Damage control surgery in weightlessness: A comparative study of simulated torso hemorrhage control comparing terrestrial and weightless conditions

Andrew W. Kirkpatrick, MD, MHSC, Jessica Lynn McKee, MSc, Homer Tien, MD, Anthony J. LaPorta, MD, Kit Lavell, Tim Leslie, MSc, David R. King, MD, Paul B. McBeth, MD, Susan Brien, MD, Derek J. Roberts, MD, PhD, Reginald Franciose, MD, Jonathan Wong, Vivian McAlistair, MD, Danielle Bouchard, *and* **Chad G. Ball, MD, MSC**, *Alberta, Canada*

BACKGROUND: Torso bleeding remains the most preventable cause of post-traumatic death worldwide. Remote damage control resuscitation (RDCR) endeavours to rescue the most catastrophically injured, but has not focused on prehospital surgical torso hemorrhage control (HC). We examined the logistics and metrics of intraperitoneal packing in weightlessness in Parabolic flight (0g) compared to terrestrial gravity (1g) as an extreme example of surgical RDCR.

METHODS: A surgical simulator was customized with high-fidelity intraperitoneal anatomy, a "blood" pump and flowmeter. A standardized HC task was to explore the simulator, identify "bleeding" from a previously unknown liver injury perfused at 80 mm Hg, and pack to gain hemostasis. Ten surgeons performed RDCR laparotomies onboard a research aircraft, first in 1g followed by 0g. The standardized laparotomy was sectioned into 20-second segments to conduct and facilitate parabolic flight comparisons, with "blood" pumped only during these time segments. A maximum of 12 segments permitted for each laparotomy.

RESULTS: All 10 surgeons successfully performed HC in both 1g and 0g. There was no difference in blood loss between 1g and 0g ($p = 0.161$) or during observation following HC ($p = 0.944$). Compared to 1g, identification of bleeding in 0g incurred less "blood" loss ($p = 0.032$). Overall surgeons rated their personal performance and relative difficulty of surgery in 0g as "harder" (median Likert, 2/5). However, conducting all phases of HC were rated equivalent between 1g and 0g (median Likert, 3/5), except for instrument control (rated slightly harder, 2.75/5).

CONCLUSION: Performing laparotomies with packing of a simulated torso hemorrhage in a high-fidelity surgical simulator was feasible onboard a research aircraft in both normal and weightless conditions. Despite being subjectively "harder," most phases of operative intervention were rated equivalently, with no statistical difference in "blood" loss in weightlessness. Direct operative control of torso hemorrhage is theoretically possible in extreme environments if logistics are provided. (*J Trauma Acute Care Surg.* 2017;82: 392–399. Copyright © 2016 Wolters Kluwer Health, Inc. All rights reserved.)

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Whether building a space habitat or engaging in military operations, in a hostile location, far from any established hospital, exsanguination is the most likely potentially treatable cause of death.[1,2] Eastridge reported that during Operations Iraqi Freedom and Enduring Freedom, 87% of all battlefield injury fatalities occurred before arrival at a medical treatment facility.[3] The single most common (67%) cause of potentially survivable deaths were related to noncompressible torso hemorrhage (NCTH).[3] Similarly traumatic injury sustained by a deployed astronaut has been deemed the most probable incident that will have the largest impact on astronaut health and subsequently the mission.[4] The ability to control hemorrhage, specifically torso hemorrhage after traumatic injury in space remains a critical limitation in astronaut health care. As in battlefield care, space medicine is conducted in a setting where the crew must continue its mission autonomously and where there are enormous difficulties with resupply, evacuation, and even communication.[5–7] For many such reasons, the crew of an Exploratory Class Space Mission (one leaving low Earth's orbit) will likely face many of the same challenges dealing with an exsanguinating team member as a small Special Forces unit.

To date, there has never been more options to ameliorate torso exsanguination, including the earliest use of blood products including fresh warm whole blood and other component therapies, junctional compressive devices, tranexamic acid, balloon

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From the Canadian Forces Health Services (A.W.K., J.W., V.M.A.); Departments of Surgery (A.W.K., P.B.M.B., D.J.R., C.G.B.), Critical Care Medicine (A.W.K., P.B.M.B), the Regional Trauma Services (A.W.K., P.B.M.B, C.G.B.), Foothills Medical Centre; University of Calgary (A.W.K., P.B.M.B, D.J.R., D.B., C.G.B.), Calgary, Alberta; Innovative Trauma Care (J.L.M.), Edmonton, Alberta; Sunnybrook Health Sciences Centre (C.H.T.), Toronto, Ontario, Canada; Rocky Vista (A.J.L.P.), University School of Medicine, Parker, Colorado; Strategic Operations (K.L.), San Diego, California; Flight Research Laboratory (T.L.), National Research Council of Canada, Ottawa, Ontario, Canada; Harvard Medical School (D.R.K.), Boston, Massachusetts; Royal College of Physicians and Surgeons (S.B.), Ottawa, Ontario, Canada; Denver Health (R.F.), Denver, Colorado; Vail Valley Medical Center (R.F.), Vail, Colorado; and University of Western Ontario (V.M.A.), London, Ontario, Canada.

