5aBAb9. Ultrasound-equipped colonoscope for point-of-procedure colorectal preparation and examination

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Colorectal cancer is the second leading cancer killer in the United States. Poor colon preparation occurs in 20–40% of colonoscopies in the community, which increases the duration of the colonoscopy by at least 10% and the cost of the procedure by up to 22% due to repeat visits. The goal of this research was to develop and preliminarily evaluate the first ultrasound-cavitation equipped colonoscope as an innovative approach to liquefy fecal matter with water/cavitation and improve colonoscope utility. Two ultrasound-equipped colonoscopes were developed. The first consisted of a 30 element 235 kHz array that was mounted as a cap on the tip of a commercial colonoscope (Olympus). The second consisted of a Time-Reversal Acoustic extroporeal 32 channel 100 kHz array that was electrically steered to the commercial colonoscope using PVDF detectors to acquire and monitor the TRA focusing routines. Both systems were evaluated in a series of bench tests for fecal liquefication, as well as in the porcine cadaver. Results show that ultrasound exposure assists the liquefaction of fecal matter and 50 kPa exposure to ultrasound increases liquefaction by greater than 50 times. Blinded histological reports on excised tissues showed no significant different findings between control and ultrasound experiments.

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INTRODUCTION

Colonoscopy, which is the gold standard screening method of choice for preventing colon cancer, uses a lighted motion-controlled tube with intraluminal ports that allows the physician to examine the inside of the rectum and colon in order to inspect for neoplastic polyps and early-stage colorectal cancer. Locating and removing polyps during colonoscopy has been shown to prevent colorectal cancer and also reduce deaths from the disease.\(^1\) Though most polyps are benign some are precancerous adenomas and removing them reduces the risk of developing colorectal cancer by 53%.\(^2\) For colonoscopy to realize its full potential, it is essential to optimize the bowel preparation before or during screening to rapidly locate and evaluate neoplastic lesions accurately. About 14 million colonoscopies are performed yearly in the United States\(^3\), and at least 20% have poor bowel preparation\(^4\), raising concern for missing a substantial number of neoplastic lesions.

Miniaturized catheter-based ultrasound has been used in intravascular thrombolysis.\(^5\) Our aim is to develop and preliminarily evaluate the first ultrasound-cavitation equipped colonoscope using time-reversal acoustics as an innovative approach to liquefy fecal matter with water/cavitation.

METHODS

An ultrasound-equipped colonoscope consisting of a 20 element array mounted as a cap on the tip of a commercial colonoscope (Olympus) was developed shown in Figure 1. The colonoscope transducer operated between 500 Hz and 1 MHz resonant frequencies. The low-profile transducer was made of rexolite due to low ultrasound attenuation factors and accurate machinability. Piezoceramic (PZT-4) crystals were glued in parallel with light-cured cyanocrylic matching layers (EBL Products) to the facets of the rexolite housing as shown in Figure 1. The parallel configuration of transducers and electrical wiring provides a uniform circumferential beam profile and low electrical impedance. As shown in Figure 1, the transducer press-fits onto the tip of the Olympus colonoscope and only slightly increases the overall width of the device by 4 mm in diameter.

![Multi-resonance transducer prototype for colonoscope.](image)

The sealed transducer (not mounted on the colonoscope) was inserted into an ex-vivo porcine colon filled with 1.5g porcine stool and saline (Figures 2A and 2B). The ultrasonic array was stimulated at 500 Hz, 20 kHz, 85 kHz, and 231 kHz at intensities varying from 50-500 kPa for 50 minutes; these
were compared to a water spray control that received no ultrasound exposure. Following the treatment, colon samples were sliced on a vibratome into transverse sections and sent to the Cornell University animal pathology lab for hematoxylin and eosin (H&E) staining and diagnosis.

Figure 2. Ultrasound liquification experiment in porcine colon.

A second ultrasound-equipped colonoscope was developed and consisted of a Time Reversal Acoustic (TRA) extracorporeal 32 channel array that was electrically focused to the commercial colonoscope (Olympus) using polyvinylidene fluoride (PVDF) detectors (Figures 3A and 3B). The PVDF detectors, located on the colonoscope tip, record the ultrasonic echoes that occur in the body due to impedance mismatch between dissimilar tissues. TRA focusing utilizes the recordings, transforms them, and retransmits on all 32 channels to focus high intensity ultrasound very accurately.

