Remains Containment Considerations for Death in Low-Earth Orbit

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BACKGROUND: Maintenance and disposition of decedent remains during spaceflight require the isolation of biohazardous products of decomposition in microgravity and in the absence of refrigeration. Containment and isolation options would preferably offer sufficient time to enable crew and ground support teams to determine appropriate disposition of remains and even potentially return remains to the Earth. The pilot study described herein undertook an effort to develop a postmortem containment unit for the isolation and maintenance of decedent remains in a microgravity environment.

METHODS: Commercial off-the-shelf containment units were modified to meet the needs of a microgravity spaceflight environment and to offer the best likelihood of successful containment and management of remains. A subsequent evaluation of modified containment unit performance was undertaken utilizing human cadavers, with measurement and analysis of volatile off-gassing over time followed by impact testing of the units containing cadaverous remains in a simulated spaceflight vehicle seat.

RESULTS: Modifications were implemented without significant negative design impact. Failure was observed in one modified unit after 9 d and attributed to improper filter application. The remaining unit successfully contained remains beyond the intended endpoint of the study.

DISCUSSION: These pilot efforts offer important insight into the development of effective postmortem containment options for future spaceflight. Further study is needed to ensure repeatability of the findings and to further characterize the failure modes of the modified units evaluated, the impact of microgravity conditions, and the identification of additional modifications that would improve remains disposition.

KEYWORDS: crew fatality, spaceflight, human remains, body bag, decedent, microgravity, bloat, decomposition, postmortem, methanethiol, hydrogen sulfide.

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Expansion of human spaceflight in low-Earth orbit and beyond will inevitably pose increased risk to the crew. Exploration missions will face onboard vehicle resource constraints, resupply limitations, and few evacuation options as crew venture farther from Earth. In a case where only one member of a crew is lost, containment and disposition of the deceased crewmember's remains would pose a significant challenge for surviving crewmembers. Successful options would ensure: isolation of biohazardous products of decomposition in the microgravity environment; offer time for surviving crewmembers and ground support teams to identify best options for determination of cause of death and final disposition of remains; and potentially enable return of remains to Earth.[5] Even in current missions in low-Earth orbit, resources and dedicated procedures for the management of decedent remains have been limited.[5]

Terrestrial management of decedent remains (in the developed world) relies upon the ready availability of refrigeration,

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even in austere locations and conditions.[2,3,8] In circumstances where refrigeration is not readily available or uncontrollable contamination is a concern, interment of remains is typically completed before the undesirable effects of decomposition arise, with options including on-site individual or mass burial, burial at sea, or similar.[2] Currently, large-volume refrigeration capable of preserving a human body is not available onboard launch vehicles or on the International Space Station (ISS). This capability would likely be cost prohibitive without additional drivers for current and future platforms. Thus, containment units that could successfully manage remains in the absence of refrigeration would be desirable.

In 2012, an unaltered commercial off-the-shelf human remains containment unit (HRCU) was flown to the ISS along with a forensic sampling kit and charcoal odor control filtration canisters.[5] The off-the-shelf unit was designed for a maximum of a 10-yr terrestrial shelf life (with the primary limiter being the filtration cartridge); there was no testing performed to determine shelf life or maximum use duration in the space environment. The HRCU filter port design did not include a baffle; in a microgravity environment, liquid products of decomposition would contact the filter surface. Once wet, the filtration membrane would solidify and cease gaseous diffusion. Removal or replacement of the filter of an occupied unit would release volatile decomposition products (and, potentially, liquids) into the vehicle's habitable environment.

Development of an improved containment unit is desirable both for implementation in current mission architecture and as a validation and development step for future exploration spaceflight applications. The goal of this pilot study was to identify and validate an improved HRCU for spaceflight applications, utilizing a commercial off-the-shelf product modified for the microgravity environment. This effort was dedicated specifically for a low-Earth orbit manifesting of resources, but with potential applications for future vehicles or missions. Design considerations included the following:

- The HRCU must contain all liquid and gaseous products of decomposition for as long as possible at atmospheric conditions similar to those of the ISS (14.7 psi, 21% oxygen, balance nitrogen);
- The HRCU must offer a minimum acceptable containment period of 48 h, ideally greater than 72 h, to provide an operational period in which support teams could determine appropriate final disposition of remains;
- The HRCU must be sized sufficiently to accommodate human remains, and
- The unit must have a storage life of a minimum of 10 yr maintenance-free.

While it may not be viable in all mission circumstances, it would be desirable to enable the return of decedent remains to Earth. Thus, design considerations would preferably include: flexibility for positioning within a vehicle seat; an interface enabling the use of seat restraints; and containment reliability under nominal or contingency entry and landing impact loads. Further, successful management of abdominal bloat through the insertion of a decompression tube could better facilitate postmortem positioning (for example, flexed positioning for a seated return), may improve restraint fit, and could decrease the potential risk of abdominal rupture on landing impact. A HRCU design that would accommodate an abdominal decompression tube, and subsequent increase of gases within the HRCU, would thus be preferable.

