DEVELOPING COMPLETE ULTRASONIC MANAGEMENT OF KIDNEY STONES FOR SPACEFLIGHT

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ABSTRACT

Bone demineralization, dehydration, and stasis put astronauts at an increased risk of forming kidney stones in space. The incidence of kidney stones and the potential for a mission-critical event are expected to rise as expeditions become longer and immediate transport to Earth becomes more problematic. At the University of Washington, we are developing an ultrasound-based stone management system to detect stones with S-mode™ ultrasound imaging, break stones with burst wave lithotripsy (BWL™), and reposition stones with ultrasonic propulsion (UP™) on Earth and in space. This review discusses the development and current state of these technologies, as well as integration on the flexible ultrasound system sponsored by NASA and the National Space Biomedical Research Institute.

1. INTRODUCTION

Astronauts are at an increased risk of kidney stone formation due to the dehydration, stasis, and bone demineralization that occur in space [1]–[3]. While stones are often innocuous in the kidney, they can cause debilitating pain when they move into the ureter and attempt to pass. Obstruction can lead to renal failure, severe urinary tract infection, or even death [4]–[6]. Over 30 symptomatic stone incidents have been reported in United States astronauts post-flight; one notable in-flight stone instance has been described in the Russian space program, where a crewmate was found “writhing in pain” [1], [7]. While no US astronaut has experienced a kidney stone event in-flight, the importance of kidney stones in space is expected to rise as missions become longer and immediate transport to Earth becomes more problematic.

There is currently no definitive pharmacological or dietetic solution to eliminate the risk of renal stone formation in long-term space expeditions or on Earth. Potassium citrate has been shown to be an effective prophylactic agent in reducing the risk of urinary stones on Earth and has been used by NASA as a countermeasure to stone formation on short duration flights [1], [2]. Another possible countermeasure under investigation by NASA involves a combination of resistive exercise plus bisphosphonates, which have been shown to reduce urinary calcium excretion during missions to the International Space Station (ISS) [8]. However, in an attempt to reduce the risk of visual impairment and increased intracranial pressure, NASA has been exploring the use of a medication known to elevate urinary pH, which increases the formation risk of certain types of kidney stones [9], [10]. The use of this agent could offset any stone risk reduction provided by potassium citrate and may synergistically increase the risk of stone formation in space [9], [10].

At the University of Washington, we are developing a suite of ultrasound-based stone management technologies to diagnose and treat kidney stones on Earth or in space. There are three primary system technologies: S-mode™, BWL™, and UP™. S-mode™ is a stone-specific ultrasound imaging mode optimized to visualize kidney stones. Burst Wave Lithotripsy (BWL™) is a non-shock based approach to break kidney stones into smaller fragments. Ultrasonic propulsion (UP™) is the application of acoustic radiation force to either facilitate passage by moving a stone or stone fragments towards the exit of the kidney or to relieve obstruction and pain by pushing a stone back into the kidney and allowing stone treatment to occur at a later time.

2. S-MODE™ ULTRASOUND IMAGING

Current ground-based technologies to detect stones, such as computed tomography (CT) and plain film x-ray are unsuitable for flight because of the size, power

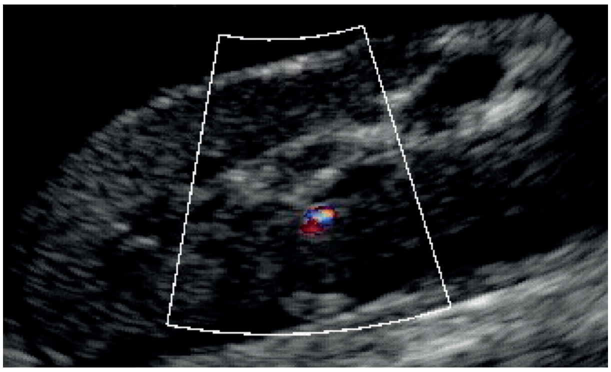

Figure 1. An example of the kidney stone twinkling artifact in a pig kidney, which shows the stone as a mosaic of colors in a greyscale ultrasound image.

