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# Ultrasound Capsule Endoscopy Components for *in vivo* and *ex vivo* Microultrasound Near-Field Imaging

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***Abstract*— Ultrasound capsule endoscopy (USCE) has attracted increased interest recently. In order to image the walls of the gastrointestinal (GI) tract with USCE efficiently, both high-frequency ultrasound (i.e. microultrasound) imaging and good acoustic coupling are needed. Tissue to be scanned is expected close to the transducer surface, but the near-field tissue echoes may be easily lost in the acoustic ring-down. Here, we present experimental *ex vivo* and *in vivo* porcine small bowel imaging results from an USCE prototype. The preliminary results show that the near-field image can be recovered after post-processing. Although some limitations in imaging the GI tract are inherent in the use of focused single element transducers, solving the problem of near-field imaging is relevant to all USCE implementations.**

***Keywords—ultrasound capsule endoscopy, high frequency, microultrasound, ex vivo, in vivo, acoustic ring-down artefact***

## I. Introduction

Ultrasound capsule endoscopy (USCE) is an evolving research field that has gained increasing attention over the past few years [1]. The goal of USCE is to assist the early diagnosis of diseases of the human gastrointestinal (GI) tract, that lead to significant morbidity and mortality in developed countries with diets characterized as "western" [2][3]. Standard Video Capsule Endoscopy (VCE) relies on optical imaging to identify mucosal (surface) pathology, while ultrasound allows examination of deeper, subsurface tissue structures. Three basic requirements for clinically effective USCE device are: a) small enough dimensions for swallowing, b) high axial and lateral resolution and c) autonomy in power source and data transfer. The prototype capsule called Sonocap, developed within the UK Sonopill Programme, solved the first two by keeping to a size similar to standard VCE devices and by using 30 MHz ultrasonic transducers [4]. The second generation of Sonocap showed promising results by reducing noise over the previous iteration as reported elsewhere [5].

In order to establish good acoustic coupling between the transducers and the tissue, close proximity is required. However, this is affected by eclipsing and ring-down artefacts. Furthermore, the limited thickness of the GI walls (i.e. 1-3 mm) means the whole tissue under evaluation lies in the near-field region of the transducers, suffering from additional signal loss. Similar problems occur in intravascular ultrasound (IVUS) where weighted averaging can help recover signals [6]. The acoustic ring-down of a robotic capsule endoscope with 30 MHz PVDF transducers was significantly reduced using an unweighted average and subtraction in [7].

Here, we present preliminary results from Sonocap *in vivo* and *ex vivo* scanning, showing that tissue echoes hidden in the acoustic ring-down could be recovered after post-processing and good agreement between *ex vivo* and *in vivo* images.

## II. Methods

### A. Ultrasound Endoscopy Capsule

The prototype capsule used was a Sonocap with incorporated second generation electronics introduced in [5]. The capsule contains a custom printed circuit board (PCB) for analogue amplification of 12 dB for the received echoes for each of its two channels, while the transmit and receive paths are protected by a twin diode and capacitor circuit (BAV99, Vishay Intertechnology, Inc., Malvern, USA). The receive amplifiers can be switched in and out of the circuit depending on situational noise performance. The capsule can be operated in pulse-echo mode relying on the protection circuits only [8]. Power supply and data transfer occur through a flexible, medical grade silicone tether attached to the capsule. The housing is 10 mm x 30 mm (see Fig. 1). Before entering trials, the capsule was parylene coated for protection against fluids.

The two active ultrasound elements are 30 MHz focused single element polyvinylidene fluoride (PVDF) transducers with a focal distance of 6 mm. The transducers have a 3 dB-bandwidth of ca 45 MHz (Fig. 2).


Fig. 1. Left: Sonocap before sealing. Right: Sonocap transducer.

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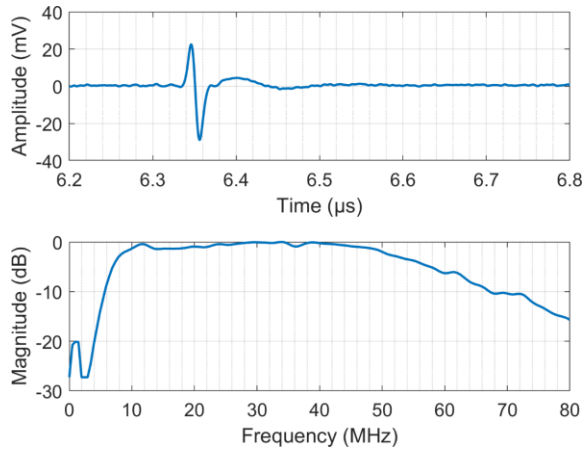


Fig. 2. Pulse-echo response and frequency spectrum of the single element transducer. Measured on a glass reflector, with a gain of 20 dB and 256 averages.