Most terrestrial body bags are not designed for use in the absence of refrigeration and have limited odor or volatile compound containment. Some military containment bags are designed for use on casualties where there are concerns of chemical warfare or biohazard exposure; such units are more robust and offer improved volatile containment and resilience to prolonged transport from austere environments.[4,6] Modification of a more robust military-grade HRCU was felt to be the most likely means of offering a successful containment option for the microgravity environment.

Pilot efforts in modifying a commercial, off-the-shelf, military-grade HRCU for use in the microgravity environment, subsequent testing, and analysis of containment capabilities of the modified HRCU using cadaverous remains are discussed below. Additional procedures regarding the management of postmortem bloat via abdominal tube insertion, repositioning of HRCUs into a flight-like seated position for simulated return, and simulated landing-load impacts were performed for additional insight into HRCU operational utility. These initial efforts were tailored to low-Earth orbit operations, with the recognition that validation of equipment and procedures for low-Earth orbit could offer insight and applicability to future and developing exploration programs.

METHODS

Two commercial off-the-shelf HRCUs were selected for initial evaluation and modification for on-orbit specifications and use in this study. The units included:

- The Isovac CBAG™ Contaminated Human Remains Pouch (Isovac Products LLC, Romeoville, IL; https://www.isovacproducts.com/), designed for containment of chemical warfare agent contamination. The unmodified product will be referred to as the "C-HRCU;" the modified unit will be referred to as the "MC-HRCU," and
- The Isovac CBAG™ Biohazard-Contaminated Human Remains Pouch (Isovac Products LLC, Romeoville, IL; https://www.isovacproducts.com/), designed for biohazardous containment. The unmodified product will be referred to as the "B-HRCU;" the modified unit will be referred to as the "MB-HRCU."

Modifications were made to both the C-HRCU and B-HRCU to improve utility in the spaceflight environment (**Fig. 1**). Modifications included:

- Addition of a circumferential absorbent lining: off-the-shelf design included absorbent lining only on the

inferior/dependent surface of the bag for a supine-positioned cadaver; the addition of circumferential lining increases containment capabilities in a microgravity environment;
- Reversal of zipper pull orientation: the off-the-shelf design provided zipper pull with an opening at the foot; reversal of zipper pull direction allows for facial viewing options via partial HRCU opening without exposure of the entire cadaver;
- Relocation of the filter port from foot to head: this modification preserves on-orbit storage options by moving the filter port to a location easily accessible to crewmembers regardless of HRCU storage location (e.g., restrained in a vehicle seat, stored in compartmented locations, etc.). This additionally improves fit in vehicle seat and restraint systems as increased availability of habitable volume around the head (compared to the feet) better accommodates the filter port;
- Addition of a loop panel on the outer portion of the bag lid: this modification allows for the placement of a crewmember nametag, national flag, or other identifiers;
- Addition of securing straps to HRCU handling loops to reduce snag hazards while stored or during translation through a vehicle; and
- Addition of securing straps to the superior corners of the HRCU to accommodate and secure seat restraints around the HRCU.

The modified HRCU was fit-tested in a high-fidelity spacecraft seat mockup to ensure maneuverability and fit of restraints in a volume-limited cabin environment. Fit-testing was performed utilizing a mannequin, then with a live male subject (within the 5^{th} to 95^{th} U.S. percentiles for height and weight) to better evaluate maneuverability and positioning. A subsequent evaluation of modified HRCU containment performance was undertaken utilizing human cadavers at the Applied Anatomical Research Center/Southeast Texas Applied Forensic Science (STAFS) main laboratory at Sam Houston State University. Three human cadavers were obtained from the STAFS facility's willed-body donation program. All cadavers were male, within the 5^{th} to 95^{th} percentile for height and weight for the U.S. population, and in the "fresh" stage of decomposition at the onset of the study. The laboratory environment included temperature control between 70 and −75°F (21 to −24°C) and humidity control between 40 and 50% relative humidity. The study was performed in a phased manner, with an initial laboratory phase followed by impact testing of the HRCU-contained remains.

All cadaver procedures were performed by individuals experienced with spaceflight operations, but with variable levels of medical experience and training (ranging from inexperienced to physician-level expertise). In addition, forensic sample collection and remains management were performed under simulated "ground control guidance," in which an Aerospace Medicine-certified flight surgeon provided remote guidance and procedural assistance via verbal prompting to simulate an on-orbit procedural approach.

Cadavers were unclothed and placed in an open HRCU as indicated below to initiate a simulation of on-orbit decedent management procedures, including forensic sampling (of hair, nails, blood, urine, and vitreous humor) and preparations for return of remains to Earth, with packing of nasal and oral orifices and placement of an absorbency garment around the cadaver pelvis.

- Cadaver A: MC-HRCU
- Cadaver B: MB-HRCU
- Cadaver C: unmodified C-HRCU

Fig. 1. Modified HRCU, including reinforced zipper with reverse orientation and opening at the head (left) and the addition of securing straps to handling loops along the length of the unit (right).