For the Damage Control Surgery in Austere Environments Research Group (DCSAERG).

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Address for reprints: Andrew W. Kirkpatrick, MD, MHSC, EG23 Foothills Medical Centre, Calgary, Alberta, T2N 2T9 Andrew; email: Andrew.kirkpatrick@albertahealthservices.ca.

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occlusive devices for the aorta, intracavitary foam, and expandable hemostatic sponges.[8–10] All these approaches and technologies fall within the paradigm of remote damage control resuscitation (RDCR). RDCR represents the prehospital application of damage control resuscitation concepts, which comprise treatment strategies designed to limit hemorrhage and to produce or preserve an adequate level of physiologic reserve to permit survival to surgical rescue through damage control surgery.[2,9,10] Of all the important concepts embraced by RDCR, compressible hemorrhage control (HC) and rapid surgical control of bleeding are the most elusive, but constitute a prehospital goal we believe requires urgent study. Yet, to date, there has been little consideration of adding prehospital, potentially on-scene direct surgical HC with the direct pressure of packing to the RDCR armamentarium. In terms of mechanics, performing a laparotomy by incising the anterior abdominal wall to access the peritoneal cavity is relatively technically simple compared with other surgical tasks.[6] Nonphysicians have even been previously reported to perform this successfully in a prehospital environment.[11] Limited work has explored the principles of performing surgical procedures in weightlessness;[12–15] however, torso HC in a human model has not been previously addressed. As part of the Damage Control Surgery in Austere Environments Research Group (DCSAERG) ongoing initiative to potentially consider surgical RDCR, a controlled study of the relative difficulty and efficacy of damage control surgery was thus conducted in the confined physical space of a research aircraft, in both normal terrestrial gravity (1g) and weightlessness (0g). The primary hypothesis was that motivated surgeons could adequately perform damage control surgery in weightlessness.

MATERIALS AND METHODS

The DCSAERG is a multinational, multidisciplinary collaborative consisting of members from Academia, National Defence, Government and Industry, coordinated through Regional Trauma Services at the Foothills Medical Centre, Calgary, Alberta. Ethical approval for this study was obtained from the University of Calgary (REB14-0634) and the National Research Council of Canada. The study was registered as Trial Registration: ID ISRCTN/77929274. The trial was observational measuring simulated blood loss from a high fidelity surgical phantom. Blood loss was measured during a standardized HC task, conducted in normal terrestrial gravity (1g) and in the weightlessness of parabolic flight (0g), using the same surgical simulator in both environments. All procedures were conducted onboard the Falcon 20 Research Aircraft operated by the Flight Research Laboratory of the National Research Council of Canada[16,17] (Fig. 1). This aircraft has a useful cabin volume of 14.2 m^3, and the payload volume is roughly 1.5 m by 1.5 m by 5.0 m with a standard life sciences payload rack size of 92 × 92 × 50 cm. The maximum scientific payload weight is 1,200 kg. The power bus of the aircraft is capable of supporting 120 V at 50 amps.[18] By flying a Parabolic flight profile, this aircraft is able to generate 20- to 25-second periods of microgravity effectively simulating weightlessness (0g), both preceded and followed by hypergravity (2g). The parabolas are conducted in a restricted airspace, between 4,000 m and 8,000 m in altitude, with the aircraft pressurized to 1000 f. above sea level, and the surgeon and assistant restrained by bungee cords over the thighs as they knelt next to the simulator. The Falcon 20 provided all electrical power for the experiments and was equipped with aft, overhead, and foremounted high-resolution DVL/DVR bullet cameras (DVR3-130, Stack Limited, Bicester, United Kingdom). The subsequent video recordings were synchronized, time-stamped, and embedded with the gravitational field recorded from onboard accelerometers.

