes of crutches available nor were walkers available. Items like crutches must be fitted to specific individual height and weight; improperly fitted crutches can cause further harm to a patient.

Small and medium crutches needed by Afghan partners did not have an established order history and were thus non-recurring. Items not used routinely are considered non-recurring because they do not have an order history established. Non-recurring items were removed from the theater Authorized Stock List (ASL) generated by TLAMMs, to buffer against surges in demand, using recurring ordered items. Non-recurring items generally are challenging to replenish because TLAMMs have not identified them as recurring orders and orders will be filled by PV in the United States Recurring items with an established order history are readily available in stock at MEDLOG or TLAMMs, but non-recurring items depleted during a mass casualty experience long lead times from PV.

A new item request (NIR) was required to get small and medium crutches added in DMLSS. NIRs are processed by USAMMC-SWA (the nearest TLAMM). Suppliers were usually in the United States, and Navy Medicine is mandated to utilize PV and ECAT for medical supplies. Receiving a quote could take anywhere from 1 to 2 weeks, causing significant delays in processing NIRs. Once the quotes are received by the end-user they are forwarded to USAMMC-SWA for approval and processing. This could take an additional 7 to 14 days. After processing, the end user could then order the item, typically from the U.S. Deliveries from the United States. to USAMMCE direct or via USAMMC-

SWA to Afghanistan could take 30 to 60 days, but less if a recurring item was available at a TLAMM.

c. Drill Events

Base-wide drills were conducted to prepare for the upcoming parliamentary polls and presidential elections. The drills revealed valuable information about which resources were available, not available, obsolete, or expired. On October 17, 2018, just 5 days after arrival, the base went into a training environment. The hospital Patient Administration Department (PAD) was informed several patients were arriving from a simulated attack. PAD sent out a mass casualty (MASCAL) activation to the NATO Role 3 MMU medical professionals and all required supporting personnel. Because the drill was anticipated all required personnel were already staged; this would not be the case when an actual mass casualty event occurred. The mass casualty drill was to train readiness for a real event receiving of multiple ambulances, patient flow, influx in patients, and resources used.

The intent of the drill was to stress the system. Operational environments create different expectations in readiness, training, and resources. During the drill, an ambulance approached the outside receiving bay. The paramedic opened the doors, yelling out medical condition, status, vitals, and interventions performed in the field. Each patient was taken behind concrete bunkers called "clearing bays" to be cleared of ordnance, weapons, and explosives. Their clothes were cut off to reveal wounds or hidden threats to medical staff, referred to as "trauma naked." Once the patient was cleared, the litter bearers moved them to the emergency room for treatment. As soon as one ambulance left, another arrived. At one point two ambulances arrived simultaneously, and two walking wounded approached the bay.

The scenarios endured in the MASCAL drill highlighted the patient flow, traffic control, and equipment and resources required and further identified resources that were limited, not available, or that would be depleted rapidly. The drill identified items that should have an established order history to ensure stock within TLAMMs and MEDLOG. It would take time not only to set order points of identified resources but time in delivery. The operational environments also created gaps in communication. During the drill, several communication devices did not function properly and not all personnel received the MASCAL activation.

d. Mass Casualty Events

Mass casualty events can overwhelm a medical facility's resources. On October 18, 2018, a MASCAL base-wide announcement went out overhead. This was not a drill. Three patients were inbound from a palace shooting in Kandahar. An insider threat had attacked the personnel attending a briefing. Many were injured, and a few perished. A senior-ranking military official was killed in the attack on the governor's palace. The situation evolved erratically. Information on the number and condition of patients kept changing. Three became four; four became eight. A helicopter approached. The back gate of the hospital opened to the airfield, allowing the ambulance to arrive within seconds of the helicopter's landing. The Auxiliary Security Force manned the gates and clearing bays, armed and ready. One had his M16 gripped so tightly, his hands were white. The ambulance arrived, and the paramedic jumped out yelling triage details. The litter bearers grabbed the first patient litter, but the patient urged them to "take care of the others."

Within seconds more ambulances arrived with severely injured and walking wounded patients. NATO Role 3 MMU was quickly overwhelmed with high-ranking military officials and their entourage, ANA, and linguists, six casualties, and 10 non-injured in total. An announcement instructed the base to "send all available walking blood bank to the Role 3". This meant any available person on base should report to donate blood. Each patient was cleared of ordnance, weapons, and explosives and then taken into the emergency room for treatment.

Patients that required extensive surgeries or rehabilitation were not discharged to the local Afghan hospital due to concerns about quality of care. However, as discussed above, those patients could not perform rehabilitation exercises because the NIR for crutches had not processed. Saline flushes, which had been ordered and were critical to administer medications, blood, and fluids to patients during long bed stays were delayed. To care for patients, the ICU nurses improvised and made the saline flushes.

A few weeks later, on November 10, a “Rocket Attack” announcement sounded during the night. Casualties arrived via rotator on the flight line and were through the hospital gates in seconds, bringing seven ANA patients with an array of medical conditions. They had been part of a reconnaissance unit that was attacked. Three rockets hit within the wire, one by the hospital flight line, one across the street from the hospital, and one on the north side of the flight line. One high ranking senior official lost his leg, and others required hand amputations and tube feeding. The transformers (converters) for medical equipment were stressed from the patient load and they frequently died or required replacement. One caught fire near a patient and was immediately extinguished by the fast response of a nurse.

The increased hostilities resulted in compounded mass casualties that strained medical equipment such as the sterilizers. Further, as a result of increased hostilities and attacks, base threat conditions increased, and all flights were grounded. This delayed the resupply of items depleted during the mass casualty as well as parts required for the installation of new sterilizers. Over the next few days, following the November Rocket Attack event, the external field sterilizers were stressed with multiple surgeries for gunshot wounds (GSW), amputations, and wound cleanings. The patients required multiple surgeries and then admission to the Intensive Care Unit (ICU). The existing sterilizers, and other equipment, were past life expectancy, but the installation of new sterilizers was delayed.

New sterilizers were eventually installed in December 2018. After several test runs of the new sterilizers, Sterilizer #2 failed. It took several days for the company contractor to arrive in theater. The contractor reported the handle to Sterilizer #2 was installed backwards, causing the locking mechanisms to not properly engage, disrupting the sterilizing process, and causing the sterilizer to shut down. Ordering the part and handle reinstallation would take several weeks. The main operating room could still use Sterilizer #1 and two external field sterilizers in the event of a mass casualty or surgery. This was not ideal because the field sterilizers took hours to bring online to start sterilizing surgical kits and to complete sterile kits for procedures. They were meant to be used as backups to the internal sterilizers but while awaiting parts the operating room relied heavily on the external sterilizers before, during and after mass casualties.

As Afghanistan's presidential elections neared, there was an increase in events and threat conditions starting in January, leading into April. In January 2019, NATO Role 3 MMU received five patients with GSWs to the head within a span of a few days. This was unprecedented and required supplies from PV in the United States. The surgical team used the last craniectomy flap and craniotomy kits, and CJTH could not spare one. CONUS hospitals were contacted for support to provide craniotomy kits while orders were in transit from PV to TLAMMs. Each patient required a cranial implant. The attending neurosurgeon sent CT images to Walter Reed National Military Medical Center (WRNMMC). WRNMMC has approximately a dozen 3D printers in their facilities, which they rely on for an array of items from models to modifications for prosthetics to surgical guides and implants. WRNMMC 3D printed a mold to create a titanium allograft implant that would be put in the patients who were victim to the GSWs to the head.

e. Available Space at the Facility

MEDLOG had limited storage capacity. There was not enough space for the right product because the warehouse was filled with obsolete products (products that never expire and therefore are never disposed of). The facility therefore had little room for building buffers of critical items identified by a new rotation. Significant challenges with space capacity are a result of the inconsistencies from rotation to rotation of deployed Navy IA units supporting NATO Role 3 MMU. Supply representatives are selected at random with no prior DMLSS training conducted in advance of deployment and the collateral is assigned upon arrival in Kandahar. Some supply representatives took the collateral seriously and were dedicated, others were not.

2. The Logistics Process for the NATO Role 3 MMU

This section provides an overview of the specific logistics process for NATO Role 3 MMU and is divided into the process for ordering supplies and the process for delivery of supplies to the facility. Characteristics of the operational environment and mass casualty events created challenges for medical logistics. Logisticians faced challenges identifying recurring orders to appropriately stock within MEDLOG. Setting reorder points or establishing inventory buffers was challenging in an operational environment characterized by erratic mass casualties and unpredictable demand.

NATO Role 3 MMU was designed for trauma care; hence rehabilitation or long patient stays posed a resupply challenge. The October 18, 2018, palace attack resulted in the rapid depletion of Class VIII(a) medical and surgical supplies. Timely receipt of supplies was challenging within this highly hostile environment when the threat of further attacks with injuries to military and coalition forces was likely. CJTH on Bagram Airfield (BAF) was one hour away and had a partnership with NATO Role 3 MMU to assist when shortages occurred. However, they faced similar challenges with unpredictable demand.

a. Overview of the Process for Ordering Supplies

The process for ordering most supplies for NATO Role 3 MMU is described here. When MEDLOG stock is out, an item is requisitioned through DMLSS and tracked through TEWLS. NATO Role 3 MMU's order is sent to the nearest TLAMM, USAMMC-SWA. The order is not requisitioned until the logistician at the TLAMM submits the order. If USAMMC-SWA is out of stock, the order is pushed to the second closest TLAMM, USAMMCE. If USAMMCE is out of stock the order is sent to PV in the United States. Class VIII(a) medical supplies are different as the supply chain for these materials is domestic; PV resides in CONUS unlike the global manufacturers for other classes of supply. To avoid stock out, TLAMMs manage inventory and buffer according to recurring orders and generate a theater ASL. Non-ASL items, i.e. non-recurring orders, have a 3 to 6 months lead time to Kandahar. Non-recurring items, i.e. critical items, are those rapidly depleted during mass casualties and due to unpredictable demand often do not have an established order history.

Mass casualties cause unpredictable demand. Class VIII(a) with non-recurring demand are not added to the ASL but does not mean they will not generate a significant burn rate during a single event. Some Class VIII(a) medical supplies with non-recurring demand can be rapidly depleted during a mass casualty and have no buffer. Some PV and ECAT Class VIII(a) medical supplies are those that do not have a recurring order history within the operational environment and resupply is filled by PV in the United States. Non-recurring PV items have long lead times, inhibiting the ability to treat uncertain medical conditions during mass casualties that may not require some stocked items. That one non-recurring item could mean life or death for a patient who needs it.

NATO Role 3 MMU MEDLOG maintained inventory from identified recurring ordered Class VIII(a) medical supplies that were then added to the theater ASL to provide TLAMMs visibility on routine orders. Theater logisticians expressed the importance of ordering small quantities routinely to establish an order history and add items to the ASL, ensuring availability at nearby TLAMMs. TLAMMs acquisition ordered items on a recurring basis that have an established order history. NATO Role 3 MMU relied on two nearby TLAMMs for recurring and non-recurring items, USAMMC-SWA and USAMMCE.

Ordering large quantities in an operational environment is not efficient. An item listed in DMLSS as non-recurring is typically one of many items rapidly depleted during a mass casualty due to unpredictable demand and uncertainty of medical conditions. Large inventory buffers of Class VIII(a) medical supplies are challenging because they have unpredictable demand, and varying shelf lives, and MEDLOG has limited storage capacity. Multiple rotations of medical professionals identifying some Class VIII(a) as recurring and not establishing an order history for the unpredictable demand has created excess stock or obsolete items. Medical professionals rotate every 9 months, and the next unit of professionals will identify their own recurring Class VIII(a), resulting in excess stock that sits idle.

b. Overview of the Process for Delivering Supplies

This section describes the process for delivery to an operational environment which is constrained by time and distance. NATO Role 3 MMU depends on nearby TLAMMs to deliver medical supplies. Orders are palletized and transported OCONUS via USTRANSCOM, MILAIR, or Class VIII tender. Deliveries of stocked items will arrive within 7 - 10 days from USAMMCE.

Medical equipment received in theater present unique challenges because parts may not be in DMLSS and may require an NIR. The medical equipment may require a PV or ECAT item to operate the equipment, which will also require an NIR. The end user must submit a USAMMC-SWA NIR form via email to USAMMC-SWA MEDLOG email distribution. USAMMC-SWA will process the request and add the item to DMLSS. This process can take anywhere from 1 to 2 months to get quotes and 14 to 20 days to process in DMLSS. Regardless of priority, a minimum of an additional 30 to 45 days is anticipated for the item to process and be added into DMLSS.