A nonphysician advanced medical practitioner performed an additional procedure on Cadaver A to insert (via surgical incision) a 7.0-mm internal diameter endotracheal tube into the abdominal cavity, secured with sutures and medical tape. The endotracheal tube was selected for the following reasons:

- A 7.0-mm endotracheal tube has a similar internal diameter as a 23 French thoracostomy tube;
- The length of the endotracheal tube is shorter than a thoracostomy tube and therefore more manageable within the HRCU; and finally,
- 7.0-mm endotracheal tubes are available in current on-orbit medical kits[9] and thus felt to be representative of equipment that might be available to crew.

Laboratory Phase

With the completion of sampling procedures, the HRCUs were closed and placed on stainless steel gurneys within the main laboratory space, with cadavers in supine positioning. Cadavers were located approximately 4 ft apart. Additional procedures varied by cadaver and will be described below.

Cadavers A and B. Cadavers A and B remained in supine positioning through study Day 9. A static measuring rod attached to the gurney with laser-leveling capability was used to measure the rise of the HRCU (i.e., abdominal rise from bloat) from the level of the gurney over time. On Day 9, the cadavers were repositioned into a loosely flexed supine position, secured with a patient spinal immobilization multi-strap system, to simulate seated positioning in a vehicle seat. Measurement of abdominal rise continued in this flexed position through the completion of the study.

Volatiles were initially captured every 2 d, then at longer intervals of 3–7 d over the course of the study. Samples were captured at the zipper and filter port of the HRCUs by using 65-µm polydimethylsiloxane/divinylbenzene solid-phase microextraction fibers, then analyzed using gas chromatograph-mass spectrometry. The volatiles were analyzed using an Agilent Technologies 7890A series gas chromatograph (GC) coupled to a 5975C series mass selective detector (MSD) located at the Texas Research Institute for Environmental Studies (TRIES) at Sam Houston State University. The GC was equipped with an Agilent J&W DB-5ms capillary column with 30 m × 250 µm dimensions and 0.25 µm coating thickness. A solid-phase microextraction (SPME) injection port liner was used and the GC injector was operated in splitless mode at 250°C, per standard protocols. Hydrogen carrier gas was set to a flow rate of 1.1873 mL $\cdot$ min^{-1} and the initial temperature for the GC oven was at 30°C for 2 min^{-1}, then raised to 80°C at a rate of 6°C $\cdot$ min^{-1}, then to 120°C at a rate of 150°C $\cdot$ min^{-1}, and finally to 300°C at a rate of 40°C $\cdot$ min^{-1}. Temperature was held at 300°C for 2 min. The total time for the run was 19.5 min and the mass selective scan range was 20–300 m/z at the rate of 2.94 scans/s. Data analysis was done using a combination of ChemStation on the instrument and Python programming language with custom code for detailed analysis. The hydrogen sulfide (H_2S) molecular ion (m/z 34) in the void fraction at 0.95 min and the methane thiol molecular ion (m/z 48) peak at 1.05 min were integrated. Full spectra for each peak during high volatile release were compared to spectra from standards and confirmed to match.

Volatile sample collection continued through the completion of the laboratory phase of the study. The laboratory phase of the study was considered terminated at the point of notable odor release or loss of fluid containment. Cadavers removed from the study were placed in a walk-in cooler in the laboratory, with the cooler environment maintaining ambient temperature at 38°F (3°C).

Cadaver C (Control). Cadaver C remained in the supine position for the duration of the laboratory phase of the study. Cadaver C's HRCU was relocated to a supplemental laboratory space (held at identical environmental conditions as the primary laboratory space) and opened daily under negative airflow ventilation for visual inspection and photographic documentation of the decomposition process. Biological samples of identified fungal colonies were obtained and analyzed. The Cadaver C relocation and use of a negative airflow fume hood prevented contamination of volatility samples from the other cadavers during HRCU opening; however, this procedure precluded collection of accurate bloat measurements and volatile compound samples for chemical analysis.

Impact Testing Phase

After 30 d of HRCU containment and analysis, impact testing was performed on Cadavers B and C. A simulated spaceflight seat pan with flight-like restraints was constructed, with the HRCUs secured using ratcheting straps in a cross-body configuration. The Cadaver C test unit was raised to a height of 1.5 ft (0.45 m) via crane and dropped at an impact velocity of 3.0 m $\cdot$ s^{-1}. The Cadaver B test unit was raised to a height of 19 ft (5.79 m) via crane and dropped at an impact velocity of 10.48 m $\cdot$ s^{-1}. Following drop tests, HRCUs were visually inspected for rupture or zipper failure and the cadavers were imaged via radiography to identify any skeletal fractures. Radiography was reviewed by a board-certified forensic pathologist with extensive postmortem radiology experience. Cadavers were then placed in the STAFS outdoor research laboratory for natural decomposition. Following 210 d of natural decomposition, cadavers were retrieved and underwent skeletal examination to identify any occult or obscure fractures that could have been missed by radiographic examination.

