Ultrasonographic Evaluation of Sinusitis During Microgravity in a Novel Animal Model

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Objectives: To develop an animal model of rhinosinusitis in microgravity, to characterize the behavior of intracavitary fluid in microgravity, and to assess the accuracy of ultrasonographic (US) diagnosis in microgravity.

Design: An animal model of acute sinusitis was developed in anesthetized swine by creating a window into a frontal sinus to allow unilateral catheter placement and injection of fluid. We performed US examinations in normal and microgravity environments on control and sinusitis conditions and recorded these for later interpretation.

Setting: Henry Ford Hospital and the National Aeronautics and Space Administration (NASA) Microgravity Research Facility in Houston, Texas.

Subjects: Ground (normal-gravity) experiments were conducted on anesthetized swine (n=4) at Henry Ford Hospital before the microgravity experiments (n=4) conducted in the NASA Microgravity Research Facility.

Main Outcome Measure: Ultrasound visualization of fluid cavity.

Results: Results of bilateral US examinations before fluid injection demonstrated typical air-filled sinuses. After unilateral injection of 1 mL of fluid, a consistent air-fluid interface was observed on the catheterized side at ground conditions. Microgravity conditions caused the rapid (<10-second) dissolution of the air-fluid interface, associated with uniform dispersion of the fluid to the walls of the sinus. The air-fluid interface reformed on return to normal gravity.

Conclusions: The US appearance of fluid in nasal sinuses during microgravity is characterized in the large animal model. On the introduction of microgravity, the typical air-fluid interface disassociates, and fluid lining the sinus can be observed. Such fluid behavior can be used to develop diagnostic criteria for acute bacterial rhinosinusitis in the microgravity environment.


Acute bacterial rhinosinusitis (ABRS) is defined as a sudden-onset bacterial infection involving inflammation of the mucous membranes of the nasal cavity and paranasal sinuses, fluids within these cavities, or underlying bone. Often ABRS develops secondarily to a viral infection and inflammation of the upper respiratory tract. When nasal passages become inflamed, normal drainage of mucus is altered and fluid can accumulate, creating an environment favorable for bacterial growth. In cases in which fluid buildup occurs, timely diagnosis and intervention is key to prevent the proliferation of a bacterial infection. Of the estimated 1 billion cases of viral upper respiratory tract infections that occur annually in the United States, approximately 20 million cases develop into ABRS. Diagnostic symptoms of ABRS include nasal congestion, purulent nasal drainage, maxillary tooth or facial pain, change of the sense of smell, and a number of other less common symptoms. Although it is difficult to distinguish a prolonged viral infection from ABRS, accurate diagnosis is imperative to determine the proper course of treatment. Unlike a viral upper respiratory tract infection, ABRS may require antibiotic treatment to cure the infection and prevent future complications or to prevent rare complications.

A number of factors are known to predispose an individual to the development of rhinosinusitis, including allergies, anatomic abnormalities, and environmental irritants, such as dry air and secondary smoke exposure. The unique characteristics of the space environment may contribute to the progression of ABRS. Mucociliary transport, which is essential for transport of mucus from the sinuses into the nasal cavity,
may be altered in microgravity. Altered mucociliary drainage may lead to blockage of the sinus passages, which can increase the incidence of secondary upper respiratory tract infections. In addition to the lack of gravity, the environment of space vehicles has recirculated air with ambient humidity. These conditions are dryer than is optimal for normal nasal function, a situation that could potentially lead to mucus stasis, bacterial colonization, and rhinosinusitis.

According to the Agency for Healthcare Policy and Research, the current diagnostic reference standard for ABRS is needle puncture and bacterial culture of the sinus contents through the canine fossa or the inferior turbinate. However, this is a complicated procedure that requires specialized techniques that can be traumatic and painful and that should be performed by an otolaryngologist or other sinus specialist because of the technical expertise required. Middle meatal cultures have been shown to be as effective as maxillary sinus taps, but middle meatal cultures also require significant technical expertise and are best performed in controlled environments. Studies have demonstrated that ultrasonography (US) is an excellent technique for detection of maxillary sinusitis. In addition, researchers at the National Aeronautics and Space Administration (NASA) have optimized training methods that allow minimally trained, nonphysician operators to obtain diagnostic US images for medical diagnosis. Thus, US offers a painless, noninvasive technique for diagnosis of ABRS that can be performed by nonexpert users.