If life, limb or eyesight priority identification is annotated in the request for the item, the item can be prioritized; however, this will require a signed letter from the requestor and will take several days to weeks to process. The average lead time is five to six weeks (often longer) due to CONUS purchases and transport process. Electronic Catalogue (ECAT) and General Services Administration (GSA) items follow the same ordering process, except GSA can take anywhere from 30 to 300 days to arrive in theater. Figure 7 shows a replenishment diagram for NATO Role 3 MMU medical supplies that I generated to show a visual of lead times and flow. There are priority codes for Class VIII(a) that are utilized for requesting critical items:

- Priority 2: Mission essential (the mission will cease if these items are unavailable)
- Priority 3: Life or death
- Priority 5: Same as standard Priority 12 shipping but with "head of line privilege" (the Priority 5 request is filled before Priority 12 and before other Priority 5s if that request was received first)
- Priority 12 Standard shipping

Timelines for all priorities:

- Priority 2 and 3: Filled in 2 to 3 days BUT is predicated on the item being stock, which means it is available in the warehouse in Qatar or Europe and also depends on the status of outbound flights for delivery; requires a Letter of Justification by an O6 or above
- Priority 5 and 12: Filled in 3 to 4 weeks

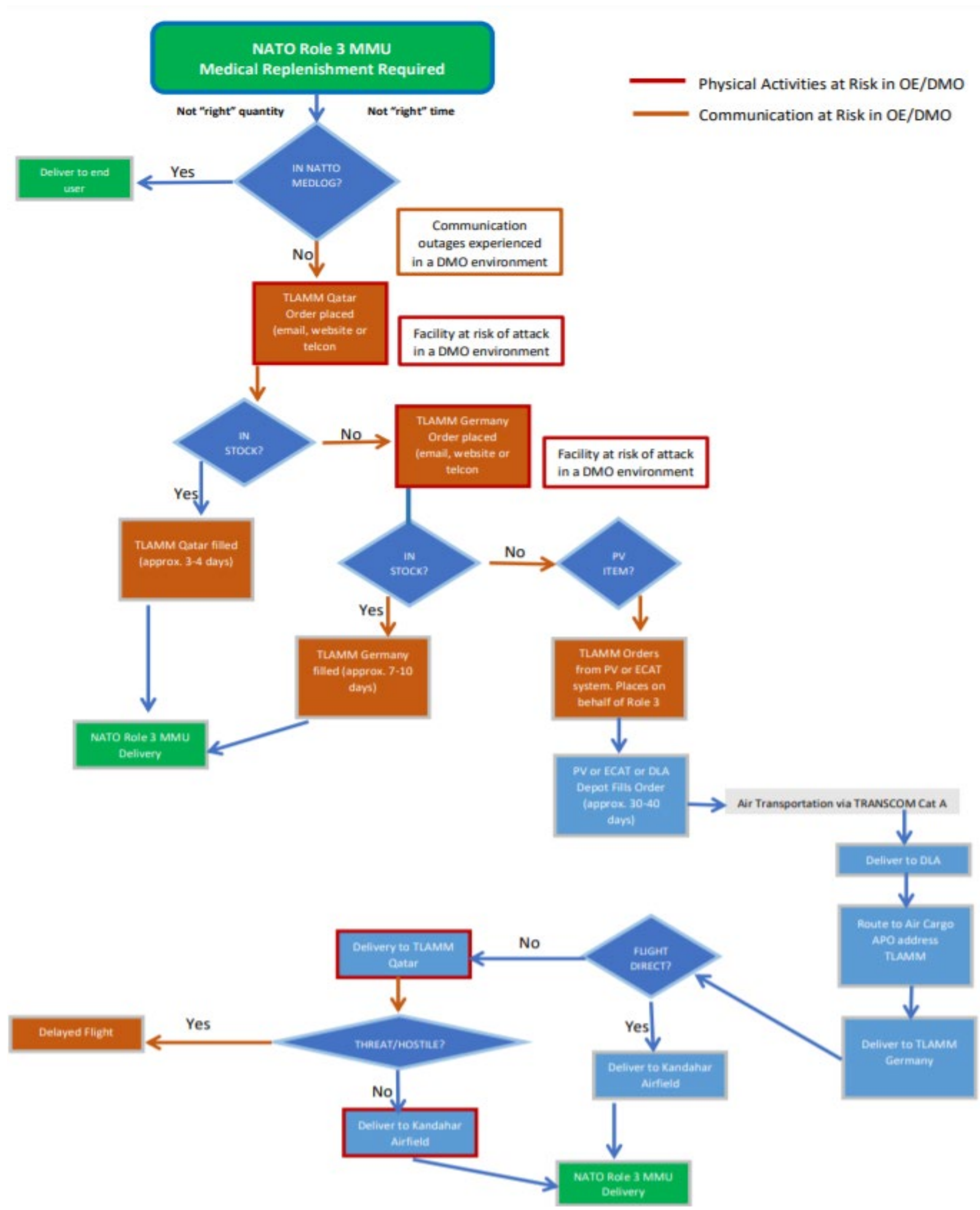

Figure 7. Replenishment of NATO Role 3 MMU Class VIII(a) Medical Supplies. Source: author's field notes

The process above is important for understanding the constraints in ordering and receiving Class VIII(a) medical supplies. The replenishment flow process for Class VIII(a) medical supplies to operational environments is constrained by time and distance compounded by intermediate stops.

B. THE SITUATION AND MEDICAL PROCESSES AT NATO ROLE 3 MMU

The embedded case, as described in Chapter III, is an analysis based on my interviews with medical professionals about specific situations they experienced within NATO Role 3 MMU. The embedded case is comprised of six critical events that occurred during the same period as the overarching case and were identified by one or both of the medical professionals interviewed as critical. Analysis of these events identified causes and consequences of shortages, inefficiencies, and deviations from standard medical practice. This analysis also identified rapidly depleted items which guided the subsequent investigation of the potential of 3D printing presented in Chapter V. The subsequent section is divided to discuss first the setting, then to identify rapidly depleted Class VIII(a), and critical events. The themes are relevant to observations within the overarching case. Table 4 summarizes drivers and outcomes.

1. The Setting

With respect to the setting, observations collected from the embedded case reinforced the observations in the overarching case with respect to location, patients treated, mass casualties, space in the facility, and critical events.

a. The Location of the Facility

The individuals interviewed reinforced observations from the overarching case regarding the location of the facility. They expressed the operational environment from their perspective. One participant interviewed described the operational environment stating:

> *It is a high-level stress environment with different expectations and limited options. There is a job to do, saves lives.* (Interview 2)

Two of the biggest challenges identified by medical professionals were supplies and communication. A relevant additional observation about the location from the interviews was related to communication. There are cultural and language constraints due to the location. Communication is an issue because of patients who are being treated but are unable to easily communicate due to language barriers. Communication plays a unique role in the operational environment because of the language within the area, either Pashto or Dari. Even though NATO Role 3 MMU has linguists, they are not medically trained so important medical precautions, procedures and after care plans for lost in translation. One participant described the environment and communication issues stating:

> *Medical units must expect the unexpected. Mass casualties and sleep deprivation are accompanied by rocket attacks, communication outages, water outages, and undesirable weather. Fatigue, supply shortages and language barriers make the operational environment unique.* (Interview 1)

The location constrains supplies and those interviewed provided new relevant insight into this problem. Supplies are an issue because of shortages. NATO Role 3 MMU dealt with an unprecedent event described in the overarching case during a mass casualty that occurred in January 2019 involving five GSW's to the head received within a few days of each other. One interview participant described shortages in the operational environment stating:

> *Supply shortages lead to anxiety and rationing of supplies. A nurse stated: During our five days receiving GSWs to the head we ran out of cranial kits.* (Interview 2)

As discussed in the overarching case, NATO Role 3 MMU is designed for trauma care, therefore rehabilitation or long patient stays pose a resupply challenge. One participant interview shared the difficulty receiving in the operational environment stating:

> *Mass casualty events would seriously deplete our supplies. Sometimes supplies came quickly (i.e. one to two weeks) other times we borrowed from nearby Role 3.* (Interview 1)

Similar to the observations in the overarching case, the interviewed medical professionals noted that partnerships with CJTH helped in some situations assisting with supply shortages. However, they experienced unpredictable demand and mass casualties that depleted their supplies. Time and distance compounded by mass casualties and patient length of stay caused shortages.

b. The Patients Treated

The medical professionals interviewed provided relevant additional information about the uniqueness of patients treated within NATO Role 3 MMU. Communication, mentioned by those interviewed as a location constraint, is also a patient constraint and plays a role in patients treated because of language barriers to describe medical treatments. Not all patients are U.S. military or NATO coalition forces that can be transported to Landstuhl Regional Medical Center in Germany. The patients that were Afghan partnered forces made discussing treatment challenging. The interview subjects identified all patient types treated within the facility, listed here:

- Afghan partnered forces
- NATO coalition forces and U.S. military
- ANA
- Afghan National Police (ANP)
- Afghan special forces called Charlie Guardians (who had to be separated to protect their families and identities)
- Contractors (who could not get care at the contracting hospital)

c. Mass Casualty Events

The three mass casualty observations from the overarching case are also discussed in the embedded case. The interviewees provided relevant information on medical conditions. Each medical condition identified by the interview subjects require different Class VIII(a) medical and surgical supplies. During one event that occurred on October 18, 2018, NATO Role 3 MMU treated 11 patients with an array of medical conditions requiring varies Class VIII(a) medical and surgical supplies. The prolonged patient care greatly strained the medical equipment. These are effects of mass casualties and the interview subjects identified the medical conditions to understand what medical and surgical supplies were used to treat those patients. Those identified medical supplies are discussed later. Both interview participants identified all medical conditions treated during the 9-month deployment:

- blast injuries
- gunshot wounds to arms, legs, head, and abdomen
- closed and open head trauma
- lower extremity amputations

- eye, orbital, globe injuries
- rib fracture
- arm and leg fractures
- spinal cord injuries
- traumatic and surgical amputations
- crush and compression injuries
- compartmental syndrome

Other medical/non-battlefield injuries included:

- ruptured brain arteriovenous malformation
- non-ST elevated myocardial infarction
- sustained/reoccurring supraventricular tachycardia

The medical professionals also commented that medical supplies rapidly depleted during mass casualty events due to prolonged patient care in the ICU. Class VIII(a) supplies were depleted and were difficult to receive in the operational environment. One interview participant said:

> *The highest burn rates for Class VIII(a) medical supplies and equipment were in the ICU due to mission creep that impacted patient length of stay.* (Interview 3)

NATO Role 3 MMU dealt with an unprecedent event during a mass casualty that occurred in January 2019 involving five GSW's to the head received within a few days of each other. One interview participant also discussed this event, which is also described in the overarching case, stating:

> *NATO Role 3 MMU received several GSW's to the head over a five-day period resulting in cranial kits, central lines, and craniotomy flaps depleted from MEDLOG.* (Interview 2)

The neurosurgeon sent CT images to WRNMMC, which 3D printed the mold to create the titanium flaps and mailed it forward. The uncertainty experienced in operational environments is reflected within the medical professionals' description of that event and a medical professional interviewed suggested that a 3D printer within NATO Role 3 MMU would have been invaluable. It is unprecedented for this facility to receive several patients with GSWs to the head within 5 days; not necessarily unprecedented for the operational environment, but to receive so many in a short period without sufficient time to resupply. It took about 4 to 6 weeks for the implant to arrive in Kandahar which meant the patient remained in the ICU, depleting other resources. One interview participant described specific medical devices and equipment issues stating:

> *A 3D printer on site that could print assistive devices would be valuable because the needs of the individual are unique. For example, a platformed walker for weight bearing restrictions on the upper extremity. Another application for 3D printing could be medical equipment parts. For example, if a ventilator failed. The manufacture is based CONUS and it will take 6 months to arrive at NATO Role 3 MMU. If 3D printer were on-site, NATO Role 3 MMU could print when required saving time and distance constraints. Being able to fabricate as needed would help with storage and supplies on hand.* (Interview 3)

Mass casualties had secondary effects on other resources from long patient stays. One interview participant described a situation stating that one patient contracted a contagious infection. ICU nurses had to conduct decontamination procedures using housekeeping supplies. Cleaning supplies are not Class VIII(a); they are ordered through General Services Administration (GSA). GSA's acquisitions solutions offer private sector professional services, equipment, supplies, and IT to government organizations and the military (GSA, 2020). Historically, items ordered from NATO Role 3 MMU through GSA took anywhere from 60 to 300 days to arrive in theater. Due to distance between GSA and PV to USCENTCOM, medical professionals adapted to the operational environment and improvised to save lives. The interview participant described the challenges with that patient in the operational environment stating:

> *The challenge here is that we were forced to break infection control protocol to take care of a patient. This is significant because our infection protocols are followed as strictly as possible to keep both the patient and staff safe, but in this case, we were forced to put aside to ensure keeping the patient alive.* (Interview 2)

d. Available Space of the Facility

The interview participants offered additional insight into the effects of space limitations supplementing the observations made in the overarching case about space issues. Limited bed capacity was affected by prolonged patient stays and unpredictable patient influx because of erratic mass casualty events within a hostile environment. Compounding mass casualties and patient length of stay took up bed capacity.

Transporting Afghan partnered patients to Kandahar Regional Military Hospital was constrained by the quality of care received there. For example, one interview participant said:

> *We treated one medical condition, a ruptured brain malformation, the clips the surgeons had to use in surgery to stop the bleeding were bigger than what neurosurgeons would have used if in the U.S. The surgery performed on that patient is not one that is typically conducted in a deployed environment and requires long-term intensive care that local Afghan facilities were not capable of doing.* (Interview 2)

The surgery performed on this patient guaranteed that prolonged patient care would be required within NATO Role 3 MMU. The consequences of not transporting patients was that many patients were required to stay for several weeks or even months which depleted other resources such as linen, bathroom supplies, intravenous flushes and many more Class VIII(a) consumables utilized daily.

e. Critical Events

Critical events experienced during the 9-months that the interviewed medical professionals were deployed provide insight into the burn rate during mass casualties. The medical professionals interviewed identified critical events that caused shortages in Class VIII(a) medical supplies commonly used and rapidly depleted. Table 3 describes the six critical events and summarizes the drivers and outcomes.

Table 3. Identified Critical Events During October 2018 to April 2019

Critical Event	Driver	Outcome	Sample quotation
Critical Event 1: Placement of tracheostomy in Afghan patient. Tracheostomy is not expected care in an operational trauma facility.	Providing intensive care beyond 72 hours. More time and intensive care than facility was intended to provide. Afghan facilities were not capable to care for patient.	Caused personnel to go through supply of suction valves incredibly quickly.	"The main reason this happened, honestly, is because we were taking care of a patient who required more time and intensive care than what our purpose was geared toward. This caused us to go through our supply of suction valves incredibly quickly after we placed a tracheostomy." "The suction valves are a one-time-use item; however, due to the necessity of their use for the patient, and our rapidly dwindling of the valves in our stock and inability to get replacements quickly, we had to reuse the valves repeatedly."
Critical Event 2: U.S. patient with abnormal heart rhythm, a medical condition not expected in an operational environment.	More time and intensive care than facility was intended to provide.	Medical condition required more rapid use of flushes, which depleted supply of flushes. Personnel was required to improvise flushes.	"We had a patient with an abnormal heart rhythm and no flushes. I had to send a nurse to run and make flushes."
Critical Event 3: Patient with extreme and highly contagious infection came in along with mass casualties.	Facility and supplies are not designed for highly contagious patients, with an open ward and limited PPE.	Personnel were forced to break infection control protocol because of rapid depletion of PPE and secondary resources (e.g., linen, pillows, cleaning supplies that had to be destroyed).	"Forced to break infection control protocol to take care of him. This is significant because our infection protocols are followed as strictly as possible to keep both the patients and staff safe, but in this case, we were forced to put them aside to ensure keeping the patient alive."
Critical Event 5: Surgery on Afghan patient with ruptured brain malformation, a	Supplies not adequate for this type of procedure. More time and intensive care	Items available were not the right size and thus personnel improvised use of	"We treated one medical condition, a ruptured brain malformation. The clips the surgeons had to use in surgery to stop the bleeding were bigger

procedure not typically conducted in a deployed environment.	than facility was intended to provide. Afghan facilities were not capable to care for patient.	surgical clips during trauma care.	than what neurosurgeons would have used if in the U.S." "The surgery performed on patient with ruptured brain malformation is not one that is typically conducted in a deployed environment and requires long-term intensive care that local Afghan facilities were not capable of doing. This guaranteed that we would be the persons to care for him as long as necessary."
Critical Event 6: Multiple patients with GSW to the head over short period of time. This number of similar cranial injuries in this short period of time was unprecedented.	Not stocked with the number of cranial kits needed to treat the specific injury, because event was not anticipated. Condition necessitated prolonged care.	Facility ran out of cranial kits and was forced to request kits from other facilities. These limitations delayed patients going into surgery. Also, facility was not stocked with sufficient items needed to treat the patients over the necessary length of stay.	"During our 5 days receiving GSWs to the head we ran out of cranial kits."