Ten certified and clinically active volunteer surgeons conducted the simulated task, each serving as their own control between 1g and 0g. Detailed characteristics of the participants training, prior experiences with surgical simulator and challenging environments, including parabolic flight, are given in Table 1. During the procedure, each surgeon wore a head-mounted video camera (GoPro Hero 3, GoPro Corp, San Mateo, CA).

The task to be completed was a laparotomy with midline incision into the peritoneal cavity followed by sponge packing of an exsanguinating liver hemorrhage. This simulated site of bleeding was produced from a molded silicone replica of the liver, in which three-dimensional printed simulated vessels were

Figure 1. Silicone molded liver from surgical simulator illustrating standardized defect in the liver parenchyma and demonstrating the site of "bleeding" from the liver.

TABLE 1. Characteristics of Volunteer Surgeons (N = 10)

Characteristics	Response	(%)
Sex	Male	100%
Age (mean), y	41.7	
Experience with surgical simulator	Yes	80%
Heard of the "cut-suit" simulator	Yes	60%
Prior experience with the "cut-suit"	Yes	30%
Previously performed trauma laparotomy	Yes	100%
Flown in commercial aircraft	Yes	100%
Flown in aircraft smaller than Falcon 20	Yes	100%
Flown in ultralight/paraglider/parasail	Yes	30%
Previously parachuted	Yes	40%
Ever held a valid pilots license	Yes	10%
Ever experienced military tactical flying	Yes	10%
Previous parabolic flight experience	Yes	20%
For those with parabolic flight experience mean parabolas	12	

connected to a pumping system to "bleed" from within a disruption of the liver surface (Fig. 1). This anatomy was identical for each surgeon participating. The surgical task itself has been previously described.[19] Briefly, the HC task was performed on the torso and viscera of a customized "Cut Suit" Human Worn Partial Task Surgical Simulator (Cut-Suit) (Strategic Operations, San Diego, CA), without human actor involvement. The specially modified cut-suit torso was equipped with a sensitive fluid flowmeter that recorded both total fluid loss and fluid loss velocities. The fluid perfusing the cut-suit was colored water thickened to a viscosity of 5 cp/L. The cut-suit was restrained within a custom fabricated fluid containment container, designed by the Flight Research Laboratory of the National Research Council of Canada (Fig. 2). During all phases of the laparotomy, a dedicated technician controlled the "blood" pressure within simulator to 80 mm Hg. The pump technician sat restrained directly viewing the cut-suit (Fig. 3). The pump technician turned the blood pump on at the timed command of the onboard study director, coordinated with the onset of a parabola (timed in 1g; actual weightlessness in 0g). The technician also turned the blood pump off, (i) when the surgeon declared the specific surgical task "complete," (ii) at the end of 20 seconds for timed "parabolas" in 1g if the task was not complete, or (iii) at the end of weightlessness in 0g which was physically obvious. "Blood" loss data were automatically downloaded into a database on a tethered dedicated research laptop computer running a specially customized data storage program (Labview, National Instruments Corporation, Austin, TX).

The standardized laparotomy was compartmentalized into six different phases with specific objective goals to be accomplished within each task (Table 2). This compartmentalization was necessary to accommodate the realities of parabolic flight in which weightlessness can only be obtained for approximately 20- to 25-second periods which are both preceded and followed by hypergravity (2g).[16] To standardize and allow comparison, the surgeons were limited to 20-second "windows" during the 1g data collection. To accommodate study logistics and to recreate realistic urgent austere conditions, each surgeon was limited to a maximum of three "parabolas" for any one phase of the total surgical task, and 12 "parabolas" for the entire

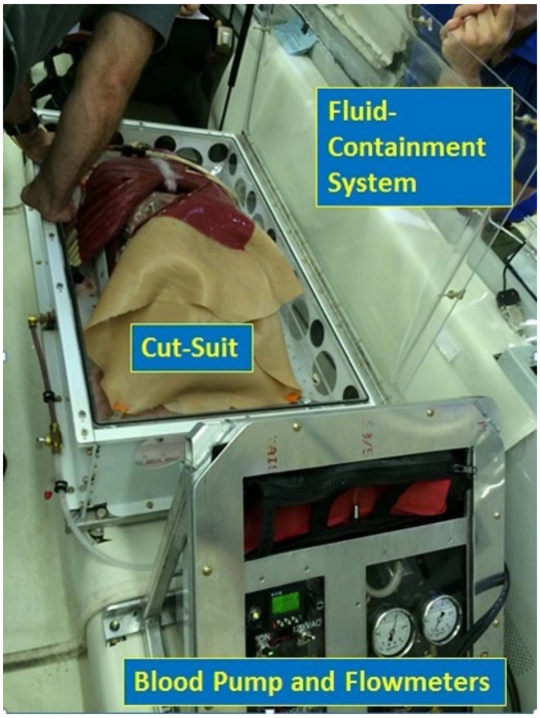

Figure 2. Configuration of cut-suit and blood primping system on-board the Falcon 20.