Nasal congestion is a frequent complaint in astronaut crew members during spaceflight. The incidence of ABRS during weightlessness is not known; however, proper diagnosis and treatment of this condition is essential, especially during longer-duration exploration-class spaceflight. The purpose of this investigation was to develop an animal model of sinusitis, to characterize fluid behavior in the sinuses during microgravity, and to evaluate the accuracy of diagnostic sinus US during zero-gravity conditions.

METHODS

The experiments described herein were reviewed and approved by the animal care committees at Henry Ford Health System, the University of Texas Medical Branch in Galveston, and the Johnson Space Center in Houston, Texas. Ground (normal-gravity) experiments were conducted on anesthetized swine (n=4) at Henry Ford Hospital before the microgravity experiments (n=4) conducted in the NASA Microgravity Research Facility in Houston.

GROUND INVESTIGATIONS

After general anesthesia and intubation of the animals, the bridge of the nose and face were shaved. An incision was made in the midline of the face from the frontal region to just above the snout and extending laterally for 3 to 4 cm. The skin and periosteum were then elevated off the side of the face. A small osteotome was used to create an opening into a small frontal sinus (approximately 2 cm³) to allow a 20-gauge catheter to be placed unilaterally for later fluid injection. A bony window was created in the porcine maxillary sinus to allow a catheter to be placed in a dependent area for fluid instillation to mimic sinusitis. Preliminary volumetric investigations demonstrated that a viscous mucous-like liquid would flow into the sinus cavity and could be reliably detected by ultrasonography.

Figure 1. A bony window was created in the porcine maxillary sinus to allow a catheter to be placed in a dependent area for fluid instillation to mimic sinusitis. Preliminary volumetric investigations demonstrated that a viscous mucus-like liquid would flow into the sinus cavity and could be reliably detected by ultrasonography.

Microgravity Investigations

The animal preparations for the zero-gravity experiments were similar to the normal-gravity counterpart with the exception of an extended transportation and preparation (2 hours) period. The animal procedures (n=4) were conducted at an off-site animal facility (University of Texas Medical Branch, Galveston) before transport to Ellington Field, Houston, for the flight. The zero-gravity studies were performed aboard NASA KC-135 research aircraft during parabolic flight profiles. Each parabola consisted of 2 phases lasting approximately 2 minutes, including 30 to 40 seconds of 1.8 g followed by 20 to 25 seconds of zero-gravity flight, and another transition period. The animal, life support, monitoring, and US equipment were secured to the aircraft floor before takeoff (Figure 2). The US operator was restrained using a combination of straps to the floor of the aircraft and leg pressure under the stretcher.

The US examinations of the animals were performed during level flight (normal gravity) before and after injection of fluid into the frontal sinus cavity. Throughout the zero-gravity periods, the fluid-filled sinus cavities underwent US imaging to visualize the behavior of sinus fluid during microgravity. Characterization of the sinus imagery and fluid behavior was based on dynamic US video that was blindly evaluated after the experimental periods by a US expert (A.E.S.).
RESULTS

An anatomically consistent frontal sinus with a thin periosteal membrane and a volume of approximately 2 cm³ was demonstrated in all the experimental animals (n=8). Before instrumentation, there was no evidence of sinus fluid in any of the animals, and after the surgical procedure but before instilling the sinus fluid, there was no difference in the US appearance of both frontal sinuses in any of the animals. Before fluid injection, all sinus cavities demonstrated a well-demarcated anterior sinus wall without visualization of the posterior wall because of hypoechogenicity secondary to the air-filled cavity (Figure 3).

Instillation of 1 mL of viscous sinus fluid at normal gravity created a reproducible air-fluid interface that was consistently seen as an air-fluid level on static and dynamic US (Figure 4). The US appearance of sinus fluid in zero gravity was appreciably different than that at ground conditions. Surface tension and fluid wetting characteristics caused the air-fluid interface of the sinus liquid to disperse along the walls of the sinus cavity in a spherical fashion (Figure 5). This was visualized as a moderately (2- to 3-mm) thick air-fluid interface along the entire sinus cavity. A classic air-fluid interface rapidly developed during the reinstitution of normal gravity.

An optimal method of animal, equipment, and operator restraint for US of the upper torso and head and neck was developed. Key features included secure restraint of all equipment with appropriate sight lines and redundant securing of the large animal model. Operator restraint consisted of a secure waist strap to the bulkhead and operator leg pressure under the stretcher, which allowed freedom of movement while providing appropriate counterpressure during zero-gravity periods.

