Intravenous Fluid Resuscitation Capabilities in Simulated Reduced Gravity

George M. Pantalos; Justin S. Heidel; Ishita M. Jain; Scott E. Warner; Thomas L. Barefoot; Rachel O. Baker; Melinda Hailey

BACKGROUND: Critical care for exploration space missions may require intravenous (IV) fluid resuscitation therapy. Resource constraints may limit availability of standard, Earth-based infusion technologies. The effect of variable acceleration on infusion flow rates using simple fluid resuscitation supplies was investigated.

METHODS: Infusions of water or blood analog (40% glycerol) from a 1 L IV bag were performed using pressure bag augmentation at 0, 150, or 300 mmHg. The solution bag rested on an adjustable mount, configured to different heights to simulate relevant gravitational accelerations (1 G, Martian G, lunar G, and 0 G). The bag emptied through an IV line with a 14- or 20-gauge angiocath into a 3-mmHg venous pressure reservoir. Flow rates were measured using an in-line flow probe. Three determinations were made for each test condition.

RESULTS: Temporal flow rate data for all test conditions displayed one-phase exponential decay. At 300 mmHg pressurization, maximum infusion rates ranged from 92–222 mL · min^{-1} for water and from 21–49 mL · min^{-1} for blood analog. All reduced gravity conditions had significantly longer infusion times in comparison to 1 G for both test solutions.

DISCUSSION: Reduced acceleration significantly altered flow rates and infusion times for fluid resuscitation. Fluid resuscitation protocols specify a desired volume to infuse for a target time (e.g., 20–30 mL · min^{-1} for a 75-kg adult). This data demonstrates that this protocol parameter can be achieved with infusion pressure bag augmentation alone and provides information for the refinement of fluid resuscitation protocols for exploration space missions.

KEYWORDS: infusion, resuscitation, trauma, spaceflight.

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As humans venture beyond low Earth orbit on deep space exploration class missions (ECMs), the likelihood of a serious medical emergency on a long-duration flight is not a matter of if, but rather when. Prior studies have estimated the risk of a serious medical event to be 0.06 per person-year of flight, which translates to at least one major event expected for a 6-person crew on a 900-d mission to Mars.[12] To prepare for upcoming ECMs, NASA presented the Technology Roadmap in 2015, which enumerates the necessary medical advancements and accommodations needed for long-duration spaceflight.[16] In the event of a mid-mission trauma, the provision of appropriate countermeasures and protocols for fluid resuscitation therapy (FRT) are paramount to ensuring health and safety of the crew members. The timeline with which to achieve the technical specifications of the Roadmap grows ever shorter as NASA works to return humans to the Moon by 2024 and, by the 2030s, send them to Mars.[5,13]

Traumatic injury has been previously cited as "the highest level of concern regarding the probable incidence versus impact" on ECM success and crew health.[10] Medical care experiences from U.S. Navy submarines and Antarctic

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expeditions—both extreme, isolated environments that serve as analogs to ECMs—demonstrate that while major surgical events are scarce, they may have devastating consequences for the mission because they necessitate evacuation.[2] This is not an option for ECMs. Blunt and penetrating traumas may occur during the routine, yet dangerous, operations of an astronaut, such as surface operations, spacecraft repair, vehicle docking, and payload deliveries.[19] Thus, crew members must be equipped with the knowledge and resources to successfully manage such an event.

In addition to the risk of blunt and penetrating traumas during routine activities aboard the spacecraft, extensive research has explored the many physiological alterations that occur in both acute and long-term weightlessness that may complicate space-based medical care. In particular, there is well-documented physiological hypovolemia, attrition of red blood cell mass, cardiovascular deconditioning, dysrhythmias, and alteration in adrenergic-receptor sensitivity that could reduce the ability of trauma victims to undergo effective hemorrhage compensation during spaceflight.[11,19] Furthermore, the evidence supporting impaired wound-healing and immune system dysregulation in weightlessness suggest risk of complication in post-operative recovery.[10]

Fluid resuscitation therapy (FRT) and management of critically injured patients necessitates the use of intravenous fluids in conjunction with techniques to limit further hypovolemic deterioration. Various protocols exist for Earth-based care, yet there remains extensive debate as to the optimal volume, fluid composition, infusion timing, and clinical population for which these therapies are best employed.[7] To prevent complications related to fluid overload, such as dilutional coagulopathies, metabolic acidosis, diffuse tissue edema, compartment syndrome, and hyperkalemia, which may be more difficult to manage mid- spaceflight, attention must be given to developing proper infusion techniques and strategies for ECMs.[20]

Practical considerations of spaceflight, such as storage, equipment mass, and electrical requirements, may limit the incorporation of certain medical technologies into the payload of ECM spacecraft. Thus, the expectation of a continuous-flow infusion pump for FRT may be unrealistic. Instead, an intravenous infusion using solely a pressure infuser sleeve has previously been shown to be feasible and easily performed in weightlessness on parabolic flights.[3] Therefore, the objective of this study was to assess the effect of variable gravitational acceleration (Earth, lunar, Martian, and microgravity) on infusion flow rates and times to achieve sufficient increase in circulating fluid volume using commercially available FRT components commonly applied in trauma scenarios on Earth. Knowledge of variations in infusion parameters under the influence of reduced gravity may illuminate the development of space-optimized fluid resuscitation protocols to manage traumatic injuries during ECMs.