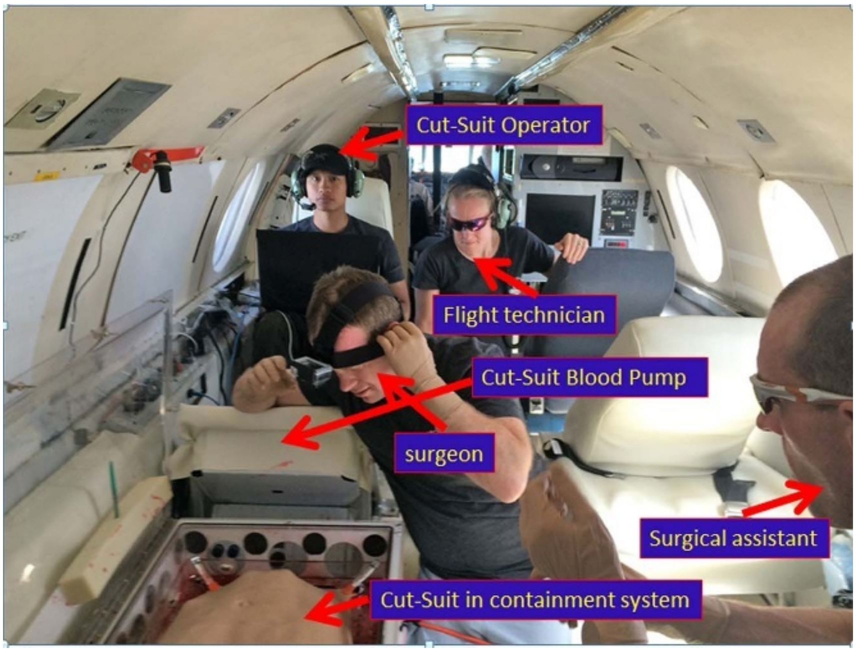

Figure 3. In-flight configuration of the human and technical resources used to conduct the simulated laparotomy.

TABLE 2. Compartmentalized Stages of the Standardized Laparotomy and Hepatic Packing Surgical Task

Surgical Task	Goal	Objective Evaluation
Incision	Open the abdominal cavity without inadvertent visceral injury	Abdominal wall fully opened (y/n) Blood lost during opening Visceral injury during opening Number of parabolas required
Retraction	Insertion of a self-retaining surgical retractor	Correct placement (y/n) Blood lost during retraction
Direction	Direction of an assistant to place and manipulate A handheld abdominal retractor to augment visualization	Visualization augmented (yes/no) Blood loss during direction
Identification	Correctly identify the intraperitoneal source of bleeding	Site of bleeding correctly identified (yes/no) Blood loss during identification
Hemostasis	Control of the visceral bleeding through the manual application of gauze sponges	Sponges placed within the peritoneal cavity (yes/no) Blood loss during hemostasis
Free bleeding evaluation	Observation of the amount of bleeding after subjective completion of the hemostasis phase (no intervention)	Blood loss during observation

laparotomy. This included a mandatory 20-second period in 1g and a dedicated parabola of free-bleeding in 0g observation after completion of the packing to evaluate the functional effectiveness of packing. To make the "Exploration" phase more realistic, surgeons were not aware that the liver was the source of hemorrhage prior to the laparotomy, having been informed that the "cut-suit" can simulate bleeding from multiple intraperitoneal sites. The 10 surgeons completed paired trauma laparotomies in 1g and 0g over June 25–26, 2015, with the 1g procedure performed before the 0g procedure in all cases. All procedures (1g and 0g) were conducted onboard the Falcon 20 aircraft without external power either in the hangar (1g) or in Parabolic Flight (0g).

ANALYSIS

All procedures were over-read in committee by three reviewers who analyzed all video segments from the aft, overhead, head-worn, and forward video cameras to corroborate blood loss data from the flowmeters to surgical activity and gravitational situation (Videos, Supplemental Digital Contents 1–8, http://links.lww.com/TA/A832, http://links.lww.com/TA/A833, http://links.lww.com/TA/A834, http://links.lww.com/TA/A835, http://links.lww.com/TA/A836, http://links.lww.com/TA/A837, http://links.lww.com/TA/A838, http://links.lww.com/TA/A839). Thus, both corrected and uncorrected blood loss calculations were computed for each surgical task. In the uncorrected analysis, the raw uncorrected pump on and off timestamps were accepted as the beginning and end of the surgical activity. In the corrected blood loss calculations, the onset and cessation of the actual surgical activity was carefully observed. If there was any discrepancy from the intended timings, volumes were normalized either up or down to correspond to a volume/second rate times the true seconds of activity.