Exception Phase

Following the initial laboratory phase, it was noted that the MC-HRCU of Cadaver A remained intact, with no apparent breach and no release of volatile compounds, odor, or fluid leakage. Cadaver A was therefore withheld from impact testing, and laboratory data collection and analysis were extended for an additional 30 d (or until containment failure if before 30 d). Cadaver A's HRCU, as well as the abdominal rise measurement rod, was relocated to an alternative stainless-steel gurney within the laboratory space. Abdominal rise measurements were taken before and after relocation of the MC-HRCU on Day 30 for calibration, and daily measurements continued for the duration of the study. Volatiles were again captured and analyzed as during the laboratory phase.

RESULTS

HRCU bag modifications were implemented without significant negative design impact to the MB-HRCU or MC-HRCU. The commercial provider was able to modify the HRCUs to provided specifications without significant constraint. Fit-testing demonstrated adequate maneuverability within a volume-constrained spaceflight capsule and ease of application of restraints via the added HRCU securing straps.

Forensic sampling procedures were performed without difficulty by all participants, including nonmedically trained individuals, according to established procedures and remote Flight Surgeon guidance. The insertion of an endotracheal tube into the abdominal cavity of Cadaver A was performed successfully by a single nonphysician advanced medical practitioner with physician oversight. No physician assistance was required during the procedure.

The HRCUs demonstrated variable fidelity during the laboratory phase, with the MC-HRCU demonstrating more effective odor control and off-gas containment than the MB-HRCU. STAFS personnel noted a faint, putrid malodor about the MB-HRCU by Day 9, which became more notable with progression of the study period. Initial volatile concentration increases were identified by mass spectrometry on Day 13, confirming MB-HRCU leakage. The MB-HRCU was determined to have failed on Day 22, as evidenced by the presence of malodor near the unit and steadily rising volatile concentrations. Following removal of the MB-HRCU from the laboratory phase, it was noted that the MB-HRCU filter was inadvertently cross-threaded at the time of attachment.

The MC-HRCU remained intact throughout the initial 30-d laboratory phase, prompting the exception phase of prolonged data collection. The MC-HRCU did ultimately fail on Day 43 of the study, with notable malodor and rising volatile concentrations prompting removal of the final unit from the study. Detailed results regarding volatile compound analysis and abdominal bloat are detailed below.

HRCU Containment

Volatile fiber analysis of samples taken at zipper and filter port locations for Cadavers A and B are demonstrated in **Fig. 2** and **Fig. 3**. Due to breakage of one fiber during the ongoing experiment, odor analysis could not be completed for all samples at all timepoints: sampling was prioritized using remaining fibers, reducing the frequency of measurements for controls. Decreased frequency of sampling did not appear to negatively impact data collection or substantially limit trend evaluation of volatile concentration analysis.

Concentration of both methanethiol and hydrogen sulfide measurements at the zipper and port locations of both HRCUs and control (in-room) measurements rose on Day 13. Notably, concentrations of both volatiles were significantly higher for Cadaver B, indicating that the MB-HRCU was the likely source of the breach. The MB-HRCU was determined to have failed on Day 22 of the study and Cadaver B was thus removed from the main laboratory. Subsequent measurements demonstrated a decline in volatile concentrations associated with Cadaver A and control measurements.

MC-HRCU (Cadaver A) containment failure, initially noted by odor release detected around the midsection of the HRCU and subsequently confirmed by off-gassing chemical analysis, was recognized on study Day 43, followed by removal of Cadaver A from further evaluation and analysis. Following removal from the laboratory phase, liquid products of decomposition were noted on the gurney beneath the upper torso external to the MC-HRCU outer shell.

Abdominal Bloat

Abdominal rise, measured as peak abdominal height from the gurney with cadavers in supine and flexed supine positioning, is demonstrated in **Fig. 4**.

Progression of Decomposition

Cadaver C decomposition was evaluated daily using total body scoring adjusted for subtropical and humid environments.[1,7,10] Overall, the cadaver progressed from incipient-fresh to late-fresh stages by the second week of the study, with head regions progressing fastest (late-fresh stage by Day 6) and truncal regions later (incipient-early stage by Day 12). Progression continued to mid-early decomposition stages by Day 17 for head and trunk regions, then late-early stages by final data collection on Day 28. Limbs were noted to reach incipient-early stages by Day 9, then remained at incipient-to-mid-early stages of decomposition for the remainder of the study data collection. Truncal bloat was noted on Day 13; head and limb bloat did not occur until Day 24. The final observation day was Day 28; at that time, the cadaver was in the late-early stage of decomposition.

Accumulation of fluid within the C-HRCU of Cadaver C was noted beginning on Day 5 and continuing throughout the inspection period. Fluid accumulation saturated the HRCU containment pad and was estimated to be approximately 2-3 L of total fluid collection over the laboratory phase. Despite fluid accumulation, the C-HRCU was not found to leak at any time. Cadaver C was removed from the study on Day 30.

Impact Testing

Cadavers B and C were utilized for impact testing, which occurred on Day 30 of the study. There was no gross rupture of the HRCU, no rupture of cadaver abdominal cavities, and no external disfigurement identified after impact. There were no fractures identified by radiography or by skeletal autopsy after natural decomposition (210 d).