The overall consequences to logistics of the critical events the MMU experienced was a shortage of medical supplies and subsequent deviation from standard medical practice. This had the potential to have negative effects on patient care. Shortages of key supplies played a formative role in the critical events and resulting deviations from standard practice. The following section identifies and describes key rapidly depleted medical supplies.

2. Rapidly Depleted Class VIII(a) Medical Supplies

Interviewed medical professionals identified the Class VIII(a) medical supplies that were rapidly depleted during mass casualty events due to unpredictable demand and prolonged patient. Understanding rapidly depleted medical medicals helped provide a list to share with 3D printing experts (discussed in Chapter V) to understand specific characteristics those medical supplies have (i.e. plastic or metal). Class VIII(a) medical supplies are different than other classes of supply due to varying shelf lives and mandated PV which add to the challenges in managing the "right" product in the "right" quantity in operational environments (Swamidass, 2000). Order them too soon and they expire. Order them too late and shortages occur. Not all Class VIII(a) medical supplies are ordered routinely due to the unique burn rate experienced during mass casualties.

Rapidly depleted Class VIII(a) ranged from recurring items to non-recurring items. The uncertainty in what type of medical condition will arrive during a mass casualty makes it challenging to identify an item to be recurring. An item may be required for several medical conditions on several patients and then not required again for days, weeks or months. That unpredictable demand makes identification of the "right" recurring product to set a reorder point challenging in operational environments. Due to unpredictable demand and prolonged patient stays some critical Class VIII(a) medical supplies were rapidly depleted. Table 4 lists the rapidly depleted Class VIII(a) medical supplies.

Table 4. NATO Role 3 MMU ICU Class VIII(a) Rapidly Depleted

Rapidly Depleted
10 cc Syringes
Suction Tubing
Flushes
Suction Canister
Primary Tubing
Secondary Tubing
Alaris Tubing
Trac Holder
Arterial Line Set Up
Depleted in Critical Events
Cranial Kits
Central Lines
Surgical Clips
Craniotomy Flaps
Central Lines
Surgical Clips Scalpel
Bulk Supply Rapidly Depleted
Alcohol Pads
2 x 2 Gauze
4 x 4 Gauze
IV Tubing
Syringes (varying sizes)
1L Normal Saline Bags
Gloves

The identified Class VIII(a) medical supplies was in the context of mass casualty events. The effects of shortages were described by both interview participants. The interview subjects identified supplies that they thought were the most critical when short and good candidates for 3D printing. Interview participants said:

IV Tubing

IV tubing is critical to patient care in delivering various fluids to include normal saline, blood, nutrients, and medications. Without IV tubing there would be no access to deliver these fluids to patients.

> *Upon arrival there was a shortage **of IV tubing and secondary IV tubing** for our pumps. And the main problem is that with the influx of patients we*

> *were burning through it quickly. We had to extend the life and reuse tubing that typically would not be done stateside.* (Interview 1)

Miscellaneous

There are many medical supplies used to provides trauma medical care. The medical condition, type of injury or post-surgical procedure will require multiple items in multiple quantities.

> *Upon arrival everything supply wise was low, but supply representatives responded quickly. Catalogs were scrubbed, and organized, and projections of requirements were done to the best of their ability. However, issues remained in receiving simple things like* ***Chux pads, flushes, individually wrapped gauze, blood pressure cuffs, leg pumps*** *(patients with leg amputations wouldn't have required but if a patient did the care would have suffered),* ***basic hygiene kits, oral care kits, trach kits*** *(NATO Role 3 MMU didn't anticipate the need because patients are trached in the field but field medical units ran out). Prolonged care required hygiene and dental care kits, but supplies were limited. The NATO Role 3 MMU had supplies that were not required such as wound dressings suitable for a Role I or II level care. There was a lot of what was not required and less of what was. There was too much of what would never be used and not enough time to get what was required.* (Interview 2)

Syringes/Flushes

IV flushes are pre-filled, by manufacturer, one-time-use 10cc syringes. When shortages occurred, the nurses in the ICU made flushes from one-liter bags of normal saline. The improvised flushes were only viable for 24 hours and had to be made to cover two shifts. In a stateside or civilian hospital, a pharmacy hood is required to create IV flushes, and this is not available in operational environments. Shortages of flushes severely strained patient care because they are used for everything from medication delivery to IV patency. **Syringes** became a secondary shortage because of IV flush shortages. The ICU patient influx and long patients stays resulted in shortages of **feeding tubing** used to deliver nutrients to patients that are intubated and **central line kits**, used for central venous access which delivers fluids, blood, medication, and antibiotics. The shortest length of stay was less than 24 hours; the longest was 30 - 45 days, which impacted availability of supplies, extended the use of certain supplies, and reduced other resources. One interview participant provided examples and described causes for shortages, shown in Table 5, said:

> *We had a patient with an abnormal heart rhythm and no flushes. I had to send a nurse to run and make flushes during the event.* (Interview 2)

Suction Valves

Suction valves and canisters are critical pieces of equipment in all levels of patient care. They are present in independent patient care, intensive and emergency care, and in the operating room. They provide patients and the medical professionals the means of utilizing fast and effective removal of potentially harmful fluids and debris in variety of places including wounds, the oral cavity, and airway.

> *One of the biggest shortages we had was* ***tracheostomy tube suction valves****. The main reason this happened, honestly, is because we were taking care of a patient who required more time and intensive care than what our purpose was geared towards. The consequence was going through our supply of suction valves incredibly quickly after we placed a tracheostomy.* (Interview 2)

> *The* ***suction valves*** *are a one-time-use item, however due to the necessity of their use for the patient, and our rapidly dwindling supply of valves in our stock and inability to get replacements quickly, the consequence was we had to reuse the vales repeatedly.* (Interview 2)

C. FINDINGS OF CASE ANALYSIS

This section integrates the analyses of the overall case and embedded case critical incidents. The analyses show that four overarching causes (time, distance, mass casualties and space) and four key consequences (long patient stays, delays, reuse, and stock/shortage) resulted in shortages and challenged the "seven rights of logistics" (Swamidass, 2000). The operational environment and critical events resulted in shortages of key items which in turn resulted in deviation from standard care.

1. Constraints and Consequences of Shortages

Four major constraints causing shortages emerged from this analysis and are divided into subsections: time, distance, mass casualties, and facility space. These constraints resulted in long patient stays, delays, reuse, and stock/storage. The process for ordering supplies is constrained by unpredictable demand while the delivery process is constrained by time and distance. Figure 8 shows the four major constraints and consequences that resulted. In the forward operating base, medical logistics were constrained by time, distance, mass casualty, and space. These constraints exacerbated weakness and gaps in the supply chain resulting in shortages and non-standard practices.

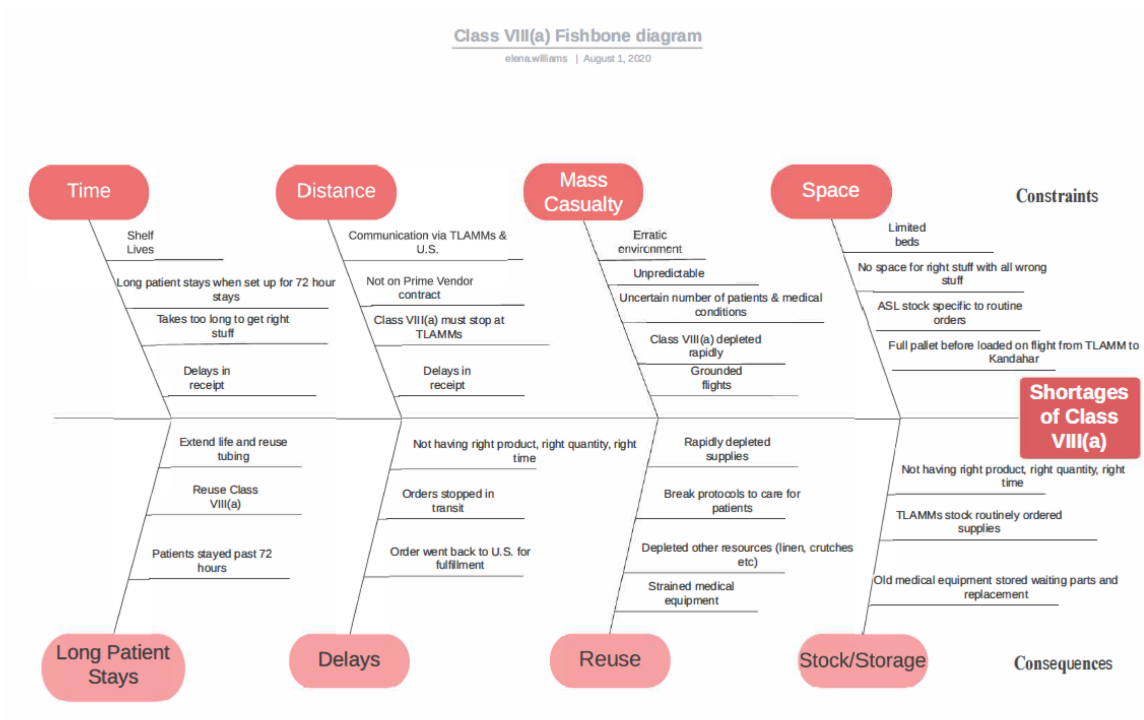

Figure 8. Fishbone Diagram of Key Constraints and Consequences

a. Time

The factor of time played a role, through the phenomenon of long patient stays as well as the way resupply time was subject to delays. The analysis of the case shows that long patient stays depleted resources and strained medical equipment. It took 7 to 10 days to resupply if the item was stocked at a nearby TLAMM. However, non-recurring items that were rapidly depleted during a mass casualty took 2 to 4 weeks shipping from PV in CONUS to a first stop TLAMM.

b. Distance

NATO Role 3 MMU is far away from PV in CONUS where mandated sources of supply are acquisitioned. As with time, PV items ship from CONUS to a first stop TLAMM. There is no direct delivery to NATO Role 3 MMU (Resnick et. al., 2014). It is within a landlocked operational environment. PV items must first stop at TLAMM in Europe, adding to the distance it takes to resupply. CJTH dealt with similar drivers and shortages as NATO Role 3 MMU. The October 18, 2018 mass casualty event took place within six days of arriving in theater, providing no significant evaluation of could be rapidly depleted. There was very little adjustment period and no time to evaluate the right product, in the right quantity of medical supplies within MEDLOG (Swamidass, 2000). The consequences identified by medical professionals were supplemented by improvised actions required to mitigate risk in delivering patient care during supply shortages. It is important to remember the differences in environments (see Table 3). Civilian and military stateside hospitals would not experience the same unpredictable demand that an operational environment does. The distance between NATO Role 3 MMU, TLAMMs and PV to resupply caused shortages and impacted availability of Class VIII(a) medical supplies. This led to limited resources and improvised actions not practiced in civilian or stateside hospitals.

c. Mass Casualties

Mass casualties are uncertain within operational environments and can occur rapidly or not at all. Mass casualties compounded with shortages, patient influx, and length of stay rapidly depleted resources impacting the availability of the right product, in the right quantity, at the right time (Swamidass, 2000). Mass casualties create unpredictable demand that makes it difficult to identify the right products in the right quantity to maintain in inventory. Stocked items in MEDLOG rapidly depleted during a single event. Unpredictable demand with uncertain types of medical conditions and number of patients caused significant challenges in identifying items that should be recurring to establish an order history. Recurring items were rapidly depleted because of long patient stays because of surgical interventions and intensive care requirements. The facility is only set up for 72-hour trauma care support. Afghan partnered forces remained in NATO Role 3 MMU the longest. Critical items required to treat a medical condition from a mass casualty event were often non-recurring items. Non-recurring items were the ones typically exhausted during extensive surgeries. When mass casualties occurred, it was often from an attack which then increased threat conditions for the base. Communication during high threat levels is challenging within a landlocked operational environment. Kandahar has one airfield that experiences limited inbound flights during high threat levels which delay receiving resupply shipments.

Characteristics of Operational Environments and Mass Casualties

The overall and embedded case illustrate the unique and challenging characteristics of medical logistics in a forward operating base experiencing mass casualty events. NATO Role 3 MMU located within USCENTCOM, is known as one of the most challenging COCOMs to resupply. The increased hostilities, inability to transport Afghan partnered forces to local hospitals, long patient stays, and erratic mass casualties with unpredictable demand, caused shortages of medical supplies. The ICU frequently experienced shortages of saline flushes, IV tubing, linen, crutches, and tube feeds and utilized expired Cordis kits. Shortages of critical items were compounded by each mass casualty event, which stressed the system. Table 5 provides some key assumptions of different environments the medical logistics supply chain process operates within and the ability to receive medical supplies.