COMMENT

Medical care capabilities for the International Space Station and future exploratory space missions are currently being investigated. Numerous human health risks associated with spaceflight have been identified, including microgravity-specific health concerns as well as routine medical care complications. Space-specific health care problems may be grouped into those related to a micro-

Figure 2. A secure, contained system for critical care monitoring of anesthetized swine was developed for use with advanced procedural skills. The system included a portable ventilator, physiologic monitor, oxygen generator, and portable ultrasonographic device using a high-frequency hockey-stick probe (GE LogicBook and 15-6 L probe; GE Medical Systems, Milwaukee, Wisconsin). The head position of the pig was maintained upright to allow full visualization of an air-fluid interface during gravity maneuvers and to maximize microgravity effects on intracavitary fluids.

Figure 3. Representation of a baseline sinus cavity before injection of liquids in the zero-gravity condition. The anterior table of the sinus is seen as a hyperechogenic line below the subcutaneous tissues. The posterior wall of the sinus is not visible because of the presence of air in the sinus cavity.

Figure 4. Air-fluid interface in the porcine maxillary sinus after instillation of 1 mL of a viscous fluid during ground (normal-gravity) conditions. The fluid appears hyperechogenic against the air-fluid interface.

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gravity environment and those for which diagnosis and treatment are complicated by the remote environment of space. Bacterial rhinosinusitis fits both categories as a disease with a presentation that is altered in the microgravity environment and a disease for which diagnosis is complicated by the remote location, lack of an on-board physician, and minimal diagnostic equipment. Prompt diagnosis and initiation of antibiotic therapy for ABRS is important to prevent persistent symptoms, development of a chronic infection, or development of complications such as osteitis, infection of the intracranial cavity, orbital cellulitis, and bacterial spread. Such complications could seriously jeopardize the function of the crew and have long-term consequences.

Although rigorous astronaut selection procedures reduce the chance of chronic health problems, acute conditions can occur during short- and long-duration spaceflight. The probability of a crew member developing a medical condition requiring intervention is increased during longer-duration or exploratory missions. Before a spaceflight, crew members undergo a quarantine period to reduce the risk of contracting communicable infections. The space environment predisposes astronauts to a number of risks that may increase the occurrence of sterile or infectious sinusitis. Numerous crew members experience nasal congestion during early spaceflight because of central fluid redistribution. The closed environment of the space vehicle with recirculated, dry air reduces mucociliary clearance. Gravity-dependent drainage of the sinus cavities is absent in zero gravity, further reducing the clearance of mucus from the sinus cavities and passages. It is also possible that normal mucociliary activity is altered in microgravity.

Small percentages of bacteria under normal conditions typically will not develop into large infectious colo-

Figure 5. Effect of microgravity on fluid contained in the porcine maxillary sinus. The fluid rapidly dispersed along the walls of the maxillary sinus (arrows) with a central area that contained air. This process occurred rapidly and stabilized during microgravity and then returned to a classic air-fluid level during normal-gravity conditions.

Figure 6. Ultrasonographic (US) examinations of the frontal and maxillary sinus areas were obtained on the International Space Station using the Human Research Facility US machine for the Advanced Diagnostic Ultrasound in Microgravity flight experiments. This in-cabin photograph shows a cosmonaut crew member performing a sinus US examination on an astronaut.
agnostic tests or maneuvers conducted in zero gravity that involve an air-fluid interface must incorporate fluid behavior characteristics for proper interpretation. Previous physical and animal experimentation from the NASA Microgravity Research Facility demonstrated that intracavitary fluids distribute around the visceral and parietal boundaries because of surface tension characteristics. The sinus experiments reported herein corroborate these earlier experimental findings and demonstrate that the sinus fluid distributed evenly around the sinus cavity in a spherical pattern. Dynamic US reliably followed this fluid redistribution and could be used to distinguish the extent of fluid in a frontal or maxillary sinus by measuring the thickness of the fluid boundary on the wall of the sinus independent of an air-fluid interface.

Traditional animal models of sinusitis would not be reliable for such experiments. Rabbits would have difficulty surviving the microgravity environment, and sheep harbor many more pathogens that would prohibit their use in these clean environments. These experiments demonstrated that a reproducible swine model of acute sinusitis could be used to evaluate the ability of US to visualize an air-fluid interface in a sinus cavity. This large-animal model of acute sinusitis could be used for diagnostic and therapeutic maneuvers, including image-guided sinus drainage procedures. The model is unobtrusive and could be combined with other complementary experiments to maximize the use of this animal resource.

Reliable medical care is a key component of the extended presence in space required for exploration-class flights. Ultrasonography has been successfully used on the shuttle and International Space Station for a number of research investigations. This report demonstrates that US can be used in microgravity to demonstrate the presence of fluid in the sinus cavity of an animal model. This technique may have clinical applicability in the current and future space program.

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