It is important to realize that conventional ways of assessing IV flow rate at the faster flow rates needed for FRT and in reduced gravity are not applicable. The guideline that 20 drops/mL for clear fluid and 15 drops/mL for thicker fluids and blood can be used as the basis of adjusting the drip rate to obtain the desired infusion rate is commonly used for low IV flow rates on Earth. However, this investigation is focused on obtaining sufficient elevated flow rates (20–30 $mL \cdot min^{-1}$) for a rapid fluid resuscitation procedure—that would be trying to count 400–600 drops/min, which would be a difficult, if not impossible, task. Working in reduced gravity or microgravity further complicates the IV fluid mechanics as there is little or no hydrostatic pressure to drive infusion flow rate, and the surface tension of the IV fluid dominates and alters the fluid behavior compared to 1 G. Consequently, in microgravity, the infusion flow fills the drip chamber in the IV set such that there is not a stream of drops to count or other visible cues to assess the flow rate. Hence, there is a need to measure the inline flow rate with a flow sensor to determine what flow rates can be generated with a pressurized sleeve around the bag of infusion fluid to drive the IV infusion, as was used in this investigation.

METHODS

Apparatus Design and Reduced Gravity Simulation

A 1-L IV infusion bag, containing either water to simulate normal saline/crystalloid (1.0 cP) solution or 40% glycerin in water solution (Sigma-Aldrich, St. Louis, MO) as an analog to the bulk viscosity and density of human whole blood (3.5 cP[18]), was rested horizontally upon an adjustable wall-mounted shelf (**Fig. 1**). The possibility of blood transfusion was also considered since progress in long-term blood storage appropriate for exploration spaceflight has recently been reported.[4,8] The infusion bag was outfitted with a standard clinical pressure infuser sleeve (Infu-Surg, Ethox International, Buffalo, NY) to generate pressures up to 300 mmHg. The solution bag was spiked with an infusion set (SmartSite, CareFusion, San Diego, CA) equipped with a 1.2-μm air eliminating filter extension (B Braun Medical Inc., Bethlehem, PA) and fitted distally with a Luer-Lok port and angiocatheter (Instye Autoguard, Becton Dickinson, Franklin Lakes, NJ); the roller flow regulator clamp in the infusion set was adjusted to the maximally opened position. The angiocatheter, to which the datum of gravitational acceleration was established, was submerged into a fluid-filled reservoir and secured using medical-grade tape. The initial level of the reservoir was calibrated to a hydrostatic pressure of 3 mmHg to simulate reduced central venous pressure in hypovolemic patients.[6] Flow rates were measured using a TS410 ultrasonic transit-time flow meter via an in-line 4PXN probe (Transonic Systems, Ithaca, NY).

To simulate reduced gravity scenarios, infusion rates were measured from various heights above the angiocatheter datum. The infusion reference height for Earth gravity (1 G) was set at 1 m. In accordance, a height of 37.8 cm was used to simulate Martian gravity (3.71 $m \cdot s^{-2}$) and 16.5 cm was used for lunar gravity (1.62 $m \cdot s^{-2}$). The infusion bag was rested at the datum level to approximate micro- or zero gravity (0 G).