Table 5. Key Assumptions of Different Environments Receiving Medical Supplies

Environment	Key Assumptions
Normal Logistics	-uncontested -all classes of supply operate the same -predictable -available capacity -seven "rights" of logistics
Medical Logistics	-rapid replenishment -Class VIII(a) mandated PV -shelf lives -CONUS/OCONUS supply operate the same
Medical Logistics Forward Operating Base	-less predictable -turn and burn -limited capacity -uncertain medical conditions -transportation
Mass Casualty at Forward Operating Base	-unpredictable -demand erratic -at capacity -prolonged patient care -uncertain number of patients

d. Space in the Facility

NATO Role 3 MMU was constrained by limited storage space. DMLSS catalogs had duplicate items, items that would never be used and inconsistencies from rotation to rotation in recurring ordered items and levels of inventory. Some items ordered incorrectly, cases instead of boxes, took up storage capacity within NATO Role 3 MMU MEDLOG. Unfortunately, MEDLOG was stocked with supplies that would never be used and carried too many of the wrong items and not enough of the right items. Rotations of medical professionals, unpredictable demand and uncertain medical conditions are challenges faced by the logisticians affecting ability to identify recurring orders to ensure they are added to the theater ASL and within TLAMMs.

2. Effects on Rights of Logistics

The following section takes the identified shortages of Class VIII(a) medical supplies and, critical events and focused on the major drivers of time, distance, mass casualties, and space. It also discusses why applying general medical logistics processes within the seven rights framework reveals gaps in the processes within operational environments (Swamidass, 2000). Only four rights from the "Rights of Logistics" framework were selected for use in this research (identified in Chapter II). As a result of the case analysis, three rights were identified as the most significant for an operational environment. Findings revealed problems with product, place, and time specific to the operational environments' unique characteristics and challenges. The three rights that were most problematic shape the subsequent sections: problems with product, problems with place, and problems with time.

a. Problems with Product

This section discusses problems with products identified within the embedded case. Shortages led to limited resources and improvised actions not practiced in civilian hospitals. For example, there was a shortage of IV tubing and secondary IV tubing for medical equipment pumps. The driver for problems with product was the influx of patients resulting in high burn rates of certain Class VIII(a) medical supplies. The consequence was extending the life of the item and reusing tubing that would not be done stateside. If this were practiced in stateside hospitals medical professionals would lose their license.

Medical equipment is a challenge and strains the delivery of patient care. Medical equipment was broken, required replacement, or needed repair parts. The glide scope in the ICU was old, outdated and recalled. Components needed to operate the scope were missing. The ICU and ER had a few of the components required and between the two units the parts could be compiled to create one good working glide scope, but it was not standardized. The ultrasound machines were past life expectancy and had to be kept plugged in or they would shut down. If the machine was not near a transformer (converter), patient care was more challenging. IV pumps were past life expectancy, and new pumps were acquisitioned. The pumps were delayed due to a software updates and contract modifications. When they arrived, the IV tubing within the DMLSS was not compatible and an NIR was required, delaying the use of the new pumps.

One issues with medical equipment was the need for transformers. Transformers are required to run all medical equipment delivering patient care. Medical equipment is procured through NMLC from United States manufacturing companies that require 140-watt voltage. NATO Role 3 MMU was built with European outlets at 240-watt voltage. All medical equipment to deliver patient care had to be plugged into a transformer that was plugged into the wall. Transformers only had two outlets compatible for United States voltage. Outlets were in short supply and could easily be all occupied on a single patient. The transformers were unsafe and would be turned off to prevent overheating. However, if the units did not keep the medical equipment plugged in, the equipment would shut off during patient care. The medical equipment and transformers required unscheduled preventive maintenance and experienced significant delays in receiving replacement parts.

b. Problems with Place

This section discusses problems with place identified within both cases which described the operating environment. The situations provide an understanding to why the operational environment must be viewed differently. Normal medical logistics practices are constrained within the operational environment. The operational environment causes anxiety, and supply shortages lead to more anxiety of the medical professionals, resulting in improvised actions and rationing supplies. Certain types of medical conditions can deplete resources rapidly due to patient demographics shaped by the increase in Afghan partnered relationships, unpredictable demand, and erratic mass casualties. The medical professionals interviewed stated that medical conditions arriving would not typically stay in a trauma care facility set up for only 72 hours of care. NATO Role 3 MMU did not just treat U.S. military and coalition forces. Poor quality of life outcomes was directly communicated with medical professionals, which influenced their willingness to transport to the local Kandahar hospital. All interventions done within the NATO Role 3 MMU for Afghan police, army, or CG patients would guarantee they stay longer than 72 hours.

c. Problems with Time

Problems with time were also identified within the embedded case. The extended time to receive supplies and the extended time patients stayed within NATO Role 3 MMU are just a few of the differences from a similarly classified civilian or stateside military treatment facility. There are long lead times affiliated with PV within the United States, which delays the arrival of resupply to operational environments. Base drills are meant to evaluate resources but having limited time to identify needed products presented challenges. It would take time not only to set reorder points of identified resources but time to deliver. An item can stock out within MEDLOG or nearest TLAMM while the ordered item is being shipped. Such long lead times required medical professionals in the operational environment to take actions, whether improvised or not. They were required to adapt and reuse medical supplies in ways not practiced by stateside hospitals. If an item is necessary to save a patient's life, measures beyond the typical scope of practice, whether improvised or reactionary, are taken. This is an understanding of medical professionals within operational environments. The problem with time is long lead times, intermediate stops, unpredictable demand, and prolonged patient stays.

D. CONCLUSION

Identification of both commonly used (see Appendix C) and rapidly depleted Class VIII(a) medical supplies is important to share with 3D printing experts for analysis regarding items with highest potential to 3D print. Medical supplies and 3D printing raw materials have specific characteristics that must be evaluated and shared with experts to determine if the critical items have potential to be 3D printed. The key shortage Class VIII(a) medical supplies were described as rapidly deleted. From those rapidly depleted items, six were identified in the embedded case by medical professionals as critical during mass casualty events. The key shortages during these critical events identified six Class VIII(a) medical supplies: syringes, IV tubing, central lines, cranial kits, suction valves, and canisters. The six critical items were shared with 3D printing experts to determine if these items have potential to be 3D printed. During interviews with 3D printing experts' specific characteristics to printing was provided. The data is analyzed in the next Chapter.

V. 3D PRINTING ANALYSIS AND FINDINGS

A. 3D PRINTING OF MEDICAL SUPPLIES

This chapter provides background on 3D printing in healthcare specific to medical devices and supplies and presents an analysis of recent developments in 3D printing with the primary goal of understanding the potential of 3D printing Class VIII(a) medical supplies and the benefit that it can provide for medical logistics in an operational environment. This chapter identifies specific 3D printing characteristics required to 3D print Class VIII(a) medical supplies in an operational environment as well as the characteristics of the supplies themselves. More importantly, this chapter identifies items with high potential for 3D printing among items that were found to be rapidly depleted during mass casualties. The analysis suggests that 3D printing could provide on-the-spot medical supplies for these items, which impacted the medical logistics supply chain in this different environment.

1. Background

3D printing involves building a "three-dimensional object using a computer-aided design" (Saptarshi & Zhou, 2019). Medical devices can be produced "using a range of media, including metals, plastics, hydrogels, or vein biological materials" (Manchanda, 2020). Medical companies have embraced 3D printing to create "personalized devices for patients or provider specific tools" (Kondor, S., Grant, G., Liacouras, P., Schmid J. R., Parsons M., Rastogi, V., Smith, L., Macy, B., Sabart, B., Macedonia, C., 2013). "3D printing has been around for decades", but there is still a need for research and testing of medical supplies and equipment not currently being investigated (Lipson, 2012). The nature of the raw materials melted and restructured into a plastic or metal object limits some medical supplies from being safe for patient care.

All medical supplies are "highly regulated by the U.S. Food and Drug Administration" because they encounter humans (Resnick et. al., p. 1, 2014). Medical supplies come in direct contact with patients making the nature of the structural integrity of specific items important to understand. Medical supplies have specific characteristics such as a plastic material that delivers medication. That material must be intact and must not introduce any other material into the patient.

Due to these two factors above, development of 3D printing medical supplies is a slow process. There are advances in 3D printing within healthcare already approved by the FDA which means with future research and development other medical supplies may have potential.

2. Relevant Research in 3D Printing

There is scholarly, military, and public health research on 3D printing medical supplies emerging. This research's primary question is focused on the potential of 3D printing to overcome challenges in medical logistics in operational environments. The following section describes three examples that illustrate the use or discussion of 3D printing of medical supplies and suggest potential for 3D printing Class VIII(a) consumable medical supplies.

a. Army, FDA Discuss 3D Printing at Workshop 6Jan2020

The Army, FDA workshop, held by the Army and Maine Corps Additive Manufacturing community, explored the possibilities and benefits to 3D printing repair parts (Defense Visual Information Distribution Service [DVIDS], 2020). This is relevant to the CNO's recent NAVADMIN 226/20 and demonstrates that the Army and Navy are committed to using, "3D printing to produce items ranging from repair parts to consumables" (CNO, 2020). The workshop communicated issues with receiving repair parts in operational environments. Workshop participants concluded that 3D printing medical repair parts on-the-spot, "could extend the life of medical equipment" and ensure it is functional for the next patient who arrives from a mass casualty event (DVIDS, 2020). This example emphasizes that it is important to consider future operating environments, such as a DMO, where readiness and preparedness are essential to save lives and suggests that 3D printing has the potential to provide solutions to some of the challenges faced within those environments.

b. Good Samaritans 3D Print Valves 16Mar2020

In December 2019, the world started to recognize the effects and influence of the COVID-19 virus as it migrated from China to Korea to Italy, and eventually to the United States, becoming a global pandemic in early 2020. During the pandemic, Italy's hospitals ran out of respirators. The innovation and quick response of manufacturers in Italy provided 3D printed respirator valves. FabLab 3D printed respirator valves to support Italy's hospitals in need (Toussaint, 2020). Michele Faini, 3D printing expert at Lonati SpA stated, "We were ready to print the valves in a couple of hours, and the day after we had 100 valves printed" (Toussaint, 2020). She further emphasized, "One 3D printer company in Italy has designed and printed 100 life-saving respirator valves in 24 hours for a hospital that had run out of them" (Toussaint, 2020). The valves "only took 3 hours to produce a prototype" (Toussaint, 2020).

This example demonstrates how 3D printing was able to cover shortages where the supply chain was short. The issues illuminated by the pandemic have strong parallels to a mass casualty events. A civilian hospital may experience a single event and it may be awhile until the next event, therefore a CONUS facility can resupply. In an operational environment hostilities and threats are uncertain, demand is unpredictable. These characteristics cause delays in resupply. During mass casualty events in operational environments, patients may keep coming, with unknown lengths of stay, depleting medical supplies. The supply chain and buffer stock may be similarly unable to keep up with unexpected, uncertain demands of pandemics and operational environments.

As this example illustrates, 3D technology has come a long way in a short period of time. It filled a sudden, urgent need caused by supply chain problems during the COVID-19 pandemic and may have similar benefits in operational environments.

c. U.S. Military Tests Prove it is Possible to Deploy 3D Printed Medical Aid in the Desert 4Oct2019

Dr. Vincent Ho is the principal investigator for the Fabrication in Austere Military Environments (FAME) initiative and chair of the Uniformed Services University (USU) of the Health Sciences Department of Radiology (Ho, 2019). Two academic universities explored 3D printing, "USU and the Military Academy West Point investigated the potential use of a 3D printer within an austere environment" (Jackson, 2019). As Jackson reported, "a pilot program was conducted using a specialty manufactured multi-tool 3D printer deployed to a desert environment" (Jackson, 2019). Within this pilot program the 3D printer was tested in Africa, where "the system was used to 3D print devices including antibiotic-laced bandages, a knee cartilage meniscus, and a scalpel" (Jackson, 2019). They took a specialty printer to an austere environment to print medical supplies.

> Dr. Ho stated in the report by Jackson in 2019, "We believe this program [FAME] has the potential to reduce logistical challenges and costs for transporting medical supplies to austere environments, which could also be applied to our special operations forces in remote locations," adds Dr. Ho. "Instead of carrying tons of supplies, they could just print them using a, hopefully, more portable, light-weight version in the future that could fit in their pack" (Jackson, 2019).

Medical professionals are deployed within austere and operational environments all around the world and medical logisticians face challenges, and it is difficult during hostile events to resupply. 3D printing has come a long way from the first industrial sized printers. 3D printers have become smaller, lighter, and more agile adding to the flexibility in their use to deploy with or to a medical unit. In the report Dr. Ho explained, "The antibiotic-laced bandages were created by 3D printing a hydrogel layer onto a structural layer. The process took just five minutes to complete and was designed to gradually elute antibiotics into a wound over several days" (Jackson, 2019). The pilot provides evidence that manufacturing Class VIII(a) in an operational environment can provide readily available surgical supplies to treat medical conditions.

d. Fabrication in Austere Military Environments (FAME) Initiative 10Jan2020

In January 2020, a proposal from BUMED M42 Expeditionary Medical Logistics department was drafted in support of a, "site visit leading the feasibility study in a specialty designed multi-purpose 3D printer sponsored by FAME program" (Guajardo, 2020). The site visit was to take place in April 2020, but due to COVID-19 it has been delayed. USU 4D Bio lab, "collaborated with external vendors to develop and test a multi-purpose 3D printer" (Interview 4). The multi-purpose printer, "was designed by USU 4D Bio lab and manufactured by NScrypts" (Interview 4). This specialty printer was used in the "pilot proof of concept research" conducted in Africa (Jackson, 2019). They used this specialty printer because it is light and easy to use in an austere environment which is relevant to my project.

Currently, there is a lack in demand for the printer possibly from lack of awareness of its existence. It is not being mass produced and is between prototype and final product. There are currently "three to four in existence" (Interview 4).

B. ASSESSMENT OF FINDINGS FROM 3D PRINTING EXPERTS

This section addresses the primary research question on the potential of 3D printing and its impact on the logistics of Class VIII(a) medical supplies. As discussed in the preceding chapter, the following Class VIII(a) medical supplies were rapidly depleted: syringes, IV tubing, central lines, cranial kits, suction valves and cannisters. This section describes the analysis of interviews with experts in 3D printing and identifies potential, limits and constraints to 3D print the six items in an operational environment.

a. Potential

My analysis of the interviews identifies three themes that suggest the potential for 3D printing in an operational environment. 3D printing provides durability making it ideal for operational environments. Small 3D printers require less material making them logistically desirable and ideal for maneuverability in operational environments. 3D printing is demonstrating feasibility of medical supplies through current research. The military test conducted in, "an austere desert environment in Africa shows potential for surgical instruments and tissue" (Jackson, 2019). As forward operating bases continue with expectations of a lesser logistics footprint, a small 3D printer, has a small footprint, demonstrating potential for on-the-spot printing.