### B. *Ultrasound Data Acquisition*

Only one of the two channels in Sonocap was operated at a time. The active element was driven by an external broadband pulser-receiver unit (DPR300, JSR Ultrasonics, Pittsford, USA) via a custom Sonocap breakout box [4]. Sonocap was operated in pulse-echo mode without making use of the on-board power amplifiers, so no separate power supply was required.

The received echoes were transferred to the pulser-receiver unit, where they were amplified with 40 dB, 50 dB and 60 dB and filtered in real time (low pass: 50 MHz, high pass: 5 MHz), before being displayed on a Tektronix mixed-domain oscilloscope (MDO3024). That oscilloscope was connected to a laptop, running custom LABVIEW software to store all A-scans of a particular acquisition for image reconstruction offline. A diagram of the data acquisition set-up used for both *in vivo* and *ex vivo* porcine tissue scans is shown in Fig. 3.

### C. *In vivo Trial Setup*

Porcine *in vivo* scans were performed in collaboration with the Wellcome Trust Critical Care Laboratory for Large Animals (Roslin Institute, UK) under license from the UK Home Office (PPL 70/8812). Two female pigs weighing 49-50 kg and 3 months of age were supplied by a local breeder. Anaesthesia was induced with propofol (Diprivan, Aspen, Dublin) and maintained with isoflurane (IsoFlo, Zoetis, Surrey) which was administered via a Bain breathing system and facemask.

Each pig was placed in the supine position and the tethered capsule was inserted either orally for oesophageal scans, or through a surgically created mid-line stoma for small bowel investigation. Static pulse-echo data were captured at several locations in both scans. M-mode scans were obtained by inserting the capsule 35 cm into the oesophagus and 20 cm into the small bowel and slowly pulling the tether back at an approximate rate of 0.5 cm $s^{-1}$. The LABVIEW software on the laptop enabled continuous pulse-echo data acquisition for each individual scan. Significant resistance to the capsule pullback in both cases suggested good contact between the capsule and the gastrointestinal tissue.

### D. *Ex vivo Trial Setup*

Tissue from the small bowel was extracted post-mortem for further experiments. The small bowel was separated from other internal structures in order to compare an isolated tissue signal (i.e. a single bowel section) against what was imaged *in vivo* scans. The Sonocap capsule was inserted into the bowel with first water, then air as surrounding material (Fig. 4, top). In both cases, static images and M-mode images from a pullback of 10 cm of tissue were created from the pulse-echo data. Next, to study the effect of the air-tissue interface, the bowel was sliced longitudinally to allow access to the inner surface as a flat tissue section. The tissue was held in place using a gig (Fig. 4). Scans were taken in close proximity to the tissue surface and both air and other layers of tissue were used as the background material.

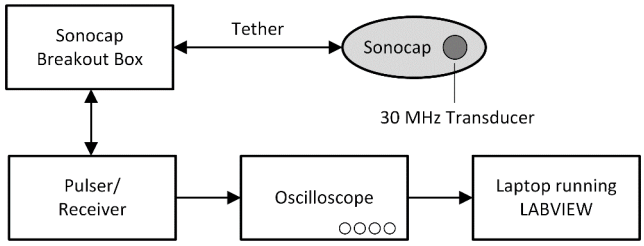


Fig. 3. Sonocap data-acquisition setup.

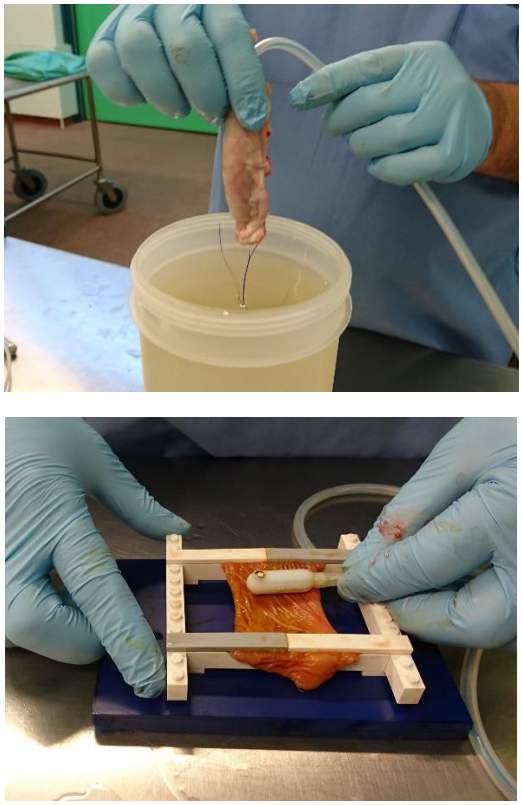

Fig. 4. *Ex* vivo scans (top) small bowel sample in air, (bottom) flattened small bowel sample in a gig in air.