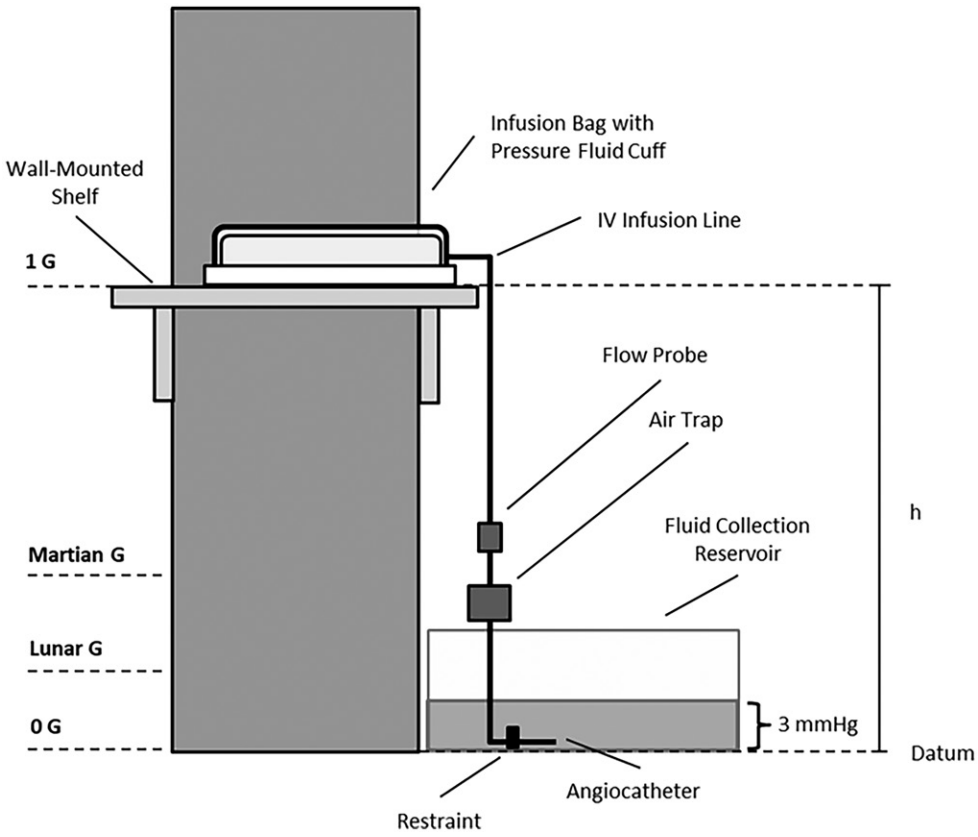

Fig. 1. Infusion apparatus schematic. The height (h) of the wall-mounted shelf was adjusted to reflect reduced gravitational acceleration relative to Earth, the baseline of which was established at 1 m. The corresponding levels of the infusion fluid bag to generate the corresponding hydrostatic infusion pressure in Martian gravity, lunar gravity, and microgravity or 0 G are indicated along with the other components of the infusion study set-up.

Procedure and Data Collection

For both water and blood analog solution, infusion was initiated at designated cuff pressurizations of 0 mm Hg, 150 mm Hg, and 300 mm Hg through both 14- and 20-gauge angiocatheters. Each test condition was repeated three times ($N = 3$). Upon initiation, the maximum flow rate was recorded. Subsequent flow rate data was recorded at a flow sensor sampling rate of 0.1 Hz to indicate average flow. A correction factor of 1.124 (determined via timed volume collection calibration) was applied to all data collected using the analog blood solution to properly correct for the transit-time probe calibration set for water. One-phase exponential decay regression models of the infusion flow rate data were generated via GraphPad Prism 8.1.2, (GraphPad Software, San Diego, CA) according to the following equation:

$$Y = \left(Y_0 - Y_{SS}\right)e^{-kx} + Y_{SS}$$

Y represents the infusion flow rate as it progresses with time. For all models, the maximum flow rate, Y_0, steady state flow rate, Y_{SS}, and the time constant, k, are reported. The regression equations for each respective condition of gravitational acceleration were integrated to calculate the time, in min, necessary to reach an infusion of clinically relevant volumes of 150, 250, 500, and 1000 mL for water and up to 500 mL (volume of a unit of blood) for the blood analog solution.

Statistical Analyses

All statistical analyses were performed using GraphPad Prism 8.1.2. Gaussian distribution of the maximum flow rate, steady state, and infusion time data were first assessed using a Shapiro-Wilk test. The statistical significance of these data sets was determined via 2-way ANOVA. Post hoc Tukey multiple comparison tests were then performed to ascertain significant alterations in infusion time and flow rates between gravitational acceleration conditions alone. For all data sets, the arithmetic mean ± SD (SD) is reported. *P*-values less than a type I error of $\alpha = 0.05$ were considered statistically significant. The following notations were used to indicate the level of statistical significance: when available, the calculated *P*-value is presented; if the calculated *P*-value was <0.0001, the *P*-value reported by the statistical software used was $P < 0.0001$. Non-significance between all groups was represented by $P > 0.05$. Detailed statistical data for all the charts presented in **Fig. 2** and **Fig. 3** are presented in supplemental **Table AI** and **Table AII** (both are available online at https://doi.org/10.3357/AMHP.6151sd.2023).

RESULTS

In this study, we sought to determine the effects of reduced gravitational acceleration on infusion of both water (a saline/crystalloid fluid analog) and 40% glycerol (a whole blood analog).