3D printing is advancing in its durability, materials and use making them ideal for maneuverability in operational environments. USU 3D and 4D biofabrication, West Point, and WRNMMC are leading the way in 3D printing medical devices and supplies (Jackson, 2019). WRNMMC has approximately a dozen 3D printers, ranging from large industrial printers to small desktop sized printers. Within WRNMMC, "some FormLab 3D printers that print dental surgical instruments have the potential to print medical surgical instruments" (Interview 5). FormLab uses FDA approved software (FormLab, 2020). 3D printer types are capable of, "Using the software, in conjunction with a CT or MRI machine, and durable biocompatible plastic resin, an implant or prostheses can be printed" (Interview 5). The radiology department at WRNMMC, 3D Medical Applications Center, has supported NATO Role 3 MMU with 3D printed implants. One interview participant said:

> *We have sent 15 - 18 implants over to Afghanistan. The majority began after April 2017. The implants are 3D printed within the WRNNMC facility and sent directly to the requesting end user via APO mail. There is no other option to mail forward currently.* (Interview 5)

However, with the potential to 3D print implants, the production and reconstruction of implants are currently better served within WRNMMC. In the future the capability could be useful in operational or DMO environments that experience shipment delays. There are printer types, "constructing instruments and implants using a laptop equating to easy use, minimal software, and are light, small and maneuverable" (Kondor, et al., 2013). This was demonstrated in a field test conducted by WRNMMC.

3D printers are light and easy to use making them ideal for operational environments. A WRNMMC project with Defense Advanced Research Projects Agency (DARPA) was conducted with DARPA Fellows (Kondor, et al., 2013). A team conducted a rapid demonstration of 3D printing surgical instruments in a mock field hospital setting. WRNMMC conducted and, "set-up the demonstration that included a Fused Disposition Modeling (FDM) printer, a laptop, and a portable generator" (Kondor, et al., 2013). The demonstration showed, "that remote site fabrication of a variety of sterile instruments is possible" with the current technology. Relevant to this research, "The instruments were printed in 6 hours and single instruments range from 1 to 3 hours" (Kondor, et al., 2013). Sterility is important for surgical procedures, "High temperatures produce sterile parts, directly out of the printer" (Kondor, et al., 2013). The FDM printed, "a complete surgical kit that was used in a simulated laparotomy surgery" (Kondor, et al., 2013). A hemostat was also printed in the field, about which one interview participant said:

WRNNMC made hemostats but they were challenging. They printed a scalpel, but the printed models were only used during a simulated surgical procedure. There is the possibility to print cutting guides for surgeries like the dental guides that are currently being printed in WRNNMC. (Interview 5)

3D printing is exploring feasibility of medical supplies and equipment. As experts noted, "Surgical instruments can be printed with a biocompatible polymer" (Kondor, et. al.,2013). Experts in 3D printing are discovering new ways to "innovate surgical tools to even be surgeon specific providing dexterity" (Kondor, et. al., 2013). The field test is relevant to this research because the results were "that time to produce an item (i.e. cycle time) was only a few hours" (Kondor, et. al., 2013).

The military test in "an austere desert environment in Africa shows potential for surgical instruments and tissue" (Jackson, 2019). 4D Bio lab at USU successfully 3D printed a medial meniscus, hemostat, and scalpel handle (pictured in Figure 9). The tools can be sterilized and "there is the ability to print up to six hemostats" (Interview 4). The medial meniscus sample is dyed for visual purposes and is not an actual "live" production, but a demonstration of the capabilities that 4D and 3D printing have. On participant interviewed said, "4D Bio3 works mostly with cells rather than resins, however, the same printer type can be used for both cells and resins" (Interview 4).

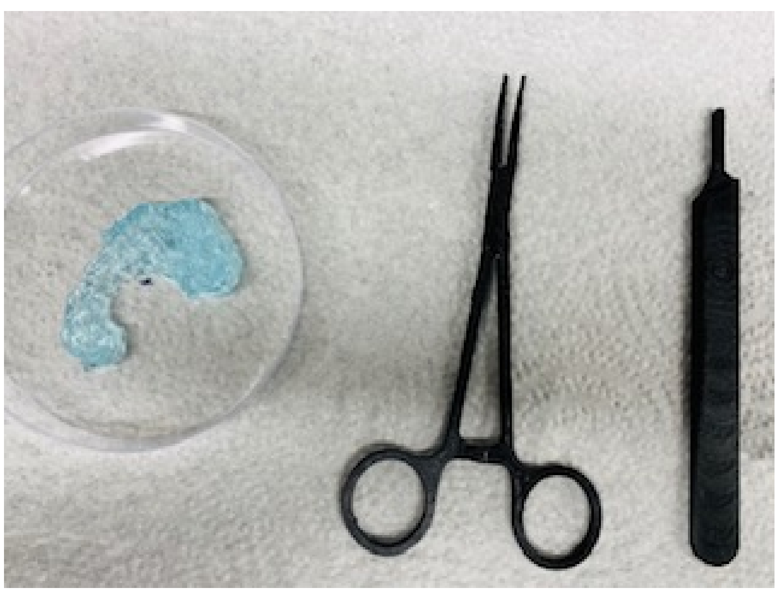

Figure 9. 3D Printed Prototype Surgical Tools and Meniscus Tissue

A small 3D printer has a small footprint and demonstrates potential for on-the-spot printing in an operational environment. For example, FDM printers are small, affordable, light, durable, easy to use, require little training, have a small footprint, and provide options to switch out materials (FormLab, 2020). If someone needs a small "widget," e.g., a repair part, to keep a machine running, this type of 3D printer is more versatile to switch out models. One interview participant said:

> *Maintenance for small printers is simple; remove printer bed and clean to make ready for the next object.* (Interview 4)

According to interviews with 3D printing experts, smaller printer types operate with fewer raw materials, making them the best logistical choice for an austere or operational environment. Small 3D printers available on the market have minimal requirements to operate efficiently. They require a design for the printer to print, a print mold or object, and very little material. A logistics officer or technician within NATO Role 3 MMU, or another Role 1, 2 or 3 level care facility or afloat, could upload a design and print. Designs can be reused. This is relevant to my projects primary research question because this identifies the affect 3D printing could have on medical logistics for an operational or DMO. One interview participant said:

> *3D printing can cut down logistical concerns in operational environments with on-site printing. Multi-purpose printers are currently being used and tested with USU. A multi-purpose 3D printer was sent to Africa, Djibouti. It weighed 200 pounds and could be powered by a jeep or solar panels. During the usage case a scalpel, hemostat, and bandage was printed and easy to produce. The 3D printer can be modified to fit the wound. This can be done with CT images for surgical conditions as well to fit a mold to reconstruct on implant.* (Interview 4)

FormLab manufacturers many printer types, "FDM is highest ranked for thermoplastics and manufacturers currently supply raw materials for standard printing to dental Class I and Class II(a)" supplies (FormLab, 2020). It is possible that these smaller printers used for dental applications could be used for medical such as scalpel handles. FormLab is taking part in advancing 3D printing in healthcare; as they note, "FormLab 3D prints models of bone structures and implants for mandibles and craniums" (FormLab, 2020). There is a range of materials, e.g., "3D printing healthcare materials has over 20 materials available on one powerful desktop 3D printer, the Form 3B" (FormLab, 2020). It is important to have FDA approved printers; "the technology has been validated in FDA-cleared workflows and FormLab develops and manufactures their own biocompatible materials in an ISO certified facility" (FormLab, 2020). For medical devices, four materials are used: clear resin, durable resin, tough 1500 resin and surgical guide resin (FormLab, 2020). Relevant research with the response to the current global COVID-19 pandemic helps by providing potential to print medical supplies during unpredictable demand. One interview participant said:

> *FormLab is printing nasal swabs for COVID-19 and can print 300 swabs in one day. The swabs are currently being used in New York and Florida.* (Interview 5)

According to a Journal of Medicine authored by Kondor & Grant (2013), "FDM print times are too long for real time, on demand printing of instruments during a surgical procedure". However, an FDM printer could replenish depleted medical or surgical supplies in a few hours to keep inventory rapidly depleted items readily available. Further research and development are required but the field study at WRNMMC and the USU field test are promising examples of the potential. Further Kondor & Grant stated, "The future could provide a catalog of medical or surgical supplies stored on digital media or remotely for printing in the field" (Kondor, et. al., 2013). Currently, the catalog is limited.

b. Potential of 3D Printing for Key Shortages

The previous analysis, in Chapter IV, identified a critical shortage of six class VIII(a) consumables medical supplies during the mass casualty events: syringes, IV tubing, central lines, cranial kits, suction valves, and canisters. This section begins by describing important characteristics of consumable medical supplies that influence their potential to be 3D printed. Then, this section assesses the potential of each of the items against the characteristics.

Analysis of the interviews identified five key characteristics that influence the potential of 3D printing the six items. Each of the six items matter to delivery trauma care and required to treat patients for long periods of time. Depending on the medical condition the patient may need a variety of items. Table 6 provides those five key characteristics.

Table 6. Key Characteristics to 3D Print Critical Items

Internal/External	"An implant is printed with materials sustainable within a patient, approved by the FDA." (Interview 5).
Material and Use	"It's not just being in the patient, it's the material of the object that matters." (Interview 4)
Watertight	Syringes or IV tubing…require being "watertight."
Flexibility	"Material/objects that are rigid (like scalpel handles) are easier to print than flexible materials (like IV tubing). From an engineering perspective, 3D printing flexible materials is not impossible but more difficult" and R&D required." (Interview 4)
Technology Requirements	"3D printing "watertight" objects requires specific printing technologies, which are bulky and take longer to print (not suitable for taking forward); therefore, they are not practical in operational environment." (Interview 5) "Some polymers can leach harmful compounds over time." (Interview 5) R&D has not been done to determine if this occurs with 3D printed plastics delivering liquids through IVs to patients' blood stream, but it likely will not be tested any time soon. "Printing implants on-site in operational environment would require a larger foot-print. Million-dollar printer to print implants, very costly. The printer, the power requirements. WRNMMC handles all DoD implant requests and is suitable to maintain all requests. Overhead and the materials alone would be expensive." (Interview 5)

These characteristics influence the potential for printing the six items. The following section assesses the potential of each item. Table 6 summarized the assessment.

(1) Syringes

Syringes are vital to administering medicine, blood, nutrition, and other fluids. In trauma care syringes are vital to gain access to internal blood streams through IV flushes and ensuring patency. Syringes are a critical item. As shown in the case analysis, when syringes are not available, medical professionals deviated from standard practice to treat patients. Syringes are used outside of the body and thus are not subject to regulation for internal use. The syringe does not have to be flexible. However, the seal must be watertight. Interviewees suggested that it may be possible to 3D print syringes, but there are some challenges. Syringes include a rubber stopper and there is currently there is no material to print rubber. One interview participant said:

> *Some biomaterials available could aid in printing the plastic of a syringe but there remains the concern about leaching. A syringe has a rubber stopper and SME's do not know any material that could print the rubber stopper.* (Interview 5)

Overall syringes exhibit moderate potential for 3D printing in an operational environment.

(2) IV Tubing

IV tubing provides the continued flow of fluids whether blood, normal saline, or medicine to keep patients alive during trauma and prolonged care. There is concern regarding the potential to 3D print IV tubing. One interview participant recommends is better currently being manufactured by companies because it is a thin plastic. Thin plastic materials holding a substance are a concern to 3D printing experts because there is no feasibility testing on the potential to leach 3D printed material into the solution. More biocompatible research is required to determine if the printed material will leach undesirable materials from the plastic, into the liquid, and thus into the patient. Specific characteristics are not compatible with 3D printing. Interview participants said:

> *IV tubing may not be feasible due to the construction of the plastic tubing being fine and thin. However, it is possible to print medical equipment replacement parts.* (Interview 4)

> *One must consider what is being printed. Consider that face shields printed by FormLabs for COVID are thin and take two hours to print. A thicker material will take longer; therefore, in a mass casualty it may not be a logical expectation that one can print an item rapidly.* (Interview 5)

Overall, IV tubing exhibits low (to none) potential for 3D printing in an operational environment.

(3) Implants

As mentioned previously, the production and reconstruction of implants are currently better served within WRNMMC. One interview participant said:

> *Printing implants on-site in operational environment would require a larger footprint. This would be a million-dollar printer to print implants, very costly. Overhead and the materials alone would be expensive plus the printer and power requirements. WRNMMC handles all DoD implant requests and is suitable to maintain all requests.* (Interview 5)

Overall implants exhibit high potential for 3D printing in an operational environment, however, they are currently better to be 3D printed within WRNMMC.

(4) Suction Canisters

Suction canisters, valves and surgical instruments are used during both trauma care and prolonged patient care.

> *Suction canisters could be printed; however, there would be concerns about water tightness. Some materials printed can absorb or leach materials. This is a complication with 3D printing IV tubing because of the thinness of the tubing, potential for leaching and the lumen within the tubing.* (Interview 5)

> *Suction canisters are possible but not yet tested and nasal cannulas using a dental long-term resin are possible but not tested. Any Class VIII(a) that goes into a patient and requires long-term patient care is not feasible yet but may be in the future. Class VIII(a) medical supplies such as syringes that do not stay with patient long-term and are disposable may be feasible. Needles are not possible because they require too fine of a metal, would not be smooth and are better manufactured in the traditional setting. Sponges and dressing will be challenging and are not likely due to the usage and material required. However, bandages are currently being tested in USU*

4D Bio Lab facilities that can provide a long-term antibiotic to treat infections. (Interview 5)

Overall suction canisters exhibit moderate potential for 3D printing in an operational environment.

Table 7 consists of the six critical Class VIII(a) medical supplies: syringes, IV tubing, central lines, cranial kits, suction valves and cannisters. It also includes representative, quotes from interviewees in both areas of expertise, and specific characteristics required for 3D printing those items. The table displays the potential and limitations due to characteristics in materials of the items and 3D printing capabilities, ranging from low to high, with illustrative quotations from the interviews above.