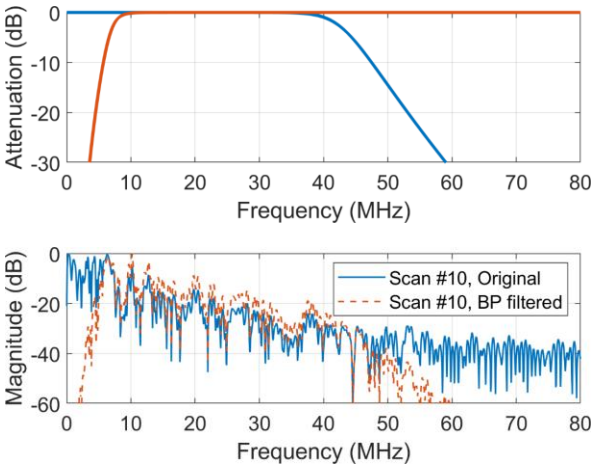


Fig. 5. Bandpass (BP) filtering: (top) low-pass (blue) and high-pass (orange) filter in the frequency domain, (bottom) example of a power spectrum of single A-Scan (Pig2, oesophagus, *in vivo* pullback), before and after filtering. A-Scan #10 before interpolation.

### *E. Post-Processing*

A digital bandpass (BP) filter was applied to the recorded RF data, created by a combination of a 10th order low-pass and a 5th order high-pass Butterworth filter (low-pass: cutoff frequency 40 MHz, stop band 80 MHz, attenuation 60 dB, high-pass: cutoff 8 MHz, attenuation 25 dB, stop band 4 MHz), see Fig. 5. Through this filter design, the desirable bandwidth of the PVDF transducers was retained, while other frequency components were highly suppressed. Then, the envelope of the data was calculated using the Hilbert transform.

Following the description in [7], a moving average of absolute values of the A-Scans envelope was applied. This average was subtracted from the next A-Scan to reduce the influence of the ring-down effect. Here, the number of A-Scans averaged was N=2. Finally, the data was interpolated by a factor of 10 in the time domain, log compressed and normalised.

## III. Results

In both *in vivo* and *ex vivo* scans the ring-down of the transducer masked tissue signals that were in close proximity to the transducer surface. Here, we present selected results that highlight the recovery of near-field tissue signals and the comparison of *in vivo* to *ex vivo* scans.

### *A. Ring-down Artefact Reduction*

Fig. 6 demonstrates the results of ring-down removal. Before processing, the ring-down artefact is still apparent 4 mm into the scan. After bandpass filtering and ring-down removal filtering, structures of the underlying tissue become clearly apparent. At the same time, there is a recognisable zone of about 1 mm that has no signal left. This is due to the initial high voltage excitation pulse feeding back into the receiver channel. As that pulse shape repeats itself from A-Scan to A-Scan, it is completely filtered by ring-down removal. Between 1 mm and 1.5 mm, the ring-down reduction by the unweighted average and subtraction seems to have been less effective than in greater depth.