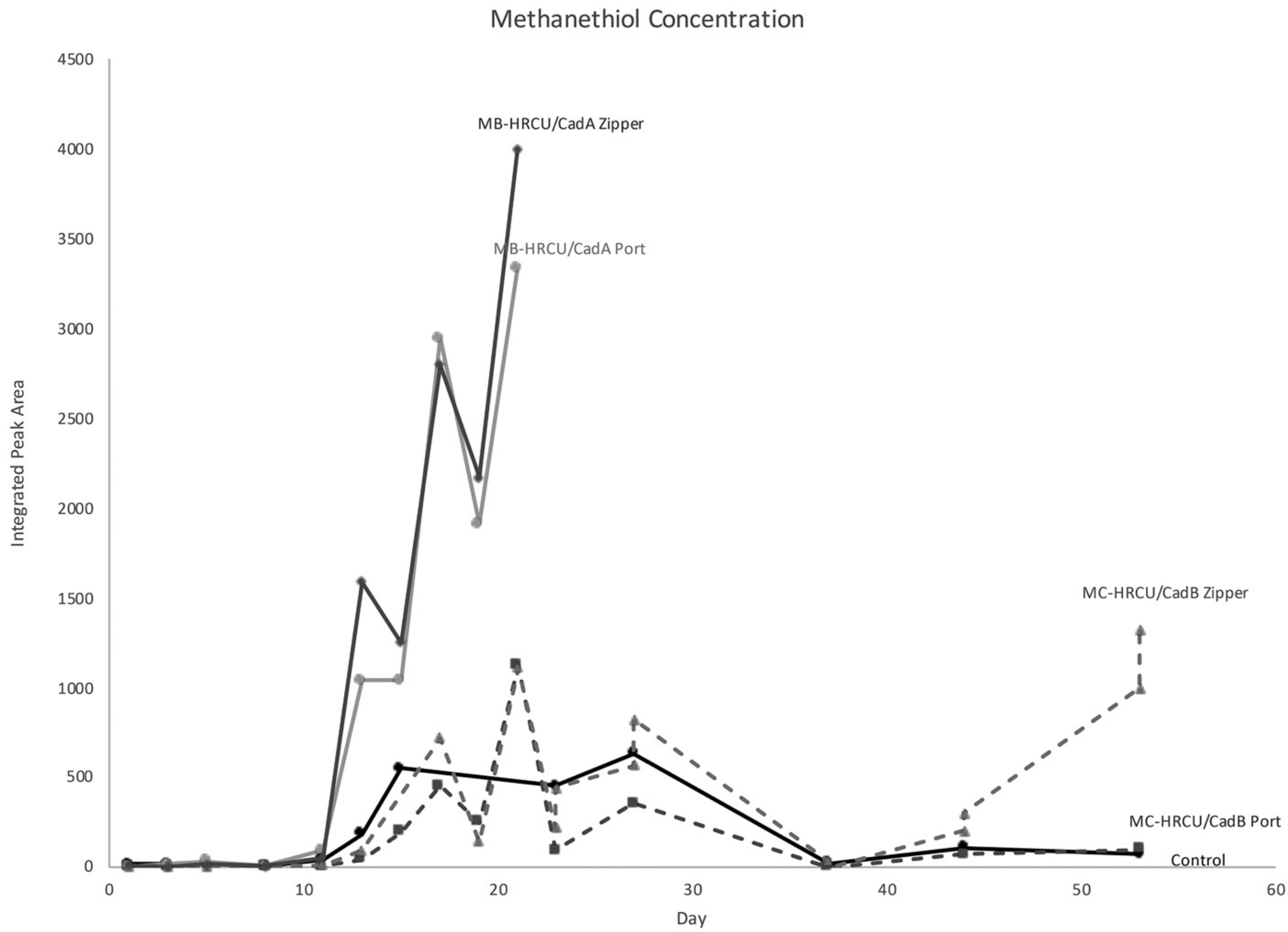

Fig. 2. Integrated peak area of methanethiol as sampled from unit port and zipper locations, as well as a control sample from a distant location in the primary laboratory. The rise of methanethiol concentration associated with MC-HRCU/CadA port/zipper and control samples on Day 13 was believed to be secondary to cross-contamination from volatile release due to failure of the MB-HRCU; this is further supported by subsequent decline of concentrations at MC-HRCU and control locations after removal of the MB-HRCU from the primary laboratory on Day 22. (Note: integrated peak area is unitless and represents peak area from total ion current on chromatogram.) CadA = Cadaver A; CadB = Cadaver B; MB-HRCU = modified biohazard-contaminated human remains containment unit; MC-HRCU = modified chemical-contaminated human remains containment unit.

DISCUSSION

Overall, the modifications to the HRCUs were found to be feasible and likely beneficial for the effectiveness of remains containment and management in a microgravity environment. While the MC-HRCU initially appears to demonstrate greater success for containment, cross-threading of the filter on the MB-HRCU may have led to volatile compound release rather than an inherent failure of the MB-HRCU versus the MC-HRCU. Failure occurred shortly after cadaver repositioning; flexion of the cadaver/HRCU may have additionally contributed to containment failure, though similar failure was not identified after repositioning of the MC-HRCU. Further study—without an error in filter threading—is necessary to better evaluate variable performance between the MB-HRCU and MC-HRCU, particularly with regard to the impact of repositioning on bag reliability. Given that attachment of the filter is a procedural step where error can occur that compromises containment, advance training or practice may be warranted prior to flight. Similarly, the inclusion of a flag in procedural steps, plus the training of ground controllers to provide increased guidance and confirm appropriate threading, may ensure effective filter attachment prior to HRCU use.