Table 7. Key Shortage Items Potential for 3D Printing

Key Shortage	Sample Quotes	Low	Moderate	High
Syringes	"Issues remained in receiving simple things like Chux pads, flushes. We had a patient with an abnormal heart rhythm and no flushes. I had to send a nurse to run and make flushes." (Interview 1)		"I think for syringes and suction valves, it may be possible to engineer '"3D printable" items that look significantly different from the traditional off the shelf versions, but still function the same, probably doable, but would require some extra engineering to get right." (Interview 4) "A syringe may be possible, but it also has a rubber stopper and SME's don't know any material that could print the rubber stopper. Some biomaterials available could aid in printing the plastic of a syringe but there	

			are concerns about leaching." (Interview 5) Potential: Not tested, R&D required	
IV Tubing	"Upon arrival there was a shortage of IV tubing and secondary IV tubing for pumps. The influx of patients burned through tubing." (Interview 2)	"IV tubing may not be feasible due to the construction of the plastic tubing being fine and thin." (Interview 5)" "Some materials printed can absorb or leach materials. This is a complication with 3D printing IV tubing because of the thinness of the tubing, potential for leaching and the lumen within the tubing." (Interview 5) Potential: Limited		
Cranial Kits	"NATO Role 3 MMU received several GSW's to the head over a 5-day period resulting in cranial kits, central lines, and craniotomy flaps depleted from MEDLOG." (Interview 1)	Potential: Limited; Not tested; R&D required		
Implants	"Printing implants on-site in operational environment would require a larger foot-print. Million-dollar printer to print implants, very costly. The printer, the power requirements. WRNMMC handles all DoD implant requests			There is high potential to 3D print implants as it is currently being done in WRNMMC. However, it would require a larger footprint and better served at its current location and process. Still it exhibits high potential.

	and is suitable to maintain all requests. Overhead and the materials alone would be expensive.” (Interview 5)			
Suction Valves	“We were taking care of a patient who required more time and intensive care than what our purpose was geared toward. This caused us to go through our supply of suction valves incredibly quickly after we placed a tracheostomy.” (Interview 2)		“I think for syringes and suction valves, it may be possible to engineer ‘"3D printable"’ items that look significantly different from the traditional off the shelf versions, but still function the same, probably doable, but would require some extra engineering to get right.” (Interview 4) Potential: Not tested; R&D required	Respirator valves were 3D printing during COVID-19 so potential for suction valves has moderate to high potential.
Suction Canister			“Suction canister could be printed; however, there would be concerns about water tightness.” (Interview 5)	

c. Potential for Other Medical Supplies

One interview participant mentioned the antibiotic bandage, although not identified by the medical professionals interviewed, has potential to be 3D printed in an operational environment. During interviews with 3D printing experts, one provided potential for medical supplies not originally considered at the start of this study, the focus was on Class VIII(a) medical supplies rapidly depleted during a deployment. Two of the 3D printing experts interviewed were involved in the field test conducted in Africa. Dr. Ho’s proof of concept provides evidence that manufacturing Class VIII(a) medical supplies in an operational environment offers readily available surgical supplies to treat medical conditions arriving during mass casualties in an operational environment with unpredictable demand. In the field test they were able to print an antibiotic bandage. Dr. Ho stated (2019) during the military test, “The antibiotic-laced bandages were created by 3D printing a hydrogel layer onto a structural layer. The process took just five minutes to complete and was designed to gradually elute antibiotics into a wound over several days” (Jackson, 2019). Additionally, one interview participant said:

> *Bioprinting the bandage is a two-part process, requiring both fused filament printing (for the solid base) and extrusion printing (for the bioactive, hydrogel portion). The USU research teams are looking at leaching antibiotics and antifungals from the bandage. The leaching time of the compounds within the bandage allows the bandage to administer antibiotics over days to weeks.* (Interview 4)

The capability to print this bandage within an operational environment could mean life or death to a warfighter at the point of injury to next level care facilities. The leaching time is days to weeks, which can be critical to survivability in prolonged field care, the “golden hour” before the patients arrives at the nearest trauma medical care unit. This is vital in combat field care and more vital in a DMO environment. In an operational environment when networks and communications are down there may be delays in transporting a patient from a Role 2 to higher level of care. Bandages could be critical in the golden hour between when the patient leaves the point of injury and arrives at a facility like NATO Role 3 MMU. This is relevant to a DMO environment where similar issues are projected in the future operating environment and during a fleet to fleet combat situation there is limited capabilities to resupply or transport injured off ship. The bandages would increase survivability during the golden hour by leaching bioactive compounds, such as antibiotics and anti-inflammatory medications induced into the patient at point of injury.

The bandage was been printed by the military in the Africa field test but has not been used clinically (Jackson, 2019). The type of printer used for the bandages has the potential to be placed within NATO Role 3 MMU or Djibouti MTF in Africa because “It is light weight (150 pounds) and operates on vehicle power or lithium ion batteries. It is easily moved to a forward deployed operational environment. Universal supplies of raw materials required to print objects are also light weight and can be stored until needed” (Interview 4). This 3D printer type ensures “the right product, in the right quantity, at the right time, in the right place” (Swamidass, 2000). The bandage can also act as a splint once hardened, allowing it to support across a joint and preventing further injury. There is also the capability of using CT images of a wound and forming the bandage to fit the wound.

Critical Event 3 (see Table 3) had a patient with a contagious infection requiring PPE and isolation protocols. This meant that every time a medical professional had to take vitals, change dressings, or administer medication they had to wear PPE, dispose of it after and wear new PPE upon every patient visit. This rapidly depleted PPE available in the operational environment. Class VIII(a) medical supplies such as PPE have been 3D printed during the current COVID-19 pandemic and have high potential to be printed in an operational environment. South Korea 3D printed face shields in response to supply shortages. However, the catalog of Class VIII(a) medical supplies to 3D print is limited at this time.

In a DMO environment units will, "experience losses in network capabilities and connectivity" (JHU/APL, 2019). Therefore, normally reliable network systems for reordering will not be as reliable. The use of online ordering tools (including Defense Medical Logistics Standard Support (DMLSS) and Theater Enterprise Wide Logistics System (TEWLS), would be negatively impacted by these future operating environments and hinder the ability of medical logisticians to replenish Class VIII(a), BIOMED equipment, and surgical supplies (JHU/APL, 2019). 3D printing has the potential to positively affect medical logistics operations for operational and DMO environments.

d. Limitations and Constraints

Analysis of the interviews identified the size of the printer, safety concerns (explosion from materials), and the types of materials required limit the potential to 3D print in an operational environment. Limitations and constraints are presented in this section from interviews with 3D printing experts. Some machines require heating small particles and run the risk of explosions due to the particle size. These machines are typically for metal 3D printing and are best for stable environments. Even some smaller printers require heat treatments; therefore, it is important to consider the type and size.

Larger capacity printers are not suitable for operational environments. WRNNMC is using many types of 3D printers large and small. Larger capacity printers cost anywhere from $500,000 to $1,000,000. They require extensive training and operations expertise, design knowledge, and a service contract. There are constraints and limitations to larger capacity printers for an operational environment. The large footprint and challenge of vetting the service contractor to arrive in theater will be difficult if not impossible. The large footprint in WRNNMC takes up two rooms within the facility and is not a feasible option for an operational environment. There is also the requirement of 480-volt power supply.

Printing metal in an operational environment may be challenging because those printer types have a larger throughput but in turn have a large footprint and may not be ideal for operational environments. As one interview participant said:

> *Metal printing is not easy. Auxiliary equipment is required, and titanium would be a safety issue. A metal printer is more complicated except for maybe the RCAM A-1.* (Interview 4)

During the interviews other limitations and constrains were mentioned. Two interview participants said:

> *The best utilization of 3D printing for medical supplies is a custom based printer such as the ones mentioned with larger capacity, costly and not feasible for operational environments.* (Interview 5)

> *3D printing involves fabricating objects from raw materials from base materials. To 3D print plastic or metal, raw materials are required. It is challenging to print metal and plastic on one printer. However, plastics are easier to print. Metal items such as crutches (assistive devices) can be 3D printed in phases but would require metal resin and a large capacity printer. Depending on the type of printer there may be a requirement for 2,000 pounds of raw materials to the location requesting materials. It would impact the way medical logistics is currently operating which would require by-in from the military services to eliminate constraints on logistical impact and concerns.* (Interview 4)

> *The standard universal supply of raw materials available are light weight and can be stored until needed, however there are limitations on what kind of raw materials are used and available within operational environments.* (Interview 4)

Some plastics will be challenging because there is not enough research and testing done currently regarding whether the 3D printed plastic object is watertight. If the 3D printed material holds a liquid, there is concern with delivering the liquid through a plastic object directly to a patient. There may be leaching from the plastic materials into the liquid, however, at this time, no feasibility testing has been conducted. It is likely that feasibility testing will not occur without FDA approval and evidence that the material demonstrates watertight integrity before it will be used in patient care.

C. CONCLUSION

This research found that while 3D printing can do many things, some things are logistically better served by manufacturers in bulk, such as IV tubing. Not a lot of Class VIII(a) medical supplies have been researched or tested using a 3D printer at this time, but some medical supplies are being tested in studies and field cases. While this study focused on two specific cases with shortages of Class VIII(a) relevant to that deployment, the analysis and findings have provided additional medical supplies that have the potential to be 3D printed in operational environments. More testing in the field should be done in the future to discover the benefits and potential of Class VIII(a) medical supplies rapidly depleted during mass casualties, but not enough data is currently available on those specific Class VIII(a) medical supplies. The analysis and findings from both cases did identify medical equipment repair parts with significant problems in receiving them due to backorder.

Specific drivers such as time and distance contribute to environmental uncertainty. Relationships with suppliers is challenging in operational environments because operational environments are constrained by remote locations, often landlocked, and anticipated to be protracted. Yet military troops have been boots on ground in Afghanistan for 2 decades. This prolonged war time with uncertain hostilities against the United States and its allied partners makes the operational environment more susceptible to unpredictable demand.

Time and faster delivery from supplier to end user requires proximity, which is not a reality for operational environments. Operational environments have two key characteristics: unpredictable demand and uncertainty. Uncertainty requires greater flexibility which a light weight 150-pound multi-purpose 3D printer provides.

An effective 3D printer within an operational environment would be a small plastic printer, such as a FormLab printer, that can do multiple small items including repair parts and non-critical parts. Generally, the materials for small printers are stable and could be successful in Kandahar. There is also the added benefit of little concern in the personnel running it and the maintenance requirements. There is little training and operation skills required in advance. A more effective printer would be the multi-purpose 3D printer from NScrypts, the nRugged, but demand and buy-in from military services is currently lacking.

This research also discovered items, while not mentioned as a shortage, tested in the field that could provide logistical supply support between regular or irregular deliveries during unpredictable demand. The most value of 3D printing on-site comes from the time an ordered Class VIII(a) consumable item is in transit from PV to OCONUS especially within an operational environment. This is also relevant to a DMO environment where fleets are far removed from logistical shore-based hubs where resupply is warehoused.

Getting necessary supplies to medical professionals forward deployed to an operational environment in time to save lives is challenging. Technology has unlocked new process improvement strategies for logistics supply with advances in 3D printing. In an operational or DMO environment where prolonged field care is likely, 3D printing Class VIII(a) consumables medical supplies in operational environments is a value-added contribution for future operating environments and medical units deployed within the operational environment providing trauma medical care to the warfighters.

VI. RECOMMENDATIONS AND CONCLUSION

This research sought to identify logistics problems in operational environments and explore causes for shortages, challenges in resupply, and the potential benefits of 3D printing in addressing these medical logistics issues in an operational environment. Throughout the research and analysis, it was important to clearly state the difference in Class VIII(a) consumables from other classes of supply to understand the unique challenges medical logistics faces. The analysis of cases included in this research revealed how a shortage of Class VIII(a) medical supplies can affect a Role 3 facility during a mass casualty event, as well as the events and conditions that cause shortages and their associated consequences.

Motivated by shortages experienced during mass casualty events in an operational environment, this study investigated the potential impacts of 3D printing on the logistics of Class VIII(a) consumable medical supplies. This research demonstrates the potential positive effect of 3D printing on medical logistics for operational environments such as DMO. Certain Class VIII(a) supplies identified as critical shortages during mass casualties are better served by manufacturers and maintained as recurring ordered items in bulk with significant buffers. Other Class VIII(a) medical supplies and equipment parts such as bandages have characteristics that indicate high potential to 3D print in austere operational environments. The ability to readily access these Class VIII(a) consumables prepositioned within an operational or projected DMO environment provides forward logistics to support patient care downrange. On the spot 3D printing, therefore, can improve medical logistics processes for operational environments otherwise challenged by time and distance from TLAMMs and PV.

My goal was to discover whether the Class VIII(a) medical supplies identified as rapidly depleted -- syringes, IV tubing, cranial kits, suction valves and cannisters, and IV flushes -- had the potential to be 3D printed in an operational environment.

Treating all medical logistics environments the same is not rational. Unpredictable demand, limited storage capacity, uncertainty, operational tempo, and distance from shore-based logistics hubs make operational and future operating environments different from current state medical logistics. Understanding and planning for these differences better ensures availability of resources and medical unit readiness. The importance of a versatile Class VIII(a) medical supply system is a multiplier to contingent operations. Current and future operating environments are remote, with mass casualties imminent and medical units vulnerable to shortages. The potential benefits of 3D printing better equip medical units to manage unpredictable environments.

A. CONCLUSION

1. Research Findings

My primary research question was:

- Does 3D printing have the potential to positively affect medical logistics operations for distributed maritime operations (DMO) environments?

The answer is yes. The follow-on research question and a secondary research question were:

- If so, which Class VIII(a) consumables show high potential?

What does recent research suggest about the potential of 3D printing for Class VIII(a) consumable items?

The catalog of Class VIII(a) consumable medical supplies researched and tested using a 3D printer is currently limited. However, recent research and field-testing in simulated trials show the potential of a few supplies to be printed and used within operational environments.

