Simulation of laparoscopic ultrasound imaging and suturing of the bile duct using silicone

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ABSTRACT

The laparoscopic treatment of gallstone is a complex procedure requiring multiple skills, notably laparoscopic ultrasounds imaging and laparoscopic suturing. This procedure has many benefits comparing to open surgery, but still fail to be generalised because of these challenging steps. Surgical simulation can provide a useful way to train for the complex skills required by the surgery in a safe environment.

This study focuses on the evaluation of the utilisation of silicone to create a simulator for this procedure. Silicone samples are tested quantitively and qualitatively. The qualitative evaluation compares the ultrasound examination of the silicone samples to the images of ultrasound captured during a real procedure. For the quantitative evaluation, the density, the speed of sound in the material, and the mechanical properties are measured and compared to the properties of the soft tissues.

The qualitative evaluation shows that silicone requires the addition of scattering agents to be visible using ultrasound, especially for the hardest silicones which are the most suitable to simulate the bile duct in term of mechanical properties. The quantitative evaluation shows that the density of silicone and the Young modulus are close to the properties of soft tissues, but the speed of sound is slower in the silicone, which results in deformed images. A solution is to perform image processing, which can lead to a more realistic appearance of the images.

Keywords: surgical simulation; ultrasound; image processing.

1. INTRODUCTION

Gallstones are a widespread problem; in the USA, they touch 15 % of the adult population and in Europe the median prevalence is of 5.9–21.9 % [1]. They account for a significant number of emergency admissions and surgical procedures globally [2]. The keyhole, or laparoscopic, approach has significant benefits to these patients in terms of length of stay in hospital, complication rate, and return to normal activities. [3–5]

Surgical simulators are proven to improve a surgeon's performance through operative rehearsal and practice [6]. This particular operation requires multiple skill sets to be undertaken in a series of well-executed steps including intra-operative ultrasound imaging and laparoscopic suturing of the bile duct. A surgical simulator will enable both young surgeons as well as experience surgeons to practice and gain experience with the steps and skills of this surgery required to achieve in confidence this procedure on their patients to their benefits. To our knowledge, there is no satisfying simulator able to teach those challenging steps yet.

In this research project, a surgical simulator for laparoscopic bile duct exploration is developed; the most critical parts of the simulator are the simulation of the intra-operative ultrasound imaging and suturing. This paper evaluates the use of silicone for the simulation of ultrasound imaging and suturing.

2. STATE OF THE ART

There are different types of surgical simulators: virtual-reality based simulators, physical simulators, and hybrid simulators. [7] The virtual reality-based simulator does not provide a physical model but generates computer-based images for the training of the surgeon. In the context of ultrasound training, they are useful to train young surgeon to analyze ultrasound images but do not provide as much tactile feedback as other types of simulators [8].

Physical simulators for ultrasound training are made of materials that can provide similar images as soft tissues. They are often made of gels such as agarose or gelatin; or a combination of a bulk material and of a scattering agent. The gels have

Medical Imaging 2022: Image-Guided Procedures, Robotic Interventions, and Modeling, edited by C. A. Linte, J. H. Siewerdsen, Proc. of SPIE Vol. 12034, 1203423 · doi: 10.1117/12.2611340

the drawback of having a low shelf-life. The scattering materials are useful to make the ultrasound image look more realistic when using gel-based materials or material with longer shelf-life such as silicones. [9] This type of simulator is useful because they provide tactile feedback and the surgeon can interact with the model in real-time, for instance the surgeon can move the probe and see the modification of the image in real-time. However, the images are sometimes less realistic as the virtual-reality based images, which can be a limitation for the training of the analysis of the images [10].

Hybrid model can combine the advantages of both methods by providing realistic looking images and an interactive model with tactile feedback. The hybrid models combine a physical model and an augmented reality technique such as image processing to improve the realism of the images [7].

3. PROPOSED METHOD

3.1 Material selection

This study focuses on the utilization of silicone to create an ultrasound simulator. The gel-based materials are not tested because of their low shelf-life and more complex manufacturing and production techniques. The materials tested are a range of two-parts silicones from Smooth-On; they have a shore hardness of 000-35, 00-10, 00-30 and, 10 A [11].

Inspiring from a study by Chanda et al. on skin surrogates [12] several products are mixed together with varying ratio to create samples with a wider range of properties. These products can be other types of silicones, or other additives such as Slacker which will change the cure silicone to a softer and more flesh-like material, and Thinner that will lower the ultimate shore-hardness. The tests performed are:

- Mixing two silicones of various shore-hardness,
- Changing the part-A and part-B ratio when mixing the two-part silicone,
- Adding different percentage of additive into the silicones.

The addition of a scattering material inside the silicone is also tested during this study. The scattering materials tested are particles of different sizes, as summarized in Table 1. The influence of the percentage of scattering material inside the silicone matrix is also tested by making samples with varying ratio of scattering material, ranging from 0.05%w to 5%w.

Table 1: Scattering materials tested in this project and their size (µm)

Polestar 450	Graphite	Glass sphere	Flour	Silica	Alumina	Sugar
2	<20	9-13	10-41	50	60	200-400

3.2 Preparation of the samples

Different types of samples are