While forensic sampling and containment preparatory procedures were performed without difficulty by individuals with even limited-to-no medical training, it was noted that procedural competence in a sterile laboratory facility is not expected to be comparable to microgravity performance in a high-stress, post-fatality environment. The psychological impact of a known decedent, situational stressors, and additional environmental factors (such as microgravity) are likely to have substantial impact on a crewmember's ability to successfully complete sampling and other preparatory procedures. In addition, minimizing and simplifying pre-containment actions is desirable when considering preflight training impact. The utility of extensive preflight training and procedural practice is likely low, especially when weighed against the impact to an already busy preflight training flow. Successful recall of preflight

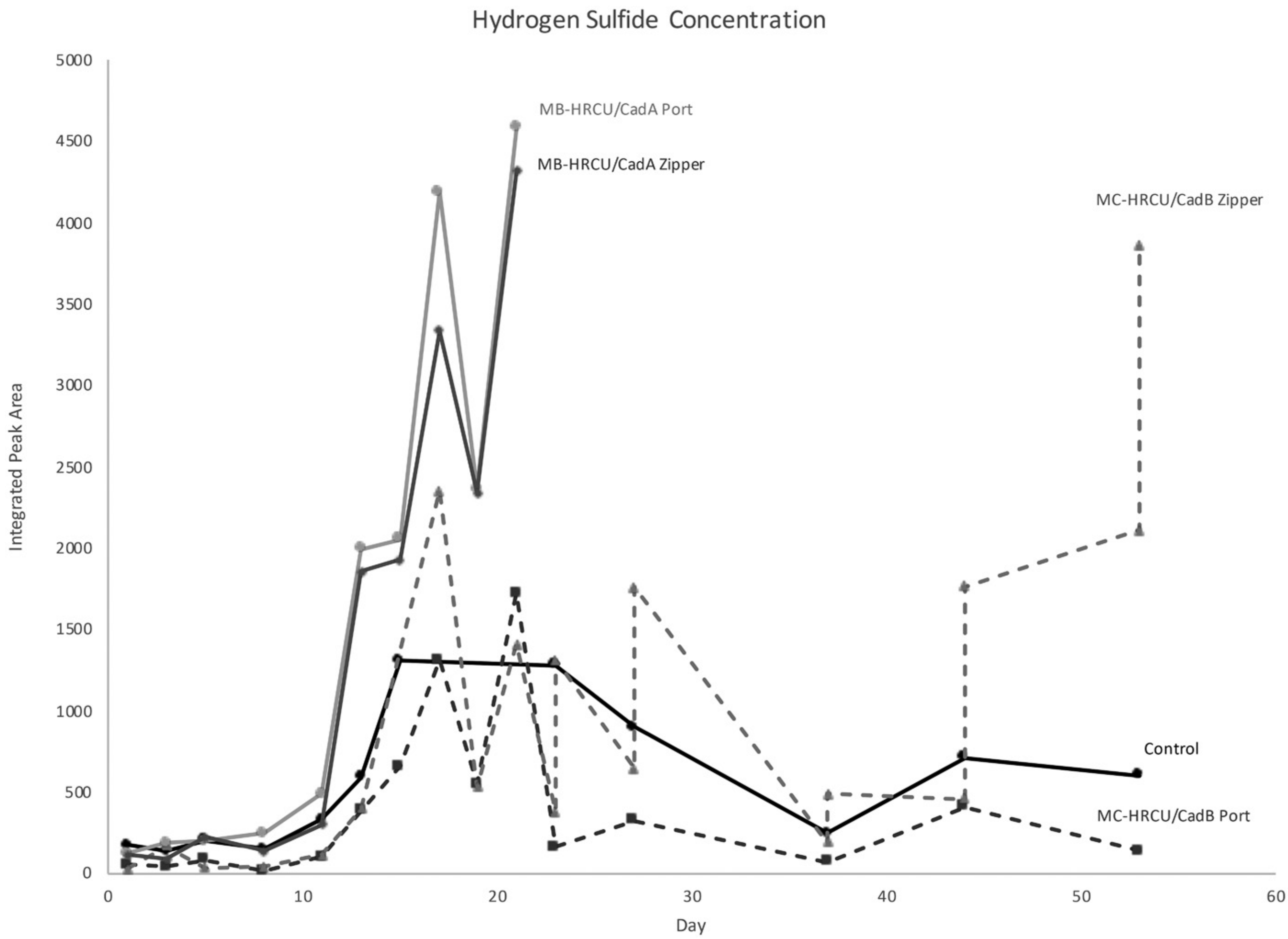

Fig. 3. Concentration of hydrogen sulfide as sampled from unit port and zipper locations as well as a control sample from a distant location in the primary laboratory. The rise of hydrogen sulfide concentration associated with MC-HRCU/CadA port/zipper and control samples on Day 13 was believed to be secondary to cross-contamination from volatile release due to failure of the MB-HRCU; this is further supported by subsequent decline of concentrations at MC-HRCU and control locations after removal of the MB-HRCU from the primary laboratory on Day 22. (Note: integrated peak area is unitless and represents peak area from total ion current on chromatogram.) CadA = Cadaver A; CadB = Cadaver B; MB-HRCU = modified biohazard-contaminated human remains containment unit; MC-HRCU = modified chemical-contaminated human remains containment unit.

training is likely to be further affected by psychological responses to the death of a known decedant.