Figure 3. TRA focusing in porcine model. (A) TRA colonoscope with PVDF transducer. (B) TRA electronic system. (C) 32 channel array placed on hindlimb.
The TRA colonoscope was tested on a Domestic Swine weighing 35-45 kg that was euthanized, cleansed, and delivered from a local farm. The cadavers were positioned on their side and the TRA colonoscope was inserted into the colon using ultrasound gel as a lubricant. The 32 channel array was placed on the hindlimb of the swine with a neoprene wrap and coupled to the body using ultrasound gel (Figure 3C). The array was stimulated at both 191 kHz and 1 MHz and focused to the tip of the colonoscope. Keeping the focus at the same location, the TRA colonoscope was slowly removed and the attenuation of the focused signal was recorded at 0.5 mm increments.

RESULTS

Results clearly show that ultrasound exposure assists the liquification of fecal matter. Figure 4 shows (A) temporal percent weight change plots for 1.5g porcine stool samples, (B) colorectal sections with and without ultrasound exposures at 50-500 kPa, (C-D) and solid stool in saline pre and post ultrasonic treatment. Both 231 kHz treatment and control swell and increase in weight with time. Treatments below 85 kHz and at 50 kPa ultrasound exposure increase the percent liquification over time by greater than 50 times. Depending on parameters such as pulse rate, acoustic intensity, and duration, an increase in liquification speed by a factor of 50 to 100 times is obtained. In fact, the effect of ultrasound was so profound that solid stool samples in saline turned into a fully dispersed liquid sludge within seconds as shown in Figure 4D. Histological reports of the colorectal tissue showed no significant

![Figure 4.](image)

(A) Porcine stool liquification plot. (B) Histological sections of colorectal tissue. (C) Solid stool pre-treatment. (D) Stool solution post-treatment
differences between the water spray control and ultrasound experiments. Rare goblet cells had pyknotic nuclei; however, histology for all animals showed only minor acute damage and slight sloughing of mucosa for all treatment and control groups. Cells were distributed evenly and proper anatomical structure was maintained throughout the mucosa.

![Figure 5](image)

**Figure 5.** Acoustic pressure graph of an ultrasound mounted colonoscope at 191 kHz and 1 MHz

In the TRA experiment, ultrasound could be successfully focused and delivered to the colonoscope mounted on the tip. Spatially, the three-dimensional resolution of the targeted ultrasound beam was 1.5 mm and 10.5 mm for 1 MHz and 191 kHz arrays respectively; this is the point at which the acoustic pressure, as determined by a hydrophone (Onda), is 3 decibels of the original strength. The focusing resolution of the ultrasonic field is shown in Figure 5. A SNR (signal to noise ratio) of 7 was obtained in the porcine colon.

**DISCUSSION**

Low-frequency ultrasound exposure assists the liquification of fecal matter and 50 kPa exposure to ultrasound increases liquification by greater than 50 times. Also, our preliminary data shows that this amount of exposure did not appear to injure excised tissues compared to controls.

These developments could have profound effects on colonoscopy procedures in the prevention and treatment of several colorectal diseases. Colon cancer is the second leading cause of cancer-related deaths in Western nations. There are multiple steps to a colorectal examination: fasting and laxative preparation, sedation, advancing the colonoscope to the cecum, cleaning off debris, and discovering and then removing polyps. The variation in detection of neoplastic lesions by colonoscopists is partly due to flat polyps, blind spots, and poor preparation. The quality of preparation impacts polyp detection, duration of the procedure, and interval between colonoscopies in screening programs.

Our method is independent of specific bowel prep compounds or colonoscope optics. Colonoscopes can irrigate the colonic lumen with a water spray of 100mL/min during a procedure by evacuating liquid debris using suction applied though the instrument’s intraluminal port. However, this method is grossly inadequate in salvage-cleaning of poorly prepared patients in 20% of colonoscopies, and time consuming for cleaning an entire colon without bowel prep. Emerging technology using
enhanced water spray is also being considered as a salvage tool for poor bowel preparation\textsuperscript{11}, however our method will be more efficient and will not interfere with scope maneuverability.

**REFERENCES**


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