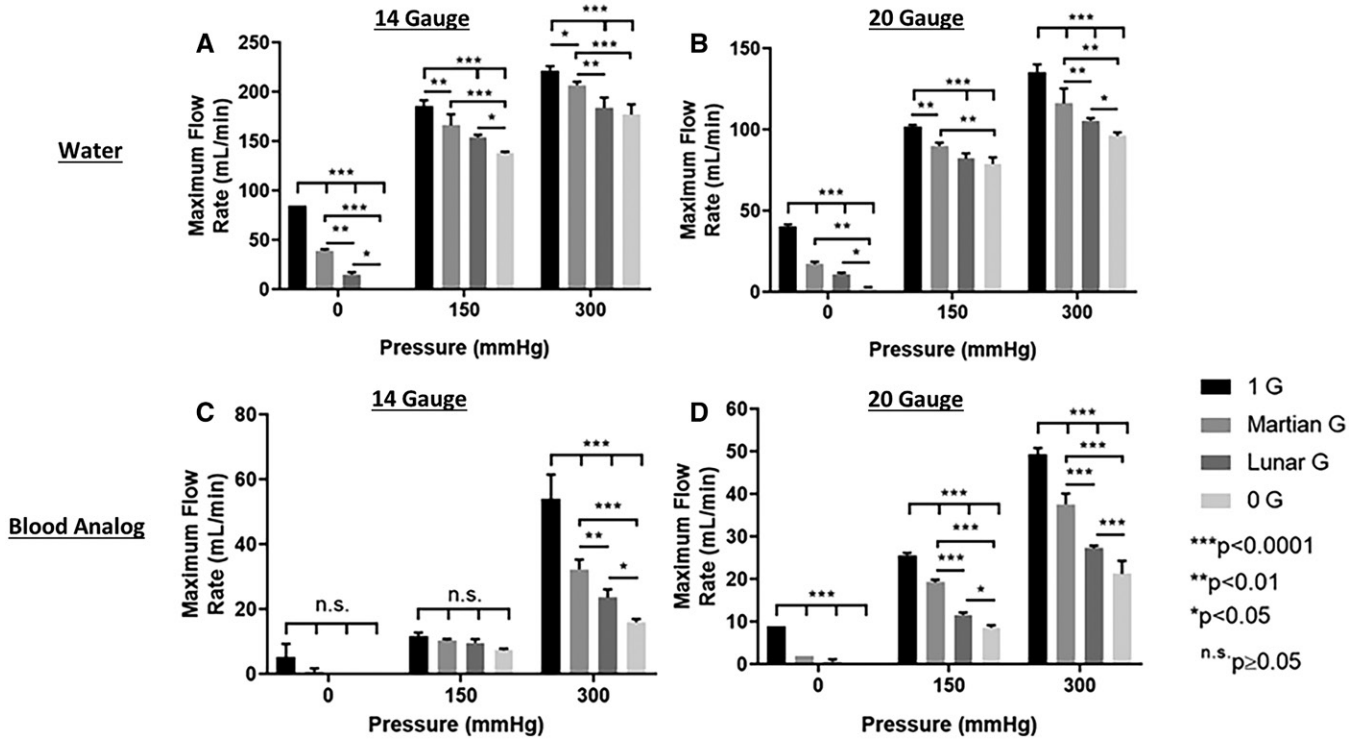

Fig. 2. Maximum flow rates achieved under the conditions of reduced gravity compared to Earth gravity. Flow rates were measured for infusion of water via (A) 14-gauge and (B) 20-gauge angiocatheters, as well as for blood analog fluid (40% glycerin in water) via (C) 14-gauge and (D) 20-gauge angiocatheters (N = 3/test condition; note the difference in the flow rate axis values) are presented. *P < 0.05, **P < 0.01, ***P < 0.0001, $^{n.s.}P \geq 0.05$. Degrees of Freedom range from 2–24. Additional statistical details are presented in Supplemental Table AI.

The infusions were performed in triplicate using the aforementioned experimental apparatus and procedure (Fig. 1). Temporal flow rate data generated for both water and blood analog solutions in combinations of angiocatheter gauge, cuff pressurization, and gravitational acceleration displayed an exponential decay from initiation. From the temporal data, regression models were determined as presented in **Tables I** and **Table II**.

Maximum flow rates were recorded for each combination of angiocatheter gauge and augmentation sleeve pressurization to generate the regression models that encompass the combined initial effects of both gravitational acceleration and cuff pressurization (Fig. 2). For the infusion of water, the maximum flow rates differed significantly between reduced and Earth gravitational acceleration conditions for all sleeve pressurizations, regardless of whether a 14- or 20-gauge angiocatheter was used ($P < 0.05$) (Fig. 2). For the infusion of 40% glycerol, however, no significant difference was observed for lower sleeve pressurizations (0 and 150 mmHg) using a 14-gauge ($P > 0.05$). Maximum flow rates at 1 G were significantly higher than those for reduced gravity conditions at 300 mmHg ($P < 0.0001$). A similar trend was observed for infusions of 40% glycerol through a 20-gauge angiocatheter, yet this was observed in all cuff pressurizations ($P < 0.0001$). The maximum flow rates achieved with a 1.0 cp solution were much greater than those that could be generated with the infusion of the blood analog (3.5 cp) solution (Fig. 2).