As each participant acted as their own control the "blood" loss data, corrected "blood" loss data, number of parabolas required and number of sponges used were compared using the Wilcoxon's signed ranks test. Whether each segment was successfully completed was compared using Fisher's exact test, and all demographic data were also examined. Data analysis was completed using SPSS (IBM Corp. Released 2013. IBM SPSS Statistics for Windows, Version 22.0; IBM Corp., Armonk, NY)

RESULTS

All 10 surgeons[10] completed all phases of HC in both 1g and 0g, although two (20%) became physically incapacitated due to vomiting during the abdominal wall closure phase in 0g. The use of a human technician to control the onset and cessation of cut-suit bleeding proved even more physiologically provocative, with even "hardened" special forces medical technicians becoming consistently nauseated in Parabolic flight. Compiled "blood loss" and associated HC data are presented in Table 3. In two cases in 0g, the data recording system failed to record blood flow data after the packing phases of the 0g laparotomy. Thus, in all instances where data from 10 surgeons could be analyzed, it was, but for free bleeding after packing and for total bleeding, there were paired comparisons between 1 and 0g.

All 10 surgeons were able to complete all phases of hemorrhage control in both 1g and 0g, including opening the anterior abdominal wall without visceral injuries. Overall surgeons required fewer parabolas (9.9 vs. 11.1; $p = 0.181$) in 0g to complete the full laparotomy sequence, and although there was less overall "blood" loss during damage control laparotomy in 0g compared to 1g, this did not reach statistical significance in either uncorrected (421.1 mL vs. 341.7 mL; $p = 0.161$) or corrected analyses (428.1 mL vs. 345.9 mL; $p = 0.161$). There was also no obvious difference in "bleeding" seen after intra-abdominal packing (uncorrected, 40.38 vs. 44.36 mL; $p = 0.944$; corrected, 40.38 mL vs. 44.63 mL; $p = 1.000$). Examining individual phases of the laparotomy, there were no differences in the "blood" loss during incision, retraction, direction, or packing phases comparing the same procedures in 1g versus 0g. However, compared with laparotomy in 1g, incising the abdominal wall required statistically fewer parabolas (1.3 vs. 2.1; $p = 0.011$), with no visceral injuries documented in 1g or 0g. The identification phase of the laparotomy in 0g required the surgeons to use fewer parabolas and was associated with less "blood" loss (uncorrected

TABLE 3. Comparative Technical Performance Terrestrial (1g) Versus Weightlessness (0g)

Task	Laparotomy in 1g Mean (SD)	Laparotomy in 0g Mean (SD)	p
No. parabolas for incision	2.1 (0.568)	1.3 (0.483)	0.011
Incision fluid loss (mL); N = 10	85.26 (0.031)	65.15 (0.059)	0.139
Incision fluid loss corrected (mL); N = 10	85.26 (0.031)	63.98 (0.059)	0.139
Visceral injury during incision	0	0	$p > 0.999$
No. parabolas for retraction	1	1	$p > 0.999$
Retractor segment complete	10/10 (100%)	10/10 (100%)	$p > 0.999$
Retraction fluid loss (mL); N = 10	31.85 (0.0887)	25.20 (0.010)	0.203
Retraction blood loss corrected (mL); N = 10	31.46 (0.009)	26.23 (0.0126)	0.285
No. parabolas for direction	1	1	$p > 0.999$
Direction fluid loss (mL); N = 10	15.83 (0.0057)	13.65 (0.0041)	0.385
Direction fluid loss corrected (mL); N = 10	15.53 (0.0054)	13.26 (0.0048)	0.283
Number of parabolas for identification	1.6 (0.516)	1.2 (0.422)	0.046
Identification blood loss (mL); N = 10	63.88 (0.025)	40.86 (0.256)	0.037*
Identification blood loss corrected (mL); N = 10	63.63 (0.025)	41.07 (0.0261)	0.047*
Site of bleeding correctly identified	8/10 (80%)	2229/10 (100%)	0.531
No. parabolas for packing	1.9 (.586)	1.9 (.738)	$p > 0.999$
Packing fluid loss (mL); N = 10	76.71 (0.036)	64.79 (0.041)	0.444
Packing blood loss corrected (mL); N = 10	80.03 (0.035)	66.67 (0.0429)	0.445
No. sponges (mean)	10 (2.981)	11.3 (4.138)	0.402
No. parabolas for free bleeding	1	1.10 (.316)	0.317
Free bleeding blood loss (mL); N = 8	40.38 (0.007)	44.36 (0.0277)	0.944
Free bleeding blood loss corrected (mL); N = 8	40.38 (0.007)	44.63 (0.0275)	$p > 0.999$
Total number of parabolas	11.1 (0.876)	9.9 (2.234)	0.181
Total laparotomy blood loss (mL)	421.1 (0.0952)	341.7 (0.1740)	0.161
Total laparotomy corrected blood loss (mL)	428.1 (0.1006)	345.9 (0.1786)	0.161

