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Dual-frequency ultrasound for detecting and sizing bubbles

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Abstract

ISS construction and Mars exploration require extensive extravehicular activity (EVA), exposing crewmembers to increased decompression sickness risk. Improved bubble detection technologies could help increase EVA efficiency and safety. Creare Inc. has developed a bubble detection and sizing instrument using dual-frequency ultrasound. The device emits "pump" and "image" signals at two frequencies. The low-frequency pump signal causes an appropriately-sized bubble to resonate. When the image frequency hits a resonating bubble, mixing signals are returned at the sum and difference of the two frequencies. To test the feasibility of transcutaneous intravascular detection, intravascular bubbles in anesthetized swine were produced using agitated saline and decompression stress. Ultrasonic transducers on the chest provided the two frequencies. Mixing signals were detected transthoracically in the right atrium using both methods. A histogram of estimated bubble sizes could be constructed. Bubbles can be detected and sized transthoracically in the right atrium using dual-frequency ultrasound.

1. Introduction

Assembly of the International Space Station (ISS) and Mars exploration require extensive and unprecedented extra-vehicular activity (EVA). The only known measures presently available to avoid decompression sickness (DCS) during EVA are denitrogenation strategies. These strategies (usually oxygen pre-breathing) are time-consuming and imprecise. In addition, the susceptibility to DCS varies greatly both among subjects and in a given subject over time [1]. As a result, decompression sickness can arise even when accepted measures are taken. Developing improved or individualized strategies would be highly advantageous, but is difficult given the limitations of existing instrumentation.

Monitoring venous gas bubbles as a marker of decompression stress is one approach to improve safety. Typically, Doppler or imaging ultrasound is used to detect the bubbles. These techniques allow for intravascular bubble detection and can show the evolution of bubbles. It has been estimated, however, that bubbles must be approximately 80 μm in diameter to be detectable by Doppler in the precordial area [2]. Doppler monitoring requires bubble motion, and the grading of

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bubbles is subjective and difficult to standardize [2]. Echocardiography can also be used to detect bubbles by imaging [3], but provides no sizing information.

A system that could both size and detect bubbles would offer advantages over current bubble detection technologies. Creare Inc. has developed a bubble detector that exploits bubble resonance properties to detect and size bubbles. To assess the feasibility of transthoracic bubble detection using this device, bubbles were produced in the venous circulation of a pig using two different approaches. First, agitated saline, which contains a range of bubbles sizes, was injected intravenously while the bubble detector imaged the right atrium and pulmonary artery. Second, venous gas emboli were produced in an anesthetized swine by a dive in a hyperbaric chamber to 6 ATA for 45 min. The results showed that intravascular bubbles could be detected, and that a histogram of bubble sizes could be produced. This study shows the feasibility of intravascular bubble detection and sizing using dual-frequency ultrasound, but further studies will be needed to assess the optimal transducer settings and refine the technology.

2. Methods

The instrument used for this project exploits the resonant behavior of gaseous emboli. A bubble's resonant frequency is a strong function of bubble diameter and is well predicted theoretically. Fig. 1 shows a graph of bubble resonance frequency vs. bubble diameter based on well-known theory [4], where the resonant frequency is given by

$$f_0 = 2\pi\sqrt{\frac{3\gamma P_0 + 2\sigma/R_0 - 2\sigma/R_0}{\rho R_0^2}}, \quad (1)$$

where f_0 is the first resonant frequency, R_0 the nominal bubble radius, ρ the suspending mass density, γ the gas phase polytropic constant, P_0 the ambient pressure, and σ the surface tension.

Extravascular tissue bubbles are thought to have a size range of 1–10 μm with corresponding resonant frequencies ranging from 5 to 1 MHz, respectively. Intravascular bubbles range from 40 to 400 μm with corresponding resonant frequencies ranging from 20 to 200 kHz, respectively. The theoretical relationship between bubble size and resonant frequency has been thoroughly validated by numerous researchers. Consequently, by basing the instrument on the resonant behavior of the bubbles, it is possible to have an instrument that provides excellent resolution and requires little or no calibration. The need for minimal calibration is key, because producing a controlled and known bubble size distribution in vivo is problematic at best. Additionally, for in vivo applications no independent means of verifying the bubble size distribution exists.

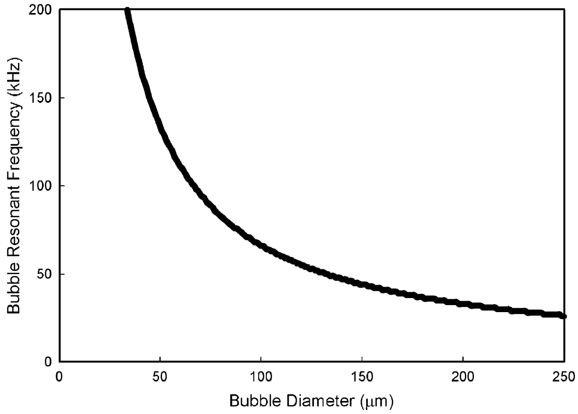

Fig. 1. Plot of bubble fundamental resonant frequency vs. bubble diameter for a free air bubble in water. By insonifying the bubble with the appropriate resonant frequency, different bubble sizes can be detected.

2.1. Bubble detection using dual-frequency ultrasound

This bubble detection instrument takes advantage of the fact that gaseous bubbles act as nonlinear mixers. To exploit this behavior, the measurement volume is insonified simultaneously with a low-frequency pump signal (at a specific frequency selected to induce resonance if the proper size bubble is present) and with a much higher image frequency. Due to the nonlinear mixing behavior of bubbles, the high-frequency return signal from the bubble will contain side lobes at the image frequency plus and minus the pump frequency if there is a resonant bubble in the measurement volume. As demonstrated both analytically and experimentally by Newhouse and Shankar [5], the intensity of the signal at the sum of the pump and image frequencies at a