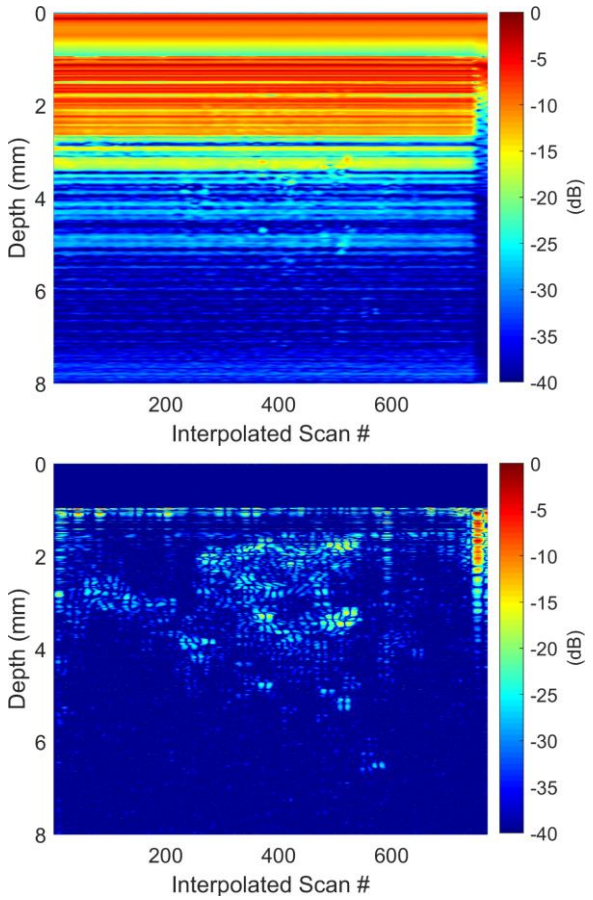


Fig. 6. M-mode images of a oesophagus pull back of ca 30 cm in Pig 2, (top): original scan dat before post processing, (bottom) after BP and ring-down filtering. Gain: 50 dB.

### *B. In vivo and Ex vivo Images*

The strongest signals were obtained where there was a strong interface between tissue and surrounding environment. In these cases, multiple reverberation artefacts were often visible as illustrated in Fig. 7, which presents images from the small bowel *in vivo* and *ex vivo*. The distance between the reverberated echoes reveals the thickness between transducer and tissue surface to be circa 1 to 2 mm. Notably, better agreement is seen between the static *in vivo* scan and the pullback *ex vivo* scan than the static one. This is because in the *in vivo* case, the capsule is not truly static but moved by the bowel movement and breathing of the animal.

## IV. Discussion and Conclusion

For the experimental results presented here, we recorded data intermittently over the course of 7 h. The Sonocap capsule remained intact and undamaged. In the *in vivo* case, the capsule was subject to significant force in all directions from the contractions of muscles of the bowl contracting and the tether was in constant adjustment highlighting its durability. Bandpass filtering and ring-down filtering aided recovery of obscured signals from tissue close to the transducer surface. A dead zone of about 1 mm is still present due to the high voltage excitation pulse feedback.

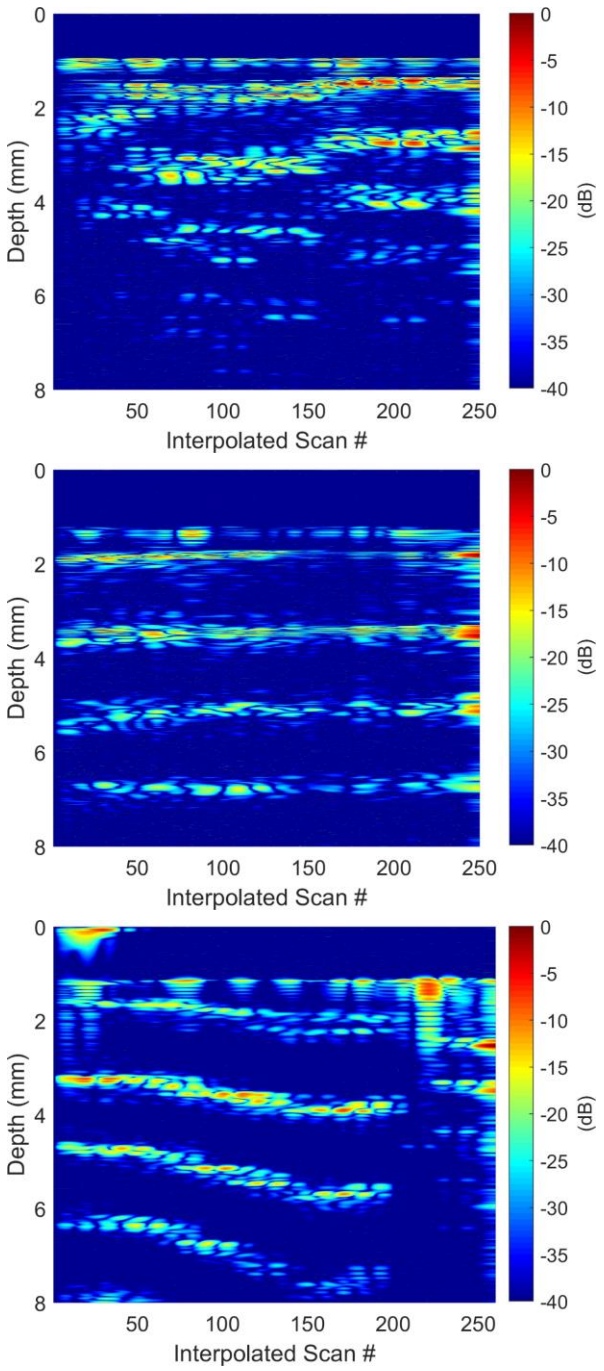


Fig. 7. M-mode images of the small bowel (Pig 2), after bandpass and ring-down filtering. (top): *in vivo* static, (middle): *ex vivo* static tube in air, (bottom) *ex vivo* pullback of ca 10 cm on flattened tissue in air.