The current, global COVID-19 pandemic shocked supply chains with sudden, unorthodox demand for PPE, increasing needs and shortages. 3D printing provided valves and PPE within a matter of days. The Navy led the DoD 3D response urgently printing PPE, face shields, and swabs during COVID demonstrating the viability of 3D printing medical supplies (NIH, 2020). In the context of this study, 3D printing has the potential to print medical devices, prosthetics, surgical scalpels, guides, hemostats, and antibiotics bandages (doubling as a splint) on the spot, reducing shortages caused by sudden mass casualties or the time and distance of supply chains. Bandages with bioactive compounds increase survivability during the golden hour. They are vital in combat field casualty care and even more vital in a DMO environment when prolonged field care is anticipated, and communication outages may cause delays in transporting the patient between echelons of care. A standard bandage can be printed in a matter of minutes, and larger bandages in 10 minutes. The cost and training involved is minimal, and the supplies required to operate the printer are distributed in bulk to the end user.

A small multi-purpose 3D printer has the greatest potential. It is light and easy to use and could deploy medical unit to improve outcomes during the golden hour. Ready access to an antibiotic bandage in the field at a Role 1 or 2 would deliver medication during transit prior to surgery. This improves patient outcomes, increases survivability, and has potential for sooner transport to either a local Afghan hospital or higher echelon of care. Saving time between resupply ensures the right product in the right quantity at the right time in right place prior to the next mass casualty. A 3D printer available in an operational environment has the potential to save resources and lives.

This research illustrates the strong potential for medical supplies such as antibiotic bandages and, with some further research, medical equipment repair parts. Currently, there is not enough research or testing to evaluate the potential for medical equipment repair parts, according to a 3D printing expert interviewed.

A collaborative effort among services in 3D printing would allow for an advanced form of standardization and support joint future operating or DMO environments.

My secondary research questions were as follows:

- How does the resupply process for Class VIII(a) consumables differ from the processes for other classes of materials?

The supply process for Class VIII(a) consumable medical supplies is different from the supply process for other classes because medical supplies must use Prime Vendor, Cardinal Health and ECAT suppliers, located in the U.S.

- How does a shortage of Class VIII(a) medical supplies affect an MMU during a mass casualty event?

NATO Role 3 MMU is not set up to provide longer than 72 hours. Unpredictable demand requires flexibility to deal with uncertainty. The unpredictable nature of operational environment demand characteristics requires the supply chain employ innovative means to ensure Class VIII(a) medical supplies are readily available. For example, a 4D biofabrication printing expert said:

"3D printing provides the ability to produce tailored healthcare solutions that meet the specific needs of the warfighter deployed to austere locations. The ability to build health-related products in near real time when and where needed also enhances operational flexibility for our commanders in the field" (Jackson, 2019).

Unpredictable demand makes identification of Class VIII(a) recurring items and non-recurring items challenging for logisticians within operational environments. When a non-recurring item is required during a single event it may not be required again for long periods. The medical conditions and patient influx from each mass casualty event vary widely. Figure 10 is a patient, an ANP officer, likely to remain at NATO Role 3 MMU for weeks, or months.

Figure 10. Surgeon Setting Pins on Afghan National Police Patient. Source: Navy Medical Service Corps Newsletter, The Rudder (2020 June-July), p. 7.

2. Recommendations

My findings suggest several recommendations. Although currently the Class VIII(a) medical supplies 3D printing catalog is limited, potential analyzed in Chapter V provides recommendations listed:

Recommendation 1: Place a small printer, such as a multi-purpose printer or an FDM printer within NATO Role 3 MMU. Other medical units, such as Fleet Surgical Teams, Role 1 and 2 or USNS Mercy, deployed to austere operational environments would benefit from a lightweight multi-purpose 3D printer.

Medical units deployed to austere operational environments would benefit from a lightweight multi-purpose 3D printer that prints antibiotics bandages on the spot, providing two critical trauma care needs during the golden hour (the time from point of injury to surgery). The bandages deliver antibiotics and act as a splint. Bandages with bioactive compounds increase survivability during the golden hour. They are vital in combat field casualty care and even more vital in a DMO environment when prolonged field care is anticipated, and communication outages may cause delays in transporting the patient between echelons of care. A standard bandage can be printed in a matter of a few minutes, and larger bandages in 10 minutes. The cost and training involved is minimal, and the supplies required to operate the printer are distributed in bulk to the end user.

Supporting Arguments: Small printers have printed several medical supplies: scalpel handles, hemostats, implants, surgical guides, and antibiotic bandages. Small printers use little raw materials to operate, require little maintenance and are affordable. A 3D printer on site could not print assistive devices due to raw material and capacity requirements. However, one application for use is that 3D printing could print medical equipment parts. NATO Role 3 MMU could print when required. There is potential for some Class VIII(a) consumable medical supplies. A small multi-purpose 3D printer could print several medical supplies: scalpel handles, hemostats, suction valves or cannisters, and antibiotic bandages. With more research, testing, and buy-in from manufacturers, these printers have the potential to also print medical equipment repair parts on site when backordered or delayed. This is an area for future research. Buy-in from the military services to eliminate constraints on logistical impact and concerns.

Recommendation 2: Communication between 3D printing researchers and deployed medical professionals would be a value-added contribution to both fields for future research in advances in 3D printing. Interviews identified other medical supplies that, although considered bulk items to be stocked readily available, are often first depleted.

Supporting Arguments: Communication with medical professionals deployed to 3D printing experts providing identified Class VIII(a) medical supplies and medical equipment repair parts could start future research and testing on items that are rapidly depleted or strain the unit within the operational environment. This would be a value-added contribution to both fields and the research and development of new advances in 3D printing. Medical logisticians inventory Class VIII(a) medical supplies and equipment within operational environments and that information can be shared with 3D printing experts.

Recommendation 3: Place medical logisticians within research and testing 3D printing sites to provide value-added contributions on medical equipment repair parts and medical supplies to print.

Supporting Arguments: This opportunity will insert a logistician directly into the manufacturing process as well as understand the planning and coordination for implementation of 3D printers throughout the Navy. Medical logistics must be considered separate from overall logistics needs in an operational environment. As governing directives note, “Specific medical logistics/resupply needs must be incorporated into the overall logistics resupply within operational environments” (JHU/APL, 2019).

Recommendation 4: A 3D printer prepositioned forward at TLAMMs would print Class VIII(a) consumable medical supplies to aid in uncertainty and bridge the gap in resupply of PV or ECAT items.

Supporting Arguments: Prepositioned forward medical supplies is challenging with varying shelf lives, unpredictable demand, and uncertainty. Class VIII(a) consumable medical supplies printed in operational environments saves time the item spends in transit when a mass casualty occurs. 3D printer prepositioned forward at TLAMMs can print some medical supplies, surgical tools, and medical equipment repair parts to aid in that uncertainty. Buy-in across all military services to implement a 3D printer within one or more of the intermediate distribution centers, whether TLAMM Europe or Qatar.

Recommendation 5: Extend of the length of time NATO Role 3 MMU is set up to care for patients beyond the 72-hour window or renegotiate a memorandum of agreement (MOA) with Afghanistan local hospital to take patients within 72 hours. Prior to 2018 NATO Role 3 MMU medical personnel could train local Afghan providers. That was not in place during 2018 -2019 deployment. Patient medical conditions require prolonged care and intensive care which NATO Role 3 MMU is not set up to provide longer than 72 hours. The logistical framework currently in place must be adjusted to adapt to the mission change occurring in Kandahar that ultimately effects NATO Role 3 MMU, it is deployed personnel and supplies. If the facility itself is not set up for longer than 72 hours leadership cannot expect patients to stay within its walls for over 72 hours. This expectation contradicts the supplies on hand and the medical logistics supply chain.

Recommendation 6: Training on DMLSS prior to deployment would be invaluable to ensure the inbound supply representative can understand and learn the system in advance, instead of on the spot the day they land in theater. It is important that a supply representative is not chosen at random. Supply representatives should be trained on DMLSS prior to arrival, and ideally have experience working with DMLSS, rather than learn and train upon arrival in theater.

Though not the primary goal or purpose of this research, COVID 19 response and innovations in 3D printing have brought the need for rapidly depleted medical supplies such as PPE to the forefront of discussion. This is relevant because currently, the Navy is printing PPE, surgical masks, and swaps to support the logistical gaps within the supply chain. This demonstrates the potential for other medical supplies. The cases findings shared with 3D printing experts revealed that 3D printing has the potential to positively affect medical logistics operations for an operational and DMO environment. The focus should not be on the cost of the potential solutions, but on the cost of the lives without the solutions in place.

NATO Role 3 MMU provides trauma medical care to partnered forces injured during combat. During my nine-month deployment we received a draw down message.

However, several rotations have been deployed to Afghanistan to support NATO Role 3 MMU. Even during a draw down NATO Role 3 MMU will be expected to support and deliver trauma medical care to injured partnered and allied forces. Operational environments with unpredictable demand and uncertainty require a robust resource mix to continue to provide the best care anywhere and save lives.

3D printing provides a way to make what medical units need when they need it support a flexible ready force in a remote location. This would improve timeliness of patient care and enable medical professionals to devote their attention to patients instead of hunting down supplies.

Buffers help for the bulk items commonly used and are more cost effective. However, when operational environments remain unpredictable, 3D printing Class VIII(a) consumable medical supplies or equipment parts will improve capabilities and ensure access to the "right product in the right quantity at the right time" (Swamidass, 2020).

Summary

3D printing has potential to add flexibility and speed in environments experiencing unpredictable demand. 3D printing provides rotational medical units the flexibility to fabricate according to size and demographics of the patient or surgeon and to print objects or widgets, surgical instruments, and some Class VIII(a) medical supplies. 3D printing has the potential to minimize deliveries of some Class VIII(a) medical supplies because raw materials ship in bulk. 3D printing in operational environments provide a sterile, unexpired Class VIII(a) consumable medical supple on-the-spot.

B. AREAS FOR FUTURE RESEARCH

Future research is required because implementing 3D printing of medical supplies in a contested environment is not as simple as stating, "Put a 3D printer in Kandahar." There will be raw materials to implement into the supply chain process that may add to the cost. However, is the cost of supplies equivalent to the cost of saving lives of the warfighters? 3D printing has the potential to improve not only medical logistics but shortages of other Class VIII(a) medical supplies that may be experienced in an operational or DMO environment. Quick access to any high potential 3D printable Class VIII(a) consumables medical supply or equipment can ensure continued quality of care.

There is future research to be done on Class VIII(a) medical supplies rapidly depleted during mass casualties that will benefit medical units in operational environments. There is so much more to be learned and gained from 3D and 4D printing. With evidence of tissue 4D printed there is potential to replicate tissue for a warfighter injured. Further, there is much to be learned and gained from the multi-purpose 3D printer, referred to as nRugged, but not enough on the market or demand to identify a cost benefit analysis at this time; this gap offers future research opportunities.

Equipping forward medical units with small light-weight printers enables the operator to print supplies in the moment (Ho, 2019). Maritime superiority and future operating environments depend on logistical resources to be available in diverse and unique environments, whether DMO or multiple domain operations. 3D printing ensures that NATO Role 3 MMU, and Role 1, 2, or 3 level of care in deployed environments, will have access to Class VIII(a) consumables on-site, readily available. 3D printing has the potential to be implemented into other medical units afloat, including the USNS Mercy or Fleet Surgical Teams. Smaller printers will take up little footprint afloat on an aircraft carrier and have the potential to eliminate large inventory stores. Smaller printers will take little footprint for Fleet Surgical Teams that carry 300 pounds of gear and must prioritize an effective and efficient resource mix to deliver patient care in the field. 3D printing provides opportunities to improve the medical logistics supply chain for deployed medical units in operational or DMO environments.

An area for future research would be to investigate 3D printing medical equipment repair parts. Currently, there is nothing related to medical equipment repair parts in research and development. There is potential for 3D printing medical equipment repair parts. The CNO announced that maintenance and repair parts are available but not specific to medical equipment repair parts. Identified within both cases are the need for medical equipment repair parts. Unfortunately, while the Army and Marine Corps 3D printing communities are already making cell phones, weapons and ammunition, there is no program currently supporting medical equipment repair parts. Probably because manufacturers of medical equipment are contracted within DoD and repair parts are shipped. In an operational environment it is difficult to receive repair parts for medical equipment, identified in the cases, due to delays, backorders, time, distance, and the environment. 3D printing medical equipment repair parts is a value-added contribution to deployed medical units. Buy-in from medical equipment manufacturers that currently supply medical equipment to DoD will be required. If manufacturer by-in is successful, Biomedical Technicians Navy-wide could be surveyed to identify common parts needed to be replaced while in operational environments to provide a list of parts to be researched by 3D printing experts. This would be a great area for on demand 3D printing to expand into. 3D printing experts currently trying to expound upon this endeavor are hitting roadblocks from manufacturers of medical equipment. Having the capability, with manufacturer buy-in, to 3D print medical equipment repair parts on demand in operational environments would be value added during backorders and delays. 3D printing and raw materials may not be a cost-effective solution, but it may be a lifesaving during Class VIII(a) consumable medical supplies and medical equipment shortages and delays in repair parts. With more research, testing, and manufacturer by-in, these printers have the potential to also print medical equipment repair parts on site when backordered or delayed.