$p = 0.037$; corrected $p = 0.047$). Two (20%) of the surgeons in 1g, and one (10%) in 0g mistakenly believed the spleen was also bleeding in addition to the liver but this was not statistically different ($p = 0.531$). Finally, although surgeons used a similar number of parabolas (mean 1.9 in both 1g and 0g), they were able to place at least as many packs in the course of the laparotomy in 0g as compared to 1g (11.3 vs. 10; $p = 0.402$).

In terms of the subjective physiological performance and the relative subjective difficulty of damage control laparotomy (DCL), surgeons rated both their personal overall ability to perform in parabolic flight and their overall abilities to physiologically perform Damage Control surgery as harder (median Likert, 2/5) in 0g compared with 1g (Table 4). Although the manipulation of retractors was felt to be equivalent between 0g and 1g (median Likert, 3/5), surgical instrument control in 0g was rated slightly harder overall (median Likert, 2.75/5). The individual phases of the laparotomy task were rated of equivalent difficulty between 1g and 0g (median Likert, all 3/5), for opening the abdominal wall, exploring the peritoneal cavity, identifying the hemorrhage source, and controlling the hemorrhage. Finally, the surgeons rated the cut-suit to be a realistic model of severe hemorrhage with no difference in opinion between 1g and 0g.

DISCUSSION

Performing laparotomies with packing of a simulated NCTH in a high-fidelity surgical simulator was feasible for

TABLE 4. Relative Performance During Damage Control Laparotomy in Both 0g and 1g Conditions

Question	Median Response	Interpretation
(1) Self-rated personal overall ability to function in parabolic flight compared to a typical operating room	2	Harder
(2) Self-rated personal overall ability to perform damage control surgery in weightlessness compared to a typical OR	2	Harder
(3) Compared with 1g, opening the anterior abdominal wall in 0g was	3	Same
(4) Compared with 1g, exploring the peritoneal cavity in 0g was	3	Same
(5) Compared with 1g, identifying the source of hemorrhage in 0g was	3	Same
(6) Compared with 1g, controlling the source of hemorrhage in 3 same 0g was	3	Same
(7) Compared to 1g, manipulating surgical instruments in 0g was harder	2.75	Slightly harder
(8) Compared to 1g, manipulating surgical instruments in 0g was	3.0	Same
(9) Cut-Suit realistically depicted severe hemorrhage in normal terrestrial 1g	3.5*	Realistic
(10) Cut-suit realistically depicted severe hemorrhage in weightlessness 0g	3.2*	Realistic

1= much harder; 2 = harder; 3 = same difficulty; 4 = easier; 5 = much easier 1= very unrealistic; 2 = somewhat unrealistic; 3 = realistic; 4 = somewhat realistic; 5 = very realistic.

*No statistical difference by either Wilcoxon signed ranks ($p = 0.317$) or Mann-Whitney U test ($p = 0.853$).

trained surgeons onboard a research aircraft in both normal and weightless conditions. Despite being subjectively considered "harder," most phases of operative intervention were rated equivalently, and there was no statistical difference in effectiveness as measured by "blood" loss in weightlessness. Further, although not statistically different, there was actually overall less blood loss in weightlessness, opening the abdominal wall was statistically quicker, and there was statistically less blood loss during the identification component of the DCL. Direct operative control of torso hemorrhage is thus theoretically possible in extreme environments if logistics are provided for.