Using the regression models (Table I and Table II) developed for the temporal infusion rate data, the steady state flow rates were derived. Overall, the steady state flow rates tended to decrease with a greater reduction in gravitational acceleration (Table I and Table II). For infusions of water, significant attenuation of steady state flow rates occurred for all sleeve pressurizations between 1 G and reduced gravity, via both 14- and 20-gauge angiocatheters ($P < 0.01$). For the blood analog infusions via a 14-gauge angiocatheter, a significant reduction was noted for 150 ($P = 0.0161$) and 300 mmHg ($P < 0.0001$) cuff pressurizations between 1 G and 0 G, but not at 0 mmHg ($P > 0.05$). Using a 20-gauge angiocatheter, significant reductions were noted between 1 G and 0 G at all cuff pressurizations ($P < 0.01$). Additional statistical data details are presented in supplemental Table AI and Table AII (both are available online at https://doi.org/10.3357/AMHP.6151sd.2023).

From the water infusion data, one-phase exponential decay regression equations were derived; the resulting model parameters for the greatest cuff pressurization, 300 mmHg, are reported (Table I). Initial flow rates (Y_0) for the 1 G condition were attenuated by 40% ± 1%, for Martian G by 45% ± 1%, for lunar G by 44% ± 1%, and for 0 G by 47% ± 1% between the 14- and 20-gauge angiocatheters. Initial flow rates were reduced by 22% ± 1% and 30% ± 1% between 1 G and 0 G for the 14- and 20-gauge angiocatheters, respectively.

The one-phase decay regression model parameters for the infusion of 40% glycerol at a sleeve pressurization of 300 mmHg were likewise reported (Table II). Between the 14- and 20-gauge angiocatheters, the initial flow rates were reduced for 1 G by only 2% ± 0%. However, for Martian G, lunar G, and 0 G, the initial flow rates were increased by 17% ± 0%, 24% ± 0%, and