APPENDIX A: 3D PRINTING REPORTS

Articles	Document Type
Ho, V. B. (2019). Fabrication in Austere Military Environments (FAME): A translational research and education initiative advancing war fighter readiness. Uniformed Services University of the Health Sciences [Memorandum].	Memorandum
Jackson, B. (2019). U.S. Military Tests Prove it is possible to Deploy 3D Printed Medical Aid in the Desert. 3D Printing Industry. https://3dprintingindustry.com/news/u-s-military-tests-prove-it-is-possible-to-deploy-3d-printed-medical-aid-in-the-desert-162802	Article
Uniformed Services University. (n.d.). 4D Bio 4-Defense Biotechnology, Biomanufacturing and Bioprinting. 4D Bio Overview.pdf [Brochure].	Brochure
Guajardo, D. (2020). 3D Printing Capabilities Proof of Concept in Norway. Memorandum for the Record. Naval Document [Memorandum].	Memorandum
Uniformed Services University. (2019). 4-dimensional bioprinting, biofabrication, and biomanufacturing program. Walter Reed National Military Medical Center. https://www.usuhs.edu/4dbio3	Website
Defense Visual Information Distribution Service. (2020, January 6). Army, FDA discuss 3D printing at workshop. https://www.dvidshub.net/news/358256/army-fda-discuss-3d-printing-workshop.	Broadcast (Media), Article
Toussaint, K. (2020, March 16). These Good Samaritans with a 3D printer are saving lives by making new respirator valves for free https://www.fastcompany.com/90477940/these-good-samaritans-with-a-3d-printer-are-saving-lives-by-making-new-respirator-valves-for-free?partner=rss&utm_source=facebook.com&utm_medium=social&utm_campaign=rss+fastcompany	Article
Kleinman, Z. (2010, March 16). Coronavirus: 3D printers save hospital with valves https://www.bbc.com/news/technology-51911070	Article
Feldman, A. (2020, March 25). Inside s Silicon Valley Unicorn's Urgent Dash To 3D-print Face Shields and Test Swabs to battle COVID-19. Forbes. https://apple.news/AiE6Qsf_FT8ORkO6c4TtHNQ	Article
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APPENDIX B: CONCEPTS, THEMES, AND IMPLICATIONS

Sample quotation	First order concept	Problem theme	3D printing implication
"Medical units must expect the unexpected. Mass casualties and sleep deprivation are accompanied by rocket attacks, communication outages, water outages, and undesirable weather. Fatigue, supply shortages and language barriers make the operational environment unique."	• Shared experience • Informative	• Operational environment • Constrained logistics	
"It is a high-level stress environment with different expectations and limited options. There is a job to do - saves lives."	• Shared experience • Informative	• Operational environment • Constrained logistics	
"Upon arrival there was a shortage of IV tubing and secondary IV tubing for pumps. The influx of patients burned through tubing."	• Shared experience • Informative • Surprise • Lack of DMLSS training • Medical supplies	• Operational environment • Constrained logistics • Short rotations of personnel	
Upon arrival everything supply wise was low, but supply representatives responded quickly. Catalogs were scrubbed, organized and projections of requirements were done to the best of their ability. However, issues remained in receiving simple things like Chux pads, flushes, individually wrapped gauze, blood pressure cuffs, leg pumps (patients with leg amputations wouldn't have required but if a patient did the care would have suffered), basic hygiene kits, oral care kits, trach kits (NATO Role 3 MMU didn't anticipate the need because patients are trached in the field but field medical units ran out). Prolonged care required hygiene and dental care kits, but supplies were limited. The NATO Role 3 MMU had supplies that were not required such as wound dressings suitable for a Role I or II level care. There was a lot of what was not required and less of what was. There was too much of what would never be used and not enough time to get what was required."	• Shared experience • Informative • Surprise • Lack of DMLSS training • Medical supplies	• Operational environment • Constrained logistics • Short rotations of personnel • DMLSS training • Problem with stuff • Problem with product • Problem with quantity	
"The highest burn rates for Class VIII(a) medical supplies and equipment were in the ICU due to mission creep that impacted patient length of stay."	• Shared experience • Informative • Observation • Medical supplies • Patient influx	• Operational environment • Constrained logistics • Prolonged patient stays • Problem with Afghan hospital	Characteristics of rapidly depleted Class VIII(a) medical supplies determine the viability of near-term 3D printing. Scalpels, hemostats, implants, and surgical guides have been tested in the field during simulated surgeries.

"NATO Role 3 MMU received several GSW's to the head over a five-day period resulting in cranial kits, central lines, and craniotomy flaps depleted from MEDLOG."	• Observation • Subject Matter Experts • Informative • Medical supplies • Patient influx	• Operational environment • Constrained logistics • Uncertain medical conditions • Problem with stuff • Problem with product • Problem with quantity	Research is required for suction cannisters, suction valves, syringes, and cranial kits.
"A 3D printer on site that could print assistive devices would be valuable because the needs of the individual are unique. For example, a platformed walker for weight bearing restrictions on the upper extremity. Another application for 3D printing could be medical equipment parts. For example, if a ventilator failed. The manufacture is based CONUS and it will take six months to arrive at NATO Role 3 MMU. If 3D printer were on-site, NATO Role 3 MMU could print when required saving time and distance constraints. Being able to fabricate as needed would help with storage and supplies on hand."	• Shared experience • Observation • Equipment	• Equipment issues • Replacement parts delayed • Time and distance from PV	An on-site 3D printer could not produce assistive devices due to raw material and capacity requirements. A 3D printer could produce medical equipment parts. A small multi-purpose 3D printer could produce scalpel handles, hemostats, suction valves or cannisters, and antibiotic bandages.
"3D printing involves fabricating objects from raw materials from base materials. To 3D print plastic or metal, raw materials are required. It is challenging to print metal and plastic on one printer. However, plastics are easier to print. Metal items such as crutches (assistive devices) can be 3D printed in phases but would require metal resin and a large capacity printer. Depending on the type of printer there may be a requirement for 2,000 pounds of raw materials to the location requesting materials. It would impact the way medical logistics is currently operating which would require by-in from the military services to eliminate constraints on logistical impact and concerns."	• Informative • Subject matter experts • Innovation	• 3D printing capacity • 3D printing type • 3D printing capabilities	Buy-in from the military services is required.
"3D printing can cut down logistical concerns in operational environments with on-site printing. Multi-purpose printers are currently being used and tested with USU. A multi-purpose 3D printer was sent to Africa, Djibouti. It weighed 200 pounds and could be powered by a jeep or solar panels. During the usage case a scalpel, hemostat, bandage was printed and easy to produce. The 3D printer can be modified to fit the wound. This can be done with CT images for surgical conditions as well to fit a mold to reconstruct on implant."	• Informative • Subject matter experts • Innovation • Mobility • Portable	• Diminish logistical concerns • Operational environment • Light, agile and flexibility • 3D printing capabilities • Distributed Maritime Operations	A lightweight, multi-purpose 3D printer could produce antibiotic bandages A standard bandage can be printed in minutes, and larger bandages in 10 minutes. The cost and training involved is minimal, and the supplies required to operate the printer can be distributed in bulk to the end user.

"We have good data on the leaching times for these compounds and can have them leach out over days to weeks."			
"It could also theoretically be taken to a more forward location; it weighs around 150 pounds and can be run off of a jeep power source or lithium ion batteries. It should be able to run off of solar cells as well, but we have not tested that out yet."			
"IV tubing may not be feasible due to the construction of the plastic tubing being fine and thin. However, it is possible to print medical equipment replacement parts."	• Informative • Subject matter experts	• Limited Class VIII(a) catalog • Research and testing	Class VIII(a) medical supplies 3D printing catalog is limited but research and testing have been done on scalpels, hemostats, implants, and surgical guides.
"Some machines require heating small particles and run the risk for explosions due to the particle size. These machines are typically for metal 3D printing and are best for stable environments. Therefore, printing anything metal in an operational environment will be challenging. Some machines have a larger throughput but in turn have a large footprint and may not be ideal for operational environments. The best utilization of 3D printing for medical supplies is a custom based printer such as the ones mentioned with larger capacity, costly and not feasible for operational environments."	• Informative • Subject matter experts	• 3D printer type	Large capacity printers have a large footprint and are not suitable for operational environments. Small printers such as the multi-purpose printer or an FDM printer are feasible. Regular maintenance and cleaning between usage decreases the likelihood of repairs and unscheduled maintenance.
"The standard universal supply of raw materials available are light weight and can be stored until needed, however there are limitations on what kind of raw materials are used and available within operational environments."	• Informative • Subject matter experts	• 3D printer type	
"Maintenance for small printers is simple, remove printer bed and clean to make ready for the next object."	• Informative • Subject matter experts	• 3D printer type	
"We have sent 15-18 implants over to Afghanistan. The majority began after April 2017. The implants are 3D printed within the WRNNMC facility and sent directly to the requesting end user via APO mail. There is no other option to mail forward currently."	• Informative • Subject matter experts	• 3D printing capabilities	Research and testing have been done on scalpels, hemostats, implants, and surgical guides. Opportunities include left-handed scalpels, forceps, cranial flaps, syringes, and surgical pins. Items that do not remain in patients are more likely to be feasible candidates for 3D printing. Some medical supplies that are considered bulk items are often first depleted. There may be value in 3D printing these items. Research focused on rapidly depleted items may provide high value. A 3D printer prepositioned forward at TLAMMs could print some medical
"FormLab is printing nasal swabs for COVID-19 and can print 300 swabs in one day. The swabs are currently being used in New York and Florida. Suction cannisters are possible but not yet tested and nasal cannulas using a dental long-term resin are possible but not tested. Any Class VIII(a) that goes into a patient and requires long-term patient care is not feasible yet but may be in the future. Class VIII(a) medical supplies such as syringes that do not stay with patient long-term and are disposable may be feasible. Needles are not possible because they require too fine of a metal, would	• Informative • Subject matter experts	• 3D printing capabilities	

not be smooth and are better manufactured in the traditional setting. Sponges and dressing will be challenging and are not likely due to the usage and material required. However, bandages are currently being tested in USU 4D Bio Lab facilities that can provide a long-term antibiotic to treat infections.”			supplies, surgical tools, and medical equipment repair parts. By-in across all military services would eliminate constraints on logistical concerns in operational, DMO or future operating environments.
“WRNNMC made hemostats but they were challenging. They printed a scalpel, but the printed models were only used during a simulated surgical procedure. There is the possibility to print cutting guides for surgeries like the dental guides that are currently being printed in WRNNMC.”	• Informative • Subject matter experts	• 3D printing capabilities • Research and testing	
“The main reason this happened, honestly, is because we were taking care of a patient who required more time and intensive care than what our purpose was geared towards. This caused us to go through our supply of suction valves incredibly quickly after we placed a tracheostomy.”	• Lack of alternative hospital • Improvised action • Informative • Medical supplies • Patient influx	• Prolonged patient stays • Rapid depletion • Problem with Afghan hospital • Problem with stuff • Problem with product • Problem with quantity	Maintaining the right product at the right time in the right quantity is challenging with unpredictable demand characteristics in an operational environment constrained by time and distance. Maintain the seven “rights” of logistics requires the right product in the right quantity at the right time in the right place. 3D-printed Class VIII(a) medical, surgical and equipment items could supplement while supplies are in transit, during a mass casualty.
“We had a patient with an abnormal heart rhythm and no flushes. I had to send a nurse to run and make flushes.”	• Improvised action • Informative • Medical supplies	• Problem with stuff • Problem with product • Problem with quantity • Uncertain medical conditions	
“Forced to break infection control protocol to take care of him. This is significant because our infection protocols are followed as strictly as possible to keep both the patients and staff safe, but in this case, we were forced to put them aside to ensure keeping the patient alive.”	• Protocol • Improvised action • Ethical dilemma • Supplies	• Problem with Afghan hospital • Problem with stuff • Uncertain medical conditions	
“The suction valves are a one-time-use item, however due to the necessity of their use for the patient, and our rapidly dwindling of the valves in our stock and inability to get replacements quickly, we had to reuse the valves repeatedly.”	• Protocol • Improvised action • Informative • Ethical dilemma • Medical supplies • Equipment • Patient influx	• Problem with stuff • Problem with product • Problem with quantity • Uncertain medical conditions • Time and distance from PV	
“We treated one medical condition, a ruptured brain malformation, the clips the surgeons had to use in surgery to stop the bleeding were bigger than what neurosurgeons would have used if in the U.S.”	• Difference from CONUS hospital • Protocol • Improvised action • Ethical dilemma • Medical supplies	• Problem with stuff • Problem with product • Problem with quantity • Uncertain medical conditions	

		• Time and distance from PV	
"During our five days receiving GSWs to the head we ran out of cranial kits."	• Informative • Shared experience • Medical supplies • Patient influx	• Problem with stuff • Problem with product • Problem with quantity • Uncertain medical conditions • Time and distance from PV	
"The surgery performed on patient with ruptured brain malformation is not one that is typically conducted in a deployed environment and requires long-term intensive care that local Afghan facilities were not capable of doing. This guaranteed that we would be the persons to care for him as long as necessary."	• Difference from CONUS hospital • Improvised action • Ethical dilemma • Medical supplies • Patient influx	• Problem with stuff • Problem with product • Problem with quantity • Uncertain medical conditions • Time and distance from PV	
"Adjusting to life in Kandahar was a process. You had to always expect the unexpected and understand that flexibility is key. Nothing was static for too long of a period. There was a shortage of IV tubing and secondary IV tubing for our pumps. And the main problem is that with the influx of patients we were burning through it quickly."	• Shared experience • Informative • Difference from CONUS hospital • Medical supplies • Lack of DMLSS training • Patient influx	• Prolonged patient stays • Problem with Afghan hospital • Problem with stuff • Problem with product • Problem with quantity • Uncertain medical conditions • Time and distance from PV	

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APPENDIX C: NATO ROLE 3 MMU MOST USED CLASS VIII(A) MEDICAL SUPPLIES

Ace Wrap
Alaris Tubing
Alcohol Pads
Arterial Line set up
Blood Tubing
Blunt Needle
BVM
Cervical Collar
Coban
CO2 Detectors
Constricting band
EKG Pads
ET Tube holder
ET Tubes
Eye Pro
Eyes Shield
EZ IO Drill
EZ IO
Foley Stat Lock
Foley Catheter
Flushes
Filter Needles
Gloves
In-Line Suction
Ioban
I stat Cartridges
IV pigtail
IV Stat Lock
IV Catheters
Limb Restraints
Litter Straps
LMA
Lure Lock
LMA
Manifold Tubing
Medipor Tape
Nasal Canula
NRB
Pressure Bag
Petroleum Gauze
Plurevac
Primary Tubing
Salem Sump
Secondary Tubing
Suction Canister
Suction Tubing
Surgical Lube
Tape Silk
Tegaderm
Trac Holder
Yankauer
Y connectors
Ventilator Tubing
10cc Syringes
1L bag Normal Saline
2x2/4x4 Gauze

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Acquisition Research Program
Graduate School of Defense Management
Naval Postgraduate School
555 Dyer Road, Ingersoll Hall
Monterey, CA 93943

www.acquisitionresearch.net