Therefore, otherwise unsurvivable injuries with no other treatment options might be considered for such a radical, psychologically daunting, but potentially lifesaving on-scene resuscitative laparotomy to provide direct pressure through packing. Most battlefield casualties die of their injuries before ever reaching a surgeon,[3,20,21] which compounds the human tragedy because recent data from highly functional systems reveals that 89% of those who reach a surgeon alive, survive.[22] For proper context, these casualties are typically not reaching surgeons, and the most recent review of Canadian Forces deaths in Afghanistan automatically deemed all cases of torso exsanguination "nonpreventable."[23]

The Trauma Hemostasis and Oxygenation Research Network has defined a lifesaving intervention as a medical procedure that if not performed conveys a high probability of morbidity or death,[10,24] with the terms far-forward and austere denoting environments in which professional health care providers do not normally operate.[10] A recent review of the current technologies potentially available in the prehospital setting to potentially control hemorrhage in catastrophic NCTH reported that intra-abdominal foam injection[25–27] and resuscitative endovascular aortic balloon occlusion[28,29] were potential techniques to be considered.[30] However, this review did not consider prehospital open surgical interventions as a potential option despite noting "manual force is one of the most effective means of controlling bleeding."[30]

Although an art unto itself, manual intraperitoneal packing is at the simplest end of the spectrum of ever more complex surgical procedures that a trained surgeon should be facile with. A recent international survey of practising surgeons on the appropriateness of damage control indications agreed that major liver injuries were one of the most consistently agreed upon anatomic indications for damage control surgery (≥90%),[31] a scenario that is most frequently utilizes packing as primary therapy. Great strides have been made through the introduction of RDCR techniques and philosophies in recent years,[10] and with major advances in communication and mentoring technologies, a far-forward damage control laparotomy focused solely on physical tamponade might not be unthinkable,[19,32] especially when death appears otherwise imminent. Space medicine concepts may also be suggestive; in 1983, NASA think tanks identified the ability to perform laparotomy as the minimum desirable surgical capability to save lives, before transfer to earth, arguably one of the most dramatic and austere prehospital settings.[5,33] Of course there remain multiple other factors that are typically required for successful DCL, such as, but not limited to, anesthesia and anesthetic management, fluid and blood product resuscitation, abdominal closure and/or visceral containment, and postoperative critical care. However, despite these many practical questions, the DCSAERG believes these experiences in simulated NCTH in the extreme environment of weightlessness demonstrate the resilience of dedicated surgeons to perform in challenging environments outside of traditional operating rooms. Thus, bringing damage control surgery far-forward is a potential option that may figure in RDCR discussion and future research initiatives.

Although self-selected by volunteering for a unique experience, the participating surgeons had minimal to no experience with parabolic flight, although nearly half had experience parachuting and a third had ultralight/paraglider experience. These surgeons self-rated their overall ability to function in weightlessness in parabolic flight and to perform DCL in weightlessness as harder than a normal terrestrial operating room. Nonetheless, they were able to overcome these self-perceived limitations to perform a complex technical procedure with apparent greater efficiency. The design of the study and the nature of parabolic flight research dictated that the 1g procedure would be performed by the surgeon prior to the 0g experience. Thus, the apparent increased efficiency of the DCL in 0g may have been due to a learning bias despite the unfamiliarity with weightlessness, relative physiologic distress in many of the subjects, and the subjective opinion that instrument control was slightly harder in weightlessness. This point is in contradistinction to the experience of astronauts and surgeons with great prior experience in parabolic flight who noted no decreases in manual dexterity with experience,[14,34,35] but may be more typical of the "average" but highly motivated surgeon operating in an adverse environment.

The DCSAERG appreciates that it is unlikely trained surgeons will be physically present in most instances of catastrophic hemorrhage in operational settings. However, such individuals may be able to be "virtually" present on earth and in low Earth's orbit.[36] As invasive HC through a prehospital DCL will be an immensely challenging task for any operator. The psychological barriers to performing such a task would be exponentiated if the operator is a nonsurgeon nonphysician and a close friend and team member of the dying casualty. Understanding that any unnecessary interventions would impart not only morbidity and mortality to the victim, but also seriously impact the operational mission. As part of the DCSAERG initiative, we have conducted parallel studies attempting to incorporate information technologies into the prehospital decision making processes if communication is possible. A randomized controlled study with fire fighters has demonstrated that nonphysician first responders are highly accurate at identifying intraperitoneal exsanguination with just in time point-of-care (POC) ultrasound when remotely mentored by experts.[37] If remote mentoring technologies are available, expert clinicians could assist in confirming the diagnosis on torso hemorrhage, confirm otherwise unavoidable mortality through POC lactate measurement, and thereafter remotely mentor an onsite nonphysician to perform a DCL and packing.[19] Our previous works suggest that medical technicians can quickly learn such techniques and may be reassured through the virtual presence of an expert.[19]