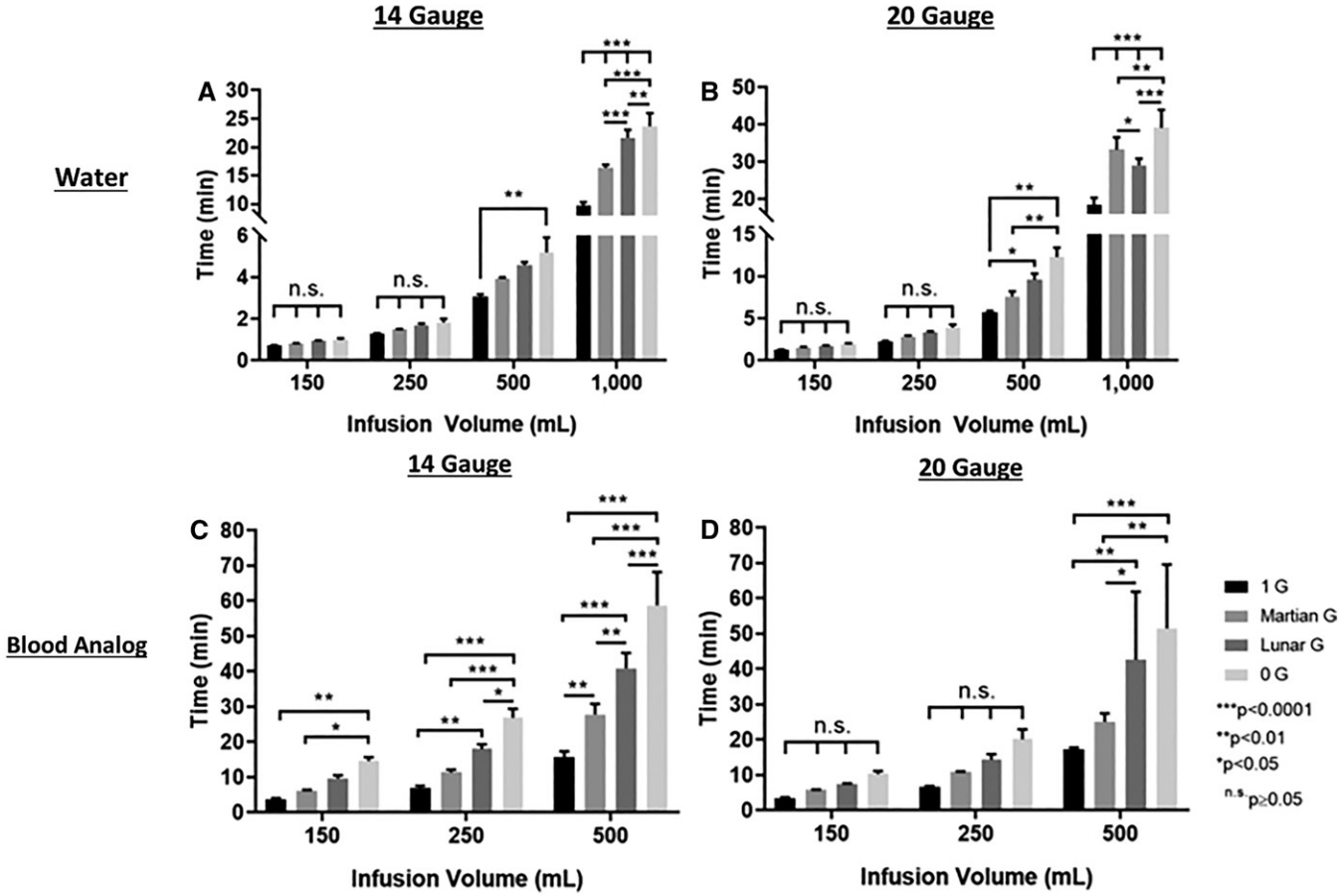

Fig. 3. (Top) Time to infuse clinically relevant volumes of water ($N = 3$/test condition; note the difference in the infusion time axis values). Average calculated infusion time ± SD are plotted. Infusions were performed using a single pressurization of the cuff to 300 mmHg and either an (A) 14-gauge or (B) 20-gauge angiocatheter. *$P < 0.05$, **$P < 0.01$, ***$P < 0.0001$, $^{n.s.}P \geq 0.05$. (Bottom) Time to infuse clinically relevant volumes of blood analog solution (40% glycerin in water; $N = 3$/test condition). Average calculated infusion time ± SD are reported. Infusions were performed using a single pressurization of the cuff at 300 mmHg and either a (C) 14-gauge or (D) 20-gauge angiocatheter. *$P < 0.05$, **$P < 0.01$, ***$P < 0.0001$, $^{n.s.}P \geq 0.05$. Degrees of Freedom range from 2–32. Additional statistical details are presented in Supplemental Table AII.

40% ± 0%, respectively, using the 20-gauge angiocatheter compared to the 14-gauge. Compared to 1 G, the 0 G initial flow rates were reduced by 69% ± 0% and 56% ± 0% for 14- and 20-gauge angiocatheters, respectively.

From the regression models, the infusion times were calculated via integration (Fig. 3). With the infusion of water through a 14-gauge angiocatheter, the time to infuse small volumes, such as 150 and 250 mL, did not differ significantly between gravitational accelerations ($P > 0.05$) (Fig. 3, top, A and B). For 500 mL, however, a significant difference in time was noted between 1 G (3.06 ± 0.12 min) and 0 G (5.20 ± 0.73 min, $P = 0.0061$). Infusion of 1000 mL differed significantly between all conditions of gravitational acceleration ($P < 0.05$). Using a 20-gauge angiocatheter, a similar lack of significant difference was observed

Table I. Regression Equation Parameters Developed for Water Infusion Rate Curves ($N = 3$).

ANGIOCATHETER GAUGE	GRAVITATIONAL ACCELERATION	Y_0 (mL/min)	Y_{SS} (mL/min)	k ($min^{-1} * 10^{-2}$)	R^2-adj	*P*-value
14	1 G	222 ± 1	36 ± 2	26.6 ± 7.4 * 10^{-1}	0.993	<0.0001
	Martian G	202 ± 1	29 ± 1	32.4 ± 5.6 * 10^{-1}	0.997	<0.0001
	lunar G	181 ± 1	21 ± 2	29.3 ± 7.2 * 10^{-1}	0.994	<0.0001
	0 G	173 ± 2	22 ± 3	31.2 ± 1.4	0.977	<0.0001
20	1 G	131 ± 1	31 ± 2	22.6 ± 7.6 * 10^{-1}	0.993	<0.0001
	Martian G	112 ± 1	15 ± 3	19.1 ± 1.3	0.978	<0.0001
	lunar G	101 ± 1	25 ± 1	26.6 ± 1.2	0.984	<0.0001
	0 G	92 ± 1	20 ± 2	27.8 ± 1.7	0.966	<0.0001

The infusion curves were fitted to a one-phase exponential decay function. The parameters include initial flow rate (Y_0), steady state flow rate (Y_{SS}), and the rate constant (k). For each parameter, the average ± SD is reported. Infusions were performed using a single compression to 300 mmHg and either a 14- or 20-gauge angiocatheter. Degrees of Freedom = 141.

Table II. Regression Equation Parameters Developed for 40% (v/v) Glycerol Infusion Rate Curves ($N = 3$).