Insertion and stabilization of an endotracheal tube in the abdominal cavity of Cadaver A was successfully performed by an individual with advanced practitioner-level training; however, it was noted that this procedure could be challenging. It was felt that with the added stressors of the microgravity environment and an in-mission fatality, this procedure may surpass the capability of a nonphysician astronaut. To reduce the complexity of the procedure, an off-the-shelf percutaneous device (for example, a percutaneous cricothyroidotomy insertion kit or a rapid thoracostomy insertion kit) may be a reasonable alternative. Additionally, a simple stab incision, rather than placement of a device, was considered; however, concern was for maintenance of patency over a prolonged period of decomposition. Thus, placement of a trocar was considered most appropriate, though alternatives should be further evaluated for effectiveness as well as training and implementation needs.

Repositioning of the cadavers to a simulated seated position was successful; both cadavers were easily repositioned regardless of presence or absence of the abdominal tube. Subsequent impact testing demonstrated no gross rupture of the HRCU, no apparent cadaverous disfigurement, and no skeletal fractures of remains. This suggests that cadaver repositioning enabled appropriate arrangement in the seat pan and effective restraint of the cadaver/HRCU for impact load protection. It is worth noting that the impact testing occurred in a generic seat mockup; specific vehicle seat designs may offer different protection and risk to remains restrained within. Similarly, any alternative return configuration (for example, restraint of remains in a cargo location) would require additional impact testing to evaluate the risk of force application to remains, HRCU resilience, risk of skeletal fracture, and potential for abdominal rupture, particularly if a decompression tube is not utilized. While further testing is necessary to evaluate HRCU restraint and impact protection in vehicle-specific conditions,