The DCSAERG perceives that the highest level deliverable of this work is to catalyze ongoing work in considering rescue strategies for those bleeding to death from NCTH in austere environments on earth. Any data concerning surgical care in physically confining environments in weightlessness are relevant to guide planning for the on-going human exploration of space. The ability of surgeons to perform well and rapidly adapt to weightless conditions corroborates a rich tradition of previous work in parabolic flight reinforcing the principles that if the patient, equipment, and operator are restrained, any surgical procedure attempted should be feasible.[13,15,34,38,39] A novel conclusion in this realm however was the greater efficiency with quicker operative times (less parabolas required) and greater efficiency (more packs inserted) which, while contradicting the impression that similar procedures require more time in weightlessness,[34] argues to the importance of any rehearsal and surgical simulation in improving surgical efficiency. In particular, simulation is a topic in which surgery has long lagged behind space medicine.[40]

Unavoidable limitations of this study involved the use of simulation rather than live patients in which to study exsanguination, and the fact that 1g procedures were performed onboard the hangered aircraft, whereas the 0g procedures were in flight. The investigators submit, however, that using simulators versus live patients is an unavoidable reality in this field of study and true randomized controlled trials will never be ethical or practical. Thus, the development of anatomically and physiologically realistic surgical simulators represents a new era in surgical education and research that will only continue to blossom. In this regard, the “blood” used to simulate exsanguination was not entirely realistic despite using thickening agents to raise the viscosity of the colored water that was used to simulate “blood.” Without any intrinsic coagulative properties, hemostasis cannot be realistically recreated. The pressure-head perfusing the bleeding was also constant and not pulsatile as in normal human physiology. Nevertheless, the technical details to physically identify and compress visceral “bleeding” remain valid, and we believe this was a conservative bias in the study. In addition to weightlessness, there were other additional stressors involved in parabolic flight notably turbulence, landing, take-off, and especially the hypergravity preceding and following the weightless segments. This does however constitute a further set of challenges to test the surgeons which was ultimately the goal of the study, and ultimately conservative biases to operator success in 0g. The use of a human technician to control the onset and cessation of cut-suit bleeding was another potential limitation, because they were consistently nauseated and may have been slightly inaccurate in controlling “bleeding” during the appropriate timings. It was reassuring that a detailed over-read and complete reanalysis with carefully corrected values, yielded exactly the same clinical interpretations.

Finally, potential enthusiasm for major invasive procedures with great potential for significant procedural complications must be carefully weighed. The physiologic robustness of fit previously healthy young combatants cannot be underestimated and thus the inherent ability of native hemostatic responses to seal major traumatic injuries needs to be considered. Therefore, adopting the principles of hypotensive resuscitation without misguided over-resuscitation is a fundamental tenant of RDCR.[9] Many seriously injured casualties will thus reach a homeostatic condition where they clot their wounds and maintain an acceptable level of organ perfusion to survive transport to definitive care. However, as Bjerkvig et al. and Hooper et al.[2,9] recently articulated, the strategy of permissive hypotension has not been adequately evaluated for safety in the setting of delayed evacuation. Alternatively, given the new availability of lightweight POC lactate monitoring devices,[2,9] repeated lactate determinations in addition to remotely mentored POC ultrasound confirmations of torso hemorrhage,[37] might allow the selection of a subset of injured, who might either expire before transport or accumulate a great enough oxygen debt that multisystem organ failure is inevitable.[41]

In conclusion, performing RDCR laparotomies with packing of a simulated NCTH exsanguination in a high-fidelity surgical phantom was feasible onboard a research aircraft in both normal and weightless conditions. Despite being subjectively “harder” most phases of operative intervention were rated equivalently, and there was no statistical difference in “blood” loss in weightlessness. Direct operative control of torso hemorrhage is theoretically possible in extreme environments that greatly physically challenge the surgeons if logistics are provided for.

AUTHORSHIP

A.W.K., J.L.M., H.T., A.J.L., K.L., T.L., D.R.K., S.B., D.J.R., J.W., and C.G.B. designed this study. A.W.K., J.L.M., A.J.L., K.L., T.L., D.R.K., P.B.M., R.F., J.W., V.M., and C.G.B. contributed to data acquisition. A.W.K., J.L.M., A.J.L., K.L., T.L., D.R.K., P.B.M., D.J.R., V.M., and D.B. conducted to data analysis and interpretation. A.W.K. and J.L.M. drafted the article. All authors contributed to critical revisions and final approval.

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DISCLOSURES

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