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.


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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.1 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.2,3 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.1,4 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.3

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 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.

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 (Figure 1). The skin and overlying fascia were replaced and sutured airtight for a subsequent US examination with a portable US device using a high-frequency hockey-stick probe (GE LogicBook and 12L-RS probe; GE Medical Systems, Milwaukee, Wisconsin).

Fluid that mimicked the consistency of pus typical of ABRS was developed by mixing water and surgical lubricant (Surgicalube; Fougera, Melville, New York). A 1-mL aliquot of the fluid was then injected into the catherized sinus to fill approximately half the volume of the cavity. Finally, a dynamic US examination of the sinuses was performed on the catheterized side and the surgically unaltered side. The 4 animals were humanely killed with a narcotic overdose and a lethal injection of potassium chloride after completion of this and other associated experiments that were performed during the same anestheisa.

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 1.8g 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.).
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.

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-
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 onboard 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 will not develop into large infectious colonies. However, when normal nasal and sinus function is altered, overgrowth of pathogenic bacteria may occur. The microgravity environment may also delay symptoms experienced at normal gravity, such as facial pressure that might herald the onset of sinusitis. Another possible health concern is that these altered nasal-sinus functions may allow conditions conducive to transmission of pathogenic bacteria from a person who is colonized but uninfected by them.

Currently, sinus puncture or selective middle meatal cultures are the acceptable definitive tests for the diagnosis of ABRS, and computed tomography, radiography, and US are accepted methods for determining fluid levels in sinuses that may indicate ABRS. However, sinus puncture or selective middle meatal cultures require an onboard expert physician and therefore are not readily feasible in the remote environment of space. Plain sinus radiography and US have a similar sensitivity and specificity. Radiographic-guided diagnosis is comparatively expensive and requires bulky equipment, whereas US is inexpensive and simple to perform, and the equipment is compact and already available on the International Space Station.

Ultrasonography performed by experts can reliably diagnose air-fluid levels or mucosal thickening that would support the diagnosis of rhinosinusitis in hospitalized patients, but the accuracy of the interpretation of US of the sinuses with limited operator training and in microgravity is not known. The Advanced Diagnostic Ultrasound in Microgravity experiments recently completed on the International Space Station evaluated the ability of nonphysician operators who are trained as needed to perform complex US examinations, including sinus imaging, in a variety of clinical conditions. The minimally trained operators were able to obtain diagnostic-quality examinations using ground-based remote expert guidance. Such techniques could be expanded for use in a number of clinical conditions that may occur during prolonged spaceflight.

Fluid behavior in a microgravity environment is defined by a number of factors, including surface tension, charge, temperature, wetability, and fluid viscosity.
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 perilosal 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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