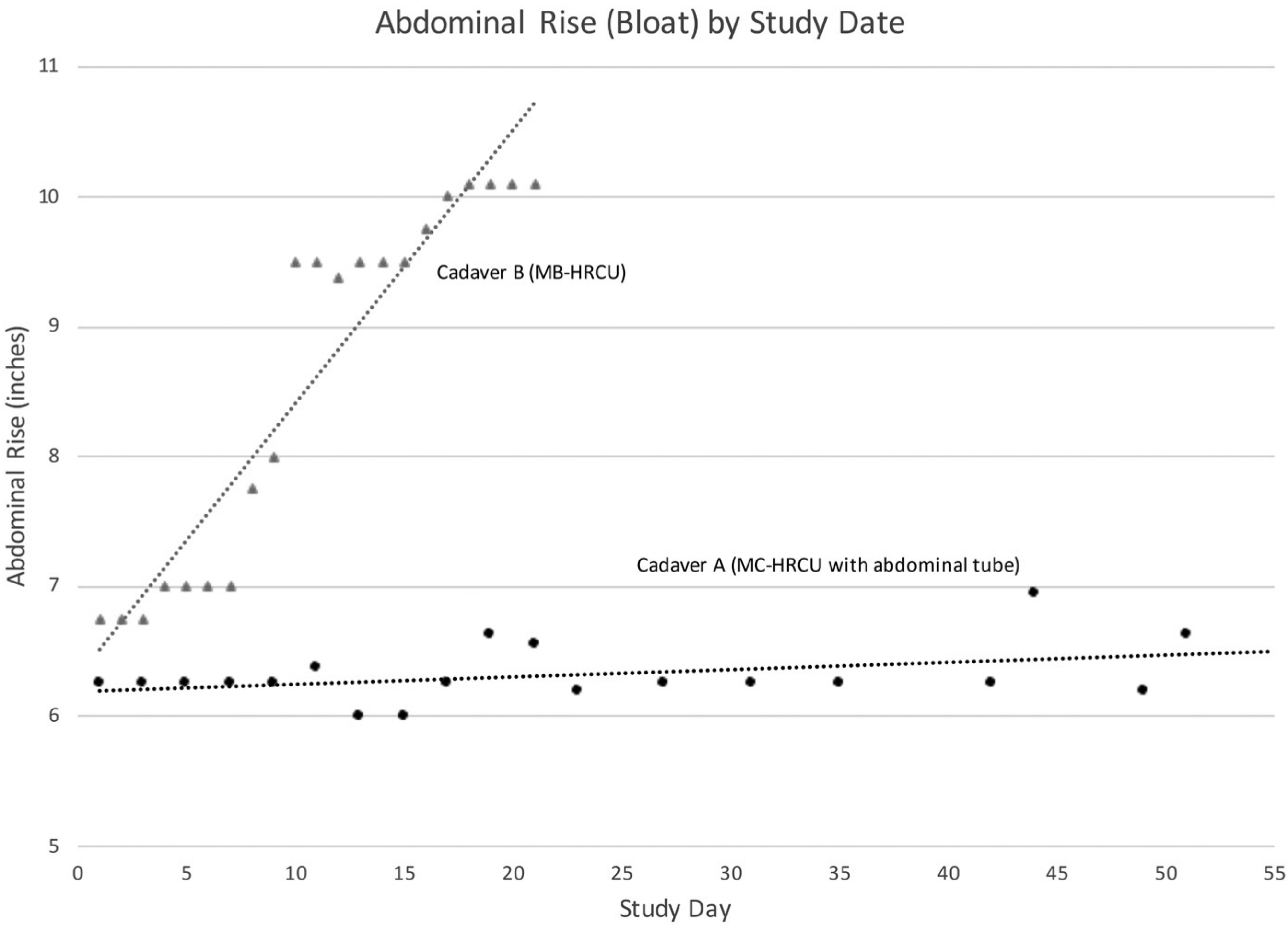

Fig. 4. Abdominal rise measurements of Cadavers A and B during the Laboratory Phase of the study. An endotracheal tube was placed in the abdominal cavity of Cadaver A prior to the study to manage abdominal bloat. MB-HRCU = modified biohazard-contaminated human remains containment unit; MC-HRCU = modified chemical-contaminated human remains containment unit.

including analysis and potential integration into future vehicle designs as well as risks to other vehicle occupants during vehicle reentry and landing, pilot findings suggest that return of remains is at least possible.

While one unit, the MC-HRCU, surpassed expected performance of 30 d containment, with successful isolation of human remains for a period of 43 d before failure, it is worth noting that failure was associated with notable odor/volatile release and subsequent identification of fluid seep through the HRCU outer shell. Fluid leaching may have been due to pressure from the weight of the remains on the gurney for a prolonged period; it is possible that liquid containment failure would not have occurred in a microgravity environment. However, breach of fluid containment in a microgravity environment would pose a substantial biohazard risk. In addition to HRCU equipment failures, risks to containment in the space environment include environmental alterations that may violate containment capabilities of the HRCU resources. For example, alteration of the pressure environment could render HRCU equipment incapable of maintaining isolation of remains; such considerations warrant further evaluation to determine the limits of containment and relative risks to cabin contamination and crew exposure. Finally, risks associated with return of remains, or alternative interment or disposal of remains in a nonterrestrial location, must be weighed against the natural desire to recover decedent remains for personal, religious, scientific, or other reasoning.

As a pilot effort, there are multiple limitations to the study described above. The HRCUs were tested in a terrestrial environment, limiting extrapolation of results to apply to microgravity conditions or altered environments. Impact acceleration following a microgravity period will induce additional factors, including fluid shifting and acceleration stressors that may exceed design limits in ways that cannot be simulated with a terrestrial effort. Positioning of the HRCU to ensure that zippers, filters, major seams, and other potential failure points are opposite from an acceleration vector may improve upon HRCU ability to withstand impact loading; however, without a higher-fidelity simulation—including microgravity and subsequent acceleration exposure—containment under gravitational transitions cannot be fully evaluated. Similarly, alternative remains management options, such as the potential for interim storage of decedent remains external to the vehicle in vacuum conditions, require evaluation to determine feasibility.

In addition, this study included only three cadaverous subjects, each in a different HRCU, with different procedures performed on each. The inadvertent cross-threading of the MB-HRCU filter largely invalidates failure data of the unit. Co-location of HRCUs led to contamination of volatile collection between units after the MB-HRCU failure. Impact testing was performed on only two units, each with different impact velocities. Each of these limitations precludes comparability of results between HRCUs.

Despite these limitations, these pilot efforts are an important step toward the development of effective postmortem containment options for future spaceflight. The MC-HRCU successfully contained remains for greater than 30 d. It is quite possible that, in the absence of filter threading error, the MB-HRCU may be similarly successful. Such prolonged containment capability would offer time for management of multiple post-fatality concerns, including forensic sampling, viewing of remains if desired, careful consideration of disposition options, and, for orbital platforms where return-to-Earth is feasible, even consideration of return of remains to Earth. Further study is warranted to ensure repeatability of the findings herein and to better characterize the failure modes of the modified HRCUs, impact of microgravity conditions, and identification of additional modifications that would improve upon desired remains disposition.

In conclusion, pilot study results suggest that modifications to current commercial off-the-shelf HRCU products may improve upon the feasibility of their use in a spaceflight environment. Limited data indicate that abdominal bloat can be managed through the insertion of an abdominal tube; identification of ideal products and procedures for such an approach warrant additional investigation. The incorporation of a modified HRCU for successful decedent management in spaceflight conditions will ultimately require additional study of technique, product evaluation and modification, collaboration with industry providers to ensure compatibility with vehicles and mission operations, and ethical and psychological considerations for crewmembers who would be required to undertake the procedures described herein.

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