ANGIOCATHETER GAUGE	GRAVITATIONAL ACCELERATION	Y_0 (mL · min^{-1})	Y_{SS} (mL · min^{-1})	k (min^{-1} * 10^{-2})	R^2-ADJ	*P*-VALUE
14	1 G	49 ± 1	27 ± 2	27.5 ± 4.8	0.780	<0.0001
	Martian G	30 ± 0	15 ± 2	16.0 ± 3.2	0.874	0.0017
	lunar G	21 ± 0	12 ± 1	21.0 ± 5.3	0.732	0.0057
	0 G	15 ± 0	9 ± 1	26.6 ± 4.4	0.810	<0.0001
20	1 G	48 ± 0	16 ± 2	13.1 ± 1.6	0.965	0.0003
	Martian G	35 ± 0	18 ± 1	29.1 ± 2.2	0.945	<0.0001
	lunar G	26 ± 0	12 ± 1	15.6 ± 2.5	0.922	0.0002
	0 G	21 ± 0	10 ± 1	20.8 ± 4.1	0.816	0.0008

The infusion curves were again fitted to a one-phase exponential decay function. The parameters include initial flow rate (Y_0), steady state flow rate (Y_{SS}), and the rate constant (k). For each parameter, the average ± SD is reported. Infusions were performed using a single compression to 300 mmHg and either a 14- or 20-gauge angiocatheter. Degrees of Freedom = 141.

for the infusion times for 150 and 250 mL ($P > 0.05$) (Fig. 3, top). Both lunar G (9.61 ± 0.72 min, $P = 0.0339$) and 0 G (12.30 ± 1.11 min, $P = 0.0002$) differed significantly from 1 G (5.74 ± 0.15 min) for a 500 mL infusion. All reduced gravity conditions were found to be significant in comparison to Earth gravity at 1000 mL infusions, as well as among one another ($P < 0.05$). In summary, the infusion time for water/crystalloid fluids does not appear to differ significantly in small volumes between Earth and reduced gravity scenarios; however, the contrary was observed in larger volumes, such as 500 and 1000 mL.

Infusion times for clinically relevant volumes of blood analog solution were calculated via integration, just as for the water infusions (Fig. 3, bottom, C and D). Whereas the infusion time for water at low volumes did not differ significantly between gravitational accelerations, the opposite was observed for blood analog infusions using a 14-gauge angiocatheter. At 150 mL, the infusion time in 1 G was significantly less than for 0 G ($P < 0.0027$). This phenomenon was also observed for infusions of 500 and 1000 mL ($P < 0.0001$). Conversely, using a 20-gauge angiocatheter, no significant differences in low volume infusion times were noted between reduced and Earth gravity conditions ($P > 0.05$) (Fig. 3D). However, at 500 mL, infusion times for lunar G (42.63 ± 19.24 min, $P = 0.0026$) and 0 G (51.52 ± 18.09 min, $P < 0.0001$) were significantly greater than at 1 G (17.26 ± 0.60 min).

DISCUSSION

It is apparent from the results of this investigation that the choice of angiocatheter gauge will greatly influence how rapidly the initial infusion of water (approximating saline or 1.0 cp crystalloid fluid) will proceed, which identifies an important factor to consider when selecting the proper gauge for FRT . The results also indicate that gravitational acceleration, in combination with angiocatheter gauge, will also influence how quickly the initiation of infusion will proceed. In addition, the results also demonstrate that gravitational acceleration or reduced gravity dramatically alters the initial capabilities for fluid administration rate of blood and other infusion solutions of higher viscosity when compared to crystalloid solutions. The data collected for both water and blood analog infusions suggest that gravitational acceleration substantially influences the time to infuse clinically relevant fluid volumes for FRT management of hypovolemia. The relevant work of other investigations corroborates the results of this study to support the hypothesis that an adequate combination of angiocatheter gauge and sleeve pressure bag pressure augmentation will deliver an adequate fluid infusion rate for effective FRT in reduced and microgravity.

Due to the aforementioned limited spacecraft payload accommodations, developing the means of providing adequate medical resources for deep space ECMs remains a topic of extensive debate. The development of proper FRT protocols for ECM demands optimization of the infusion strategy, fluid type, vascular access, and post-infusion reevaluation. The results of this study demonstrate that a reduction in gravitational acceleration significantly alters the flow rates and infusion times of saline and whole blood analog fluids, yet the difference may not be of clinical consequence given the range of infusion flow rates that can be achieved. FRT protocols often do not directly specify a continuous or average infusion rate based on time; rather, they specify a desired volume to infuse for a target time. Wise et al. specify a rate of 4 mL · kg^{-1} for clear fluid infusion over 10–15 min.[20] This, for example, would yield an average flow rate of 20–30 mL · min^{-1} for a 75-kg astronaut receiving only 300 mL of fluid during the initial resuscitation phase. Based on the calculated infusion times for saline/crystalloid analog and blood analog with pressure sleeve augmentation, these conditions are satisfied using either the 14- or 20-gauge angiocatheters (Fig. 2 and Fig. 3). The lack of specification of strict flow rate restrictions for some FRT protocols suggests that continuous flow rate infusion pumps, which consume electrical power and add mass and volume to the spacecraft, are not needed for the ECM supply manifest.