*In vivo* results were in line with *ex vivo* scans with strong reflections seen on both. Unlike in laboratory work on *ex vivo* porcine tissue by Lay et al [9], no distinct tissue layers were recognizable. We attribute this the different transducer design applied with higher centre frequencies and thus higher axial resolution as well as the position of the tissue in the focal zone, avoiding the obscuring by the acoustic ring-down. Similarly, Wang et al [10] were able to distinguish porcine small intestine tissue layers in an *in vitro* experiment setting presumably partly because of a greater distance between transducer and tissue than we have evaluated here.

Future USCE designs will replace the single element transducers with arrays. However, the need for good tissue contact to allow acoustic coupling means shadowing will still be an issue and post-processing will be required as suggested here will be necessary to allow imaging of near-field layers. Thus, we have demonstrated a further step towards the implementation of USCE with specialized transducers and front-end electronics.

## REFERENCES

[1] Cox, B.F., Stewart, F., Lay, H., Cummins, G., Newton, I.P., Desmulliez, M.P., Steele, R.J., Näthke, I., Cochran, S. (2017). Ultrasound capsule endoscopy: sounding out the future. *Annals of Translational Medicine*, *5*(9), 201–201.

[2] Williams, J. G., Roberts, S. E., Ali, M. F., Cheung, W. Y., Cohen, D. R., Demery, G., Edwards, A., Greer, M. et al. (2007). Gastroenterology services in the UK. The burden of disease, and the organisation and delivery of services for gastrointestinal and liver disorders: a review of the evidence. Gut, 56, 1-–113.

[3] Peery, A. F., Dellon, E. S., Lund, J., Crockett, S. D., McGowan, et al. (2012). Burden of gastrointestinal disease in the United States: 2012 update. Gastroenterology, 143(5), 1179-87. e1-3.

[4] Lay, H. S., Cummins, G., Cox, B. F., Qiu, Y., Turcanu, M. V., McPhillips, R., Connor, C., Gregson, R., Clutton, E., et al (2019). In-Vivo Evaluation of Microultrasound and Thermometric Capsule Endoscopes. *IEEE Transactions on Biomedical Engineering*, *66*(3), 632–639.

[5] Lay, H.S., Lemke, C., Cox, B.F., Qiu, Y., Cummins, G., Ferrazzano, E., West, C., Desmuilliez, M., Clutton, E. and Cochran, S., Integrated Front End Circuitry for Microultrasound Capsule Endoscopy. Proceedings IEEE International Ultrasonics Symposium (IUS) 2018. February 2019.

[6] Haines, D.E., Wright, M., Harks, E., Deladi, S., Fokkenrood, S., Brink, R., Belt, H., et al. (2017). Near-Field Ultrasound Imaging during Radiofrequency Catheter Ablation: Tissue Thickness and Epicardial Wall Visualization and Assessment of Radiofrequency Ablation Lesion Formation and Depth. Circ Arrhythm Electrophysiol., *10*(12), 1–12.

[7] Norton, J. C., Slawinski, P. R., Lay, H. S., Martin, J. W., Cox, B. F., Cummins5, G., et al.. (2019). Intelligent magnetic manipulation for gastrointestinal ultrasound. *Science Robotics*, 1–12.

[8] Lockwood, G. R., Hunt, J. W., & Foster, F. S. (1991). The Design of Protection Circuitry for High-Frequency Ultrasound Imaging Systems. *IEEE Trans. on Ultrasonics, Ferr., and Freq. Control*, *38*(1), 48–55.

[9] Lay, H. S., Cox, B. F., Sunoqrot, M., Démoré, C. E. M., Näthke, I., Gomez, T., & Cochran, S. (2017). Microultrasound characterisation of *ex vivo* porcine tissue for ultrasound capsule endoscopy. *Journal of Physics*

[10] Wang, X., Seetohul, V., Chen, R., Zhang, Z., Qian, M., Shi, Z., et al. (2017). Development of a Mechanical Scanning Device With High-Frequency Ultrasound Transducer for Ultrasonic Capsule Endoscopy. *IEEE Transactions on Biomedical Engineering*, *36*(9), 1922–192