Assessment of Hydrogels to Aid in Point of Care Ultrasound Barrier Reduction at the University of Virginia

A Technical Report submitted to the Department of Biomedical Engineering

Presented to the Faculty of the School of Engineering and Applied Science
University of Virginia • Charlottesville, Virginia

In Partial Fulfillment of the Requirements for the Degree
Bachelor of Science, School of Engineering

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Spring 2022

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On my honor as a University Student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments

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Abstract
Point-of-care ultrasound (POCUS) describes the practice of trained physicians obtaining and interpreting ultrasound images on a patient to diagnose medical problems at the bedside. Though POCUS is widely used by emergency medicine physicians, primary care physicians can use this practice as an alternative to the stethoscope to provide more timely diagnosis. However, many institutional barriers exist for POCUS at UVA, such as the lack of machines, funding, and a governing body to oversee ultrasound image storage. This project focused on how physicians can efficiently implement POCUS to incentivize addressing these barriers. Since ultrasound gel is messy and single-use, reusable accessible hydrogels were assessed as replacement acoustic couplants.

Keywords: Point-of-care ultrasound, barriers, hydrogel, ultrasound gel

Introduction

Point-of-care ultrasound (POCUS) refers to the use of a portable ultrasound by a medical professional at the patient's bedside for diagnostic purposes. This increases patient-physician interactions and decreases the amount of time for diagnostic testing, since patients do not have to make a separate trip to the radiology department (Figure 1). A curriculum guideline published by the American Academy of Family physicians called POCUS the biggest advance in bedside diagnosis since the stethoscope[1,2].

POCUS is already widely used in emergency medicine (EM), with comprehensive POCUS training built into the EM curriculum in North America[3]. One common application of POCUS in EM is for the FAST (Focused Assessment with Sonography in Trauma) exam which examines the cardiac, right and left upper abdominal, and pelvic locations and is standard practice for evaluation of abdominal trauma[4]. Though POCUS has already been adopted in EM, one area where there is great potential for POCUS is in primary care. It has been shown that POCUS in primary care aids in the completion of procedures, lowers costs, decreases emergency department visits, and reduces the need for further imaging[5]. If primary care physicians used POCUS as a replacement for the stethoscope, which relies solely on auscultation, they would be able to diagnose patients more quickly. However, there are several barriers to POCUS in primary care. Institutional barriers include the lack of a structured curriculum, lack of funding, and machine availability. Other barriers include insufficient mentorship, bedtime space, and the time to retrieve and operate the machine[6,7].

This project focuses on the barrier of the time to operate the machine. More specifically, one factor that negatively impacts the time for a POCUS exam is the lack of an efficient acoustic couplant. Ultrasound requires an acoustic couplant as the interface between the ultrasound transducer and the skin to ensure there is no air to inhibit traveling sound waves. The currently used acoustic couplant is ultrasound gel, which is made primarily of water and propylene glycol[8]. It is single-use and must be reapplied for each body part that is imaged. Ultrasound gel is also sticky and uncomfortable for patients. Therefore, the aim of this project was to find a reusable alternative to ultrasound gel.

Existing alternatives to commercial ultrasound gel include low-cost formulations made using household ingredients such as cassava flour, cornstarch, and xanthan gum. These gels are often used in resource-limited settings and have been shown to be comparable to ultrasound gel in image quality and patient comfort[9,10]. However, they are also single-use and similar in consistency to ultrasound gel.

Hydrogels are attractive alternatives for ultrasound gel due to their high water content and tissue-mimicking properties, which provide the ideal acoustic impedance for ultrasound imaging. Hydrogels consist of water insoluble networks of crosslinked hydrophilic polymers that hold high contents of water. They also have tunable elastic moduli to achieve desired elasticity[11]. Due to these properties, hydrogels were investigated to evaluate their use as acoustic couplants.

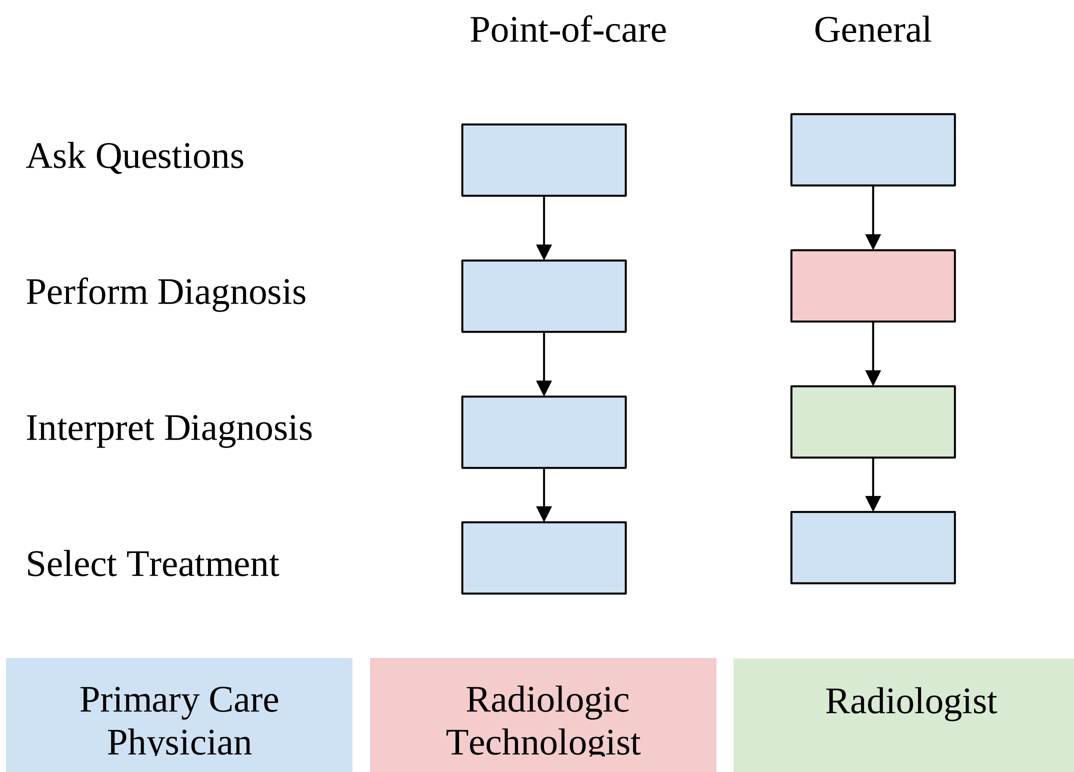

Fig. 1. Comparison of Steps Taken to Perform Ultrasound Diagnostics. Point-of-care ultrasound requires input from primary care physicians only, while general ultrasound diagnostics encompass interdepartmental efforts between primary care physicians and radiologists.

Results

Interviews with UVA Physicians

Interviews were conducted with internal medicine physicians to determine how POCUS was being implemented at UVA. Questions ranged from whether the physician had some introduction to point-of-care ultrasound to specific barriers experienced during medical training or as attending physicians. All physicians interviewed had heard of POCUS and used it at some point throughout their careers, as residents, fellows, or attending physicians. In all cases, POCUS training was performed over durations of 9 months or more, with intermittent training sessions being most common. Despite this, only half of the physicians interviewed believed that their training was sufficient to perform POCUS, indicating that there were deficits in the training they had received. Likewise, there were no structured board certifications put in place to gauge learning across the various training styles used. In addition to the lack of a structured curriculum, there were also concerns about the cost of ultrasound machines. Many machines cost upwards of $50,000[12]. These high costs reduce machine availability, resulting in additional time needed to retrieve available machines from other areas of the hospital.

Table 1. Barriers for POCUS Implementation at UVA and Other Institutions

UVA	Shared	Other Institutions[6]
Protocol for image storage	No structured curriculum	Insufficient mentorship
No governing body	Lack of funding	Consultant pushback
Sanitization (COVID-19)	Bedside space	Department resistance
	Machine availability	Machine size
	Time to retrieve and operate	

Another concern was the ambiguity over how ultrasound images should be stored for further use since it is hard to transfer ultrasound images from a machine to a computer for record-keeping. Furthermore, if the images were stored, then patient and quality improvement would be required and medical records would need to align with HIPAA regulations. In order to do this, an additional governing body would need to be created to ensure that internal policing and physician competency are maintained. The last major concern was that the ultrasound machine would need to be sanitized after each use, which increases the time it takes to operate the machine.

These results were then compared to literature discussing barriers to POCUS use at other institutions. Given the similarity between physician barriers at UVA and prior research performed at other institutions, consideration was given to how improvements could be made in the time to operate an ultrasound machine during POCUS diagnostics (Table 1). Ultrasound images were collected using hydrogels as acoustic couplants. Qualitative and quantitative metrics were used to determine if one or more of the hydrogels could replace ultrasound gel during POCUS use.

Hydrogel Testing

Hydrogel testing was performed with commercially-available, or accessible, hydrogels. Questionnaires were created to qualitatively compare the hydrogels with each other and ultrasound gel. The first questionnaire consisted of questions indicating how easy it was to use a specific hydrogel based on properties such as the area that the hydrogel could operate as a couplant with, the adhesiveness of the hydrogel, and the capacity for the hydrogel to adhere to another body part after initial use. Additional questions considered the feasibility of getting ultrasound images with a linear transducer and the corresponding time it took to obtain those ultrasound images (Supplementary Figure 1). Median numerical ratings were derived from multiple participants (Figure 2). Defining variations in hydrogels as responses that had ranges in numerical ratings of 3 or more, the hydrogels were only distinguishable by how large they were, with the OHYAIAYN hydrogel being small relative to the other three hydrogels.

Since discomfort is a hallmark concern for ultrasound gel use, a second questionnaire was incorporated to investigate how satisfied participants were with the hydrogel after contact with the skin was made[10]. This questionnaire focused on comfortability and general tactile properties of the hydrogels, such as the degree of warmth, coolness, stickiness, and dryness. Ultrasound gel was also added to make direct comparisons between its predetermined tactile properties and those of the hydrogels. Just as was the case with the ease of use questionnaire, the participant satisfaction questionnaire had very little variability in median numerical ratings (Figure 3). There were, however, some differences in coolness and stickiness between the hydrogels and ultrasound gel. Three out of four of the hydrogels were not as cool as ultrasound gel (Medela, OHYAIAYN, and CVS) while two out of four of the hydrogels were less sticky than ultrasound gel (Care Science and CVS).

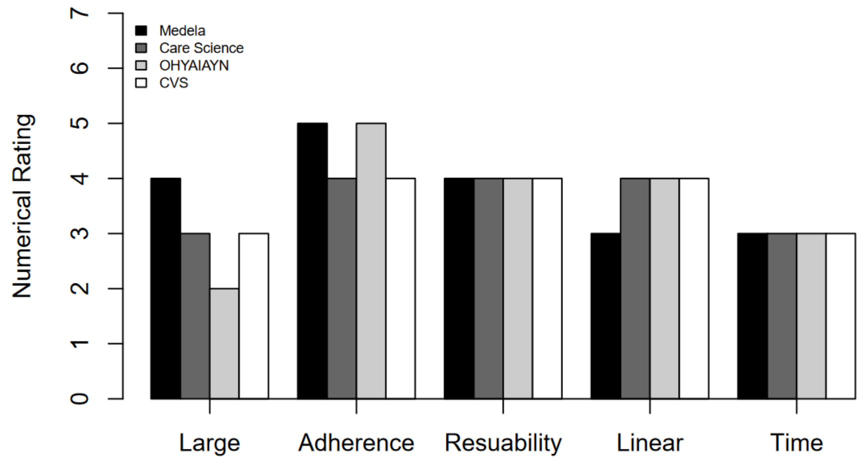

Fig. 2. Ease of Use Questionnaire. An overview of the results seen after conducting the questionnaire on how easy it was to use the accessible hydrogel. Differences were apparent in median numerical ratings for the size of the hydrogels but not in how well they adhered to the skin, whether they could be reused on another body part, and how easy it was and how long it took to use the linear transducer.

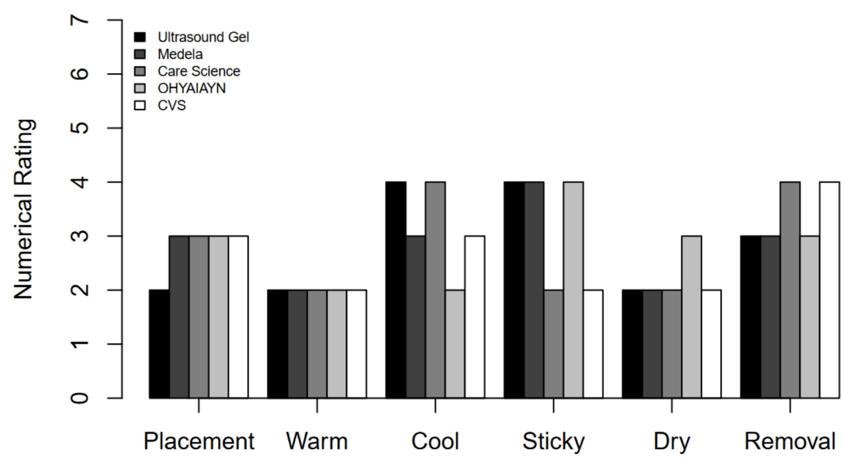

Fig. 3. Participant Satisfaction Questionnaire. An overview of the results seen after conducting the questionnaire on how comfortable it was for the participant to have the material on the skin. Differences were seen in median numerical ratings, where only the Care Science hydrogel was as cool as ultrasound gel and both the Care Science and CVS hydrogels were less sticky than Aquasonic ultrasound gel.

Because primary care physicians need to perform ultrasound imaging diagnostics and guide medical procedures with POCUS, emphasis was placed on how well the hydrogels captured image contrast between various bodily structures and showed motion artifacts when the transducer was moved. Using physician input, both static (taking images with a still transducer) and dynamic (jiggling the transducer to create movement) ultrasound imaging were conducted on each of the hydrogels. Across all four hydrogels, image quality was considered poor, with numerical ratings for image contrast reaching a maximum of 2 (disagree) and all other questions receiving a minimum numerical rating of 1 (strongly disagree). This indicated that none of the hydrogels were sufficient for POCUS based on physician perception. To validate this finding, quantitative image quality metrics were determined based on their previous use in image quality analysis[13,14].

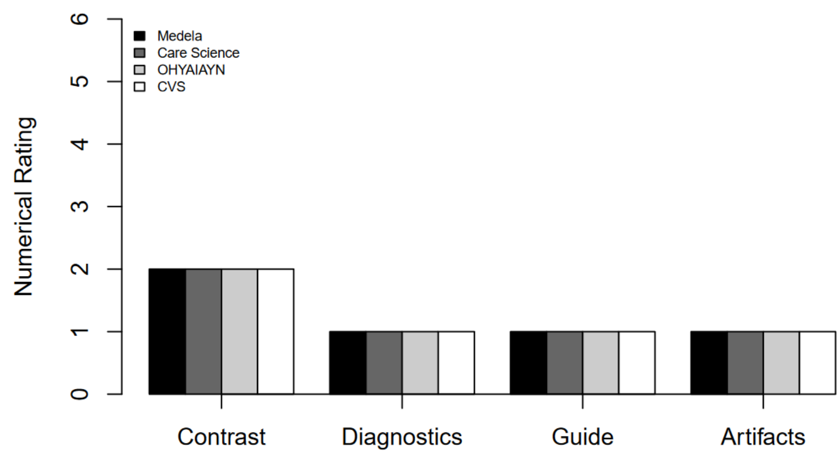

Fig. 4. Image Quality Questionnaire. An overview of the results seen after conducting the questionnaire on image quality based on physician perception. Differences were not seen in numerical ratings, suggesting that all accessible hydrogels had comparable image quality.

Peak-signal-to-noise ratio (PSNR) represents the ratio between the maximum possible value (power) of a signal and the power of distorting noise that affects the quality of its representation. A higher value indicates that an image has better quality relative to an image with a lower PSNR value. Additionally, structural similarity index measure (SSIM) is a method to measure how similar two images are to one another with one used as reference for the other. SSIM scores range from 0 to 1, with values closer to 1 indicating more similarity. Ultrasound images were taken using ultrasound gel as well as with the four accessible hydrogels (Supplementary Figure 2). Using MATLAB functions for PSNR and SSIM, PSNR and SSIM values were derived across four sets of ultrasound images for each hydrogel with the ultrasound gel image as a reference. The means and standard deviations were taken, where mean PSNR scores ranged from 14.8723 to 16.1073 (Table 2). Because of close proximity between the PSNR values in addition to the wide standard deviations, statistical testing was performed using the Kruskal Wallis Test. At an alpha level of 0.05, both PSNR and SSIM scores were deemed statistically significant, such that two or more of the hydrogels had different PSNR and SSIM scores. Post-hoc testing with the Dunn Test indicated that statistically significant differences were only apparent in the Medela and OHYAIAYN hydrogels, where both the PSNR and SSIM values for the CVS hydrogel were higher than those of the Medela hydrogel (Table 3).

Table 2. Summary of Kruskal-Wallis Tests on Hydrogels

	Medela		Care Science		OHYAIAYN		CVS		P Value
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	
PSNR	14.8723	0.2972	15.0891	0.5226	15.1498	0.1664	16.1073	0.4774	0.0228*
SSIM	0.6044	0.0255	0.6597	0.0154	0.6642	0.0129	0.7046	0.0339	0.0081*

*Indicates statistical significance at the alpha level of 0.05

Table 3. Summary of Dunn Test on Hydrogels

	PSNR	SSIM
Medela-Care Science	1.0000	0.2629
Medela-OHYAIAYN	1.0000	0.1349
Medela-CVS	0.0089*	0.0019*
Care Science-OHYAIAYN	1.0000	1.0000
Care Science-CVS	0.0094	0.2629
OHYAIAYN-CVS	0.1349	0.4748

*Indicates statistical significance at the alpha level of $p < 0.05$

A design solution selection matrix was created using each of the hydrogel testing metrics previously described (Figure 6). Ultrasound gel was given values of 0 because it was the reference design the hydrogels were being compared alongside. The Medela, Care Science, and CVS hydrogels showed little variation in numerical ratings for the ease of use questionnaire, so values of 0 were assigned to the ease of use evaluation criteria. Because the OHYAIAYN hydrogel was smaller than the other three hydrogels, it received a score of -1 for ease of use. There were no discernible differences in the participant satisfaction numerical ratings for ultrasound gel and the Medela and OHYAIAYN hydrogels, so scores of 0 were assigned to the evaluation criteria for these two hydrogels. The Care Science and CVS hydrogels, however, were notably less sticky and cool, respectively, in relation to ultrasound gel, such that assignments of 1 were made for the participant satisfaction questionnaire. All hydrogels performed poorly with the image quality questionnaire, so all were given ratings of -1. Only PSNR and SSIM scores for the Medela hydrogel were significantly lower than those of the CVS hydrogel. This resulted in ratings of -1 for the Medela hydrogel for both metrics and ratings of 0 for the PSNR and SSIM evaluation criteria for the other three hydrogels.

Evaluation Critera	Ultrasound Gel	Medela	Care Science	OHYAIAYN	CVS
Ease of Use (1)	0	0	0	-1	0
Participant Satisfaction (2)	0	0	1	0	1
Image Quality (2)	0	-1	-1	-1	-1
PSNR (1)	0	-1	0	0	0
SSIM (2)	0	-1	0	0	0
Weighted Total	0	-5	0	-3	0

Fig. 6. Design Solution Selection Matrix. Final assessments of each hydrogel were made using the hydrogel testing metrics. Each hydrogel was ranked with -1, 0, or 1 to indicate criteria in which the hydrogel did not meet, met, or exceeded ultrasound gel.

Discussion

Implications

Based on the results of the design solution selection matrix, the Care Science and CVS wound healing hydrogels were comparable to ultrasound gel (Figure 6). Though none of the tested hydrogels were better than ultrasound gel, the Care Science and CVS hydrogels can be reusable alternatives to ultrasound gel. The Medela and OHYAIAYN hydrogels scored poorly in the design solution selection matrix, with values of -5 and -3, respectively. Overall, qualitative testing suggested that none of the commercially available hydrogels were able to produce ultrasound images of satisfactory quality. However, the quantitative metrics of PSNR and SSIM indicated that the difference in image quality between the Care Science, OHYAIAYN, and CVS hydrogels was not statistically significant (Table 2).

Limitations
Due to time constraints, a significant number of participants could not be recruited in the study, which limits the significance of the results. Another limitation was the use of accessible commercial hydrogels for testing. It was difficult to determine the exact formulation of the commercial hydrogels based on the provided manufacturing information. The placement of the transducer between images collected was a potential source of error. A mark was made with a surgical marker on the skin in order to indicate where the center of the hydrogel should be oriented and the transducer subsequently placed. An assumption made when comparing images using SSIM and PSNR is that they are of the same object, but this might not have occurred while each ultrasound image was collected.

Future Work
The hydrogel design could be improved upon by incorporating a double network. Double-network hydrogels have a second interpenetrating network increasing the toughness of the hydrogel, making it less fragile and increasing its reusability. Different DN hydrogel formulations, such as a poly(vinyl alcohol)-polyacrylamide-polydopamine (PVA-PAM-PDA) hydrogel and PAM/Alginate hydrogel have already been shown to make acoustic couplants for intraoral ultrasound imaging[15,16]. Hydrogel reusability can also be improved upon by developing a hydrogel disinfection chamber, which would disinfect the hydrogel between uses and allow the hydrogel to be used on multiple patients.

Creating and implementing a more efficient acoustic couplant is one piece of the puzzle in incentivizing POCUS use at UVA. By reducing the amount of time needed to perform POCUS, physicians may be inclined to incorporate it into their daily rounds. However, it is also crucial that other institutional barriers, such as a guiding curriculum and a protocol for POCUS in primary care be implemented.

Materials and Methods

Interview Conduction
Interviews were conducted with physicians over Zoom or in an in-person setting. Questions for the interview were determined based on prior surveys made to assess barriers for POCUS. These questions were then added to a Qualtrics survey, where answer choices were selected based on contiguity between physician responses. When an answer required additional explanation beyond the existing answer choices, transcriptions of physician responses were written in Google documents created for each physician.

Qualitative Hydrogel Testing
Hydrogels were purchased online via Amazon (Medela, Care Science, and OHYAIAYN) or in-store (CVS). Questionnaires were created using prior studies concerning image quality for ultrasound gel alternatives, where all answer choices used a Likert scale of strongly disagree to strongly agree (Supplementary Figure 1). Ultrasound images were evaluated with either the GE Healthcare Vscan Ultrasound Machine with Dual Probe or the Acuson Sequoia C512 Ultrasound Machine while the ease of use, participant satisfaction, and image quality questionnaires were given after a given hydrogel was placed on the participant's hand. Once completed, answers were converted into numerical ratings, where 1 represented strongly disagree and 5 represented strongly agree.

Quantitative Hydrogel Testing
Surgical markers were used to make dots on participants. Hydrogels were then placed on the skin such that their centers matched with the location of the dot to standardize where the linear transducer was applied for ultrasound image collection. Four ultrasound images for each hydrogel and one for ultrasound gel were taken with the Acuson Sequoia C512 Ultrasound Machine (Supplementary Figure 2). Using the ultrasound

image taken with ultrasound gel as a reference, PSNR and SSIM values were obtained for all of the hydrogel ultrasound images with built-in functions for PSNR and SSIM in the MATLAB image processing toolbox. The means and standard deviations of these scores were then derived for each hydrogel ultrasound image. The Kruskal-Wallis test was used to compare differences between means across all four hydrogels since little was known about the population distributions of the PSNR and SSIM values. Subsequent nonparametric post-hoc testing was performed with the Dunn Test to ascertain which of the hydrogels had significantly different PSNR and SSIM scores from one another.

Design Solution Selection Matrix

To create the design solution selection matrix, weights of 1 or 2 were given to each testing metric. The numerical ratings for ease of use and the PSNR scores were given weights of 1, while the numerical ratings for participant satisfaction and image quality as well as the SSIM scores were given weights of 2. Since the hydrogels need to be comfortable for patients and produce quality ultrasound images for physicians to perform diagnostics, higher weights were given to the participant satisfaction and image quality numerical ratings relative to those acquired from the ease of use questionnaire. Because SSIM directly compares how similar two images are and more closely approximates human perception compared to PSNR, it was given a higher weight.

End Matter

Author Contributions and Notes

Shetty, A. and Wood, D. designed questionnaires for physician interviews and qualitative hydrogel testing, performed hydrogel testing, determined qualitative and quantitative hydrogel testing metrics, and wrote the final report. Wood, D. interviewed internal medicine physicians, performed quantitative image quality analysis and statistical testing in MATLAB, and created figures and tables for the final report. The authors declare no conflict of interest.

Acknowledgments

We thank Dr. Timothy Allen, Dr. Shannon Barker, and the rest of the Biomedical Engineering Capstone teaching team for advising our project. We would also like to show gratitude to the internal medicine physicians who participated in interviews, Dr. Masahiro Morikawa for advising our project, and Dr. John Hossack for providing consultations on ultrasonography and allowing us to use his lab.

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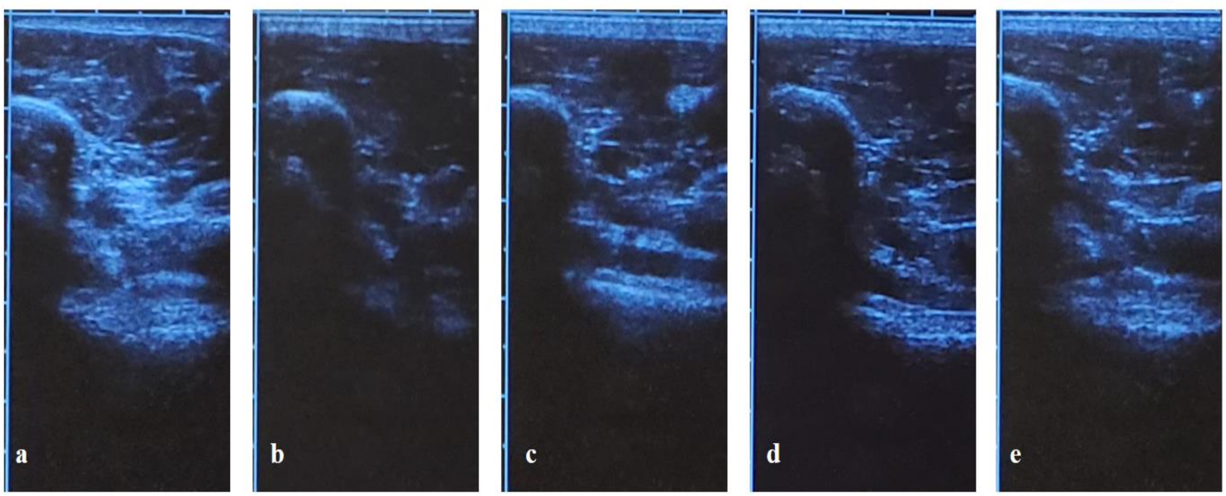
Supplementary Material

Questionnaire Type	Label	Question
Ease of Use	Large	Is the hydrogel large enough to obtain images in locations for desired ultrasound procedure?
	Adherence	Does the hydrogel stick well when contact is made with skin?
	Reusability	Does the hydrogel adhere when removed and placed onto an additional area of skin?
	Linear	Does the hydrogel obstruct the ability to obtain an image with the linear array transducer?
	Time	Does it take less time to obtain an image with the linear array transducer relative to ultrasound gel?
Participant Satisfaction	Placement	How comfortable was it for the gel to be placed on your skin?
	Warm	Was the gel especially warm?
	Cool	Was the gel especially cool?
	Sticky	Was the gel too sticky?
	Dry	Was the gel too dry?
	Removal	How comfortable was it for the gel to be removed from your skin?
Image Quality	Contrast	Does this hydrogel capture image contrast between bodily structures?
	Diagnostics	Can this hydrogel be used for ultrasound imaging diagnostics?
	Guide	Can this hydrogel be used to guide medical procedures with ultrasound imaging?
	Artifacts	Can this hydrogel be used to assess the presence of motion artifacts in ultrasound images?

Supplementary Fig. 1. Questionnaires and corresponding labels for images created. The ease of use, participant satisfaction, and image quality questionnaires were conducted and labels were developed for each question while creating the figures for their respective numerical ratings to conserve space.



Supplementary Fig. 2. Ultrasound Images Taken with Ultrasound Gel and Accessible Hydrogels. (2a) Aquasonic Ultrasound Gel. (2b) Medela Tender Care HydroGel Soothing Gel Pads (2c). Care Science Hydrogel Sterile Burn Pads & Wound Dressing for Burn Relief. (2d) OHYAIAYN Gel Sheets for Abdominal Toning. (2e) CVS Health Sterile Hydrogel Burn Pads.