A demonstration of rapid fluid infusion during orbital spaceflight (though not intended for that purpose) occurred on the STS-55 (D2) mission in 1993 as a part of a renal and endocrine response investigation.[17] Over a 20–22-min period, 4 human test subjects underwent an isotonic/isothermal saline infusion challenge (2% of preflight body weight) using a standard infusion set with an inline air bubble filter. The size of the short venous catheter inserted in a forearm vein was not reported. The pressure difference to drive the saline through the infusion set and into the vein was created by wrapping a standard blood pressure cuff around the bag of saline and

inflating the cuff to create an elevated pressure in the bag sufficient to infuse the desired volume of saline in the desired time. Infusion rates were not reported, but given the reported fluid volume infused and the reported time for infusion challenge, an infusion rate of 90 ml · min^{-1} could be calculated. This value is consistent with the flow rates observed in this investigation when infusing water through a comparable infusion set with a 20-gauge angiocath at the fluid exit into the venous collection reservoir. We further corroborate this finding with yet to be published data from recent parabolic flights using the same infusion test set-up.

Conditions other than blunt and penetrating traumatic injuries, which require prespecified FRT protocols, may also occur during ECMs. The Surviving Sepsis Campaign (SSC) has published on the management of sepsis-induced shock, which may be likely to occur due to immunosuppression and impaired wound-healing processes in weightlessness, identifying an infusion rate of 30 mL · kg^{-1} within 3 h.[2,14] For a 75-kg astronaut, this would necessitate the infusion of 2.25 L of crystalloid fluid over 3 h, which is reasonable to accomplish with only manually powered FRT components, despite the influence of reduced gravity on infusion time (Fig. 3). FRT management of burns during ECMs also requires optimized protocols. The Parkland formula specifies the infusion of Lactated Ringer's solution at 4 mL · kg^{-1} · $\%TBSA^{-1}$ (total body surface area burned) over 24 h.[1] Knowledge of the infusion rate characteristics based on pressurization, angiocatheter gauge, fluid viscosity, and gravitational acceleration presented in this study may aid in the optimization of FRT protocols for each of these scenarios, as well as for traumatic injuries.

The infusion rate data collection was limited by the resolution of the flow meter, which did not report the mL · min^{-1} to the tenths decimal place; however, this is unlikely to make any considerable, clinically relevant impact on the usefulness of the data and operation clinical management of infusion therapy. The resolution of the flow meter is reflected in the significant figures included in the regression table parameters [Table I and Table II and supplemental Table AI and Table AII(both are available online at https://doi.org/10.3357/AMHP.6151sd.2023)]. In addition, the method of vascular access is paramount to the establishment of proper FRS protocols in ECMs. This study was limited to the investigation of IV angiocatheters, yet the notion of using intraosseous (IO) access kits to achieve FRT in reduced gravity has been previously entertained.[12] IO access may provide a viable alternative to peripheral IV infusion, which may be challenging due to hypotensive venous collapse and central venous catheterization, which is technically demanding and poses a higher risk of complication.[9] However, the nature of the traumatic injury may limit the feasibility of employing IO access.

While the results of this study suggest that commercially available FRT components may be capable of supporting previously established guidelines for FRS care, further challenges prevent the direct translation of Earth-bound FRT principles to ECMs. Future studies should investigate the training necessary for crew members to master the operation of the FRT components and understand the algorithms used in resuscitating trauma patients. The development of space-based FRT strategies should account for practical storage and IV fluid selection considerations for ECMs. The availability of 0.9% saline fluid regeneration capabilities using the IVGEN system should also be regarded in the discussion of what fluids to incorporate into the manifest.[12,15] In addition, attention should be paid to the selection of necessary diagnostic equipment, such as blood analyzers for identifying FRT-induced coagulopathy, that may reduce complications associated with improper FRT in trauma patients.[12,20]

In conclusion, this study suggests that the maximum flow rate, steady state flow rate, and infusion time for fluids of similar composition to saline and whole blood is greatly influenced by a reduction in gravitational acceleration, but clinically effective infusion flow rates for FRT are in reduced and microgravity are achievable with the optimal combination of angiocatheter gauge and sleeve pressure bag pressure augmentation, while requiring minimal supply resources. The results presented in this study are intended to be applied to developing FRT protocols and providing information on the capabilities of common IV infusion supplies in reduced gravity conditions. Because FRT is a complex aspect of emergency readiness during deep space ECMs, the refinement of protocols, supplies, vascular access techniques, fluid management, and crew training are all essential to ensuring the safety and health of crewmembers embarking on extended, arduous spaceflight campaigns.

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