requirements, and/or exposure to ionizing radiation. Standard B-mode ultrasound has been used to diagnose kidney stones, which ideally appear as hyperechoic objects with a posterior hypoechoic shadow; however, ultrasound sensitivity is low compared to CT and highly dependent upon stone size and the interpretation of the operator [11]. Sensitivity has been reported at 45% overall [12]–[14], with numbers as low as 13% for the detection of stones <3 mm and 71% for the detection of stones >7 mm [11]. The literature measurement of stone size with ultrasound is also variable and tends to be overestimated with clinical ultrasound [11], [13], [15], again particularly for small stones. Management decisions are in part based on the size of the stone, and overestimation of a small stone can lead to treatment when instead the stone potentially can be passed. The reverse can occur with larger stones, which are often asymmetric, and sometimes underestimated with ultrasound due to its 2D nature, where the largest stone dimension is missed. The color Doppler ultrasound "twinkling artifact", which highlights stones with rapidly changing color as shown in fig. 1, is a supplement to B-mode to increase specificity [16]–[20]; however, because of the inconsistent appearance of the twinkling artifact, sensitivity is not significantly improved.

Early detection of small stones is critical in the space program as stone size is a significant predictor for the duration and severity of a stone incident [21]; small stones, generally defined as <5 mm diameter, pass spontaneously in 68% of cases, whereas less than 50% of stones 5-10 mm diameter pass naturally [22]. S-mode™ ultrasound imaging is under development to improve kidney stone detection and sizing by optimizing an ultrasound system to delineate hard structures. Commercial ultrasound systems are generally optimized to distinguish subtle differences in soft tissue, which can result in poor contrast and resolution when imaging hard objects such as kidney stones. Stone-specific ultrasound, or S-mode™, improves the resolution of kidney stones, but as a tradeoff there is some reduction in soft tissue image quality, as shown in fig. 2.

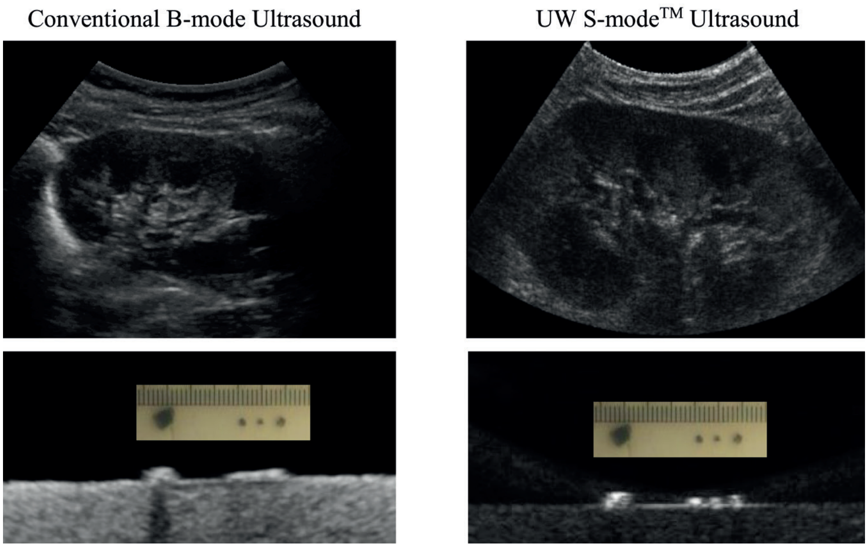

Figure 2. Ultrasound images of (upper) a human kidney and (lower) stones on a tissue phantom taken with (left) conventional B-mode ultrasound and (right) with S-modeTM ultrasound developed at the University of Washington. Left: Conventional B-mode ultrasound clearly shows kidney structures including the collecting system, calyces, and papilla of the kidney; however, the lower image shows that the kidney stone brightness is not different than the tissue phantom and small stones of 1-2 mm diameter spaced 3-4 mm apart cannot be resolved. Right: S-modeTM ultrasound clearly shows the collecting system and calyces of the kidney, though without the same degree of soft tissue resolution as shown in the conventional B-mode ultrasound image; however, the lower image shows that stones appear significantly brighter than the soft tissue phantom and the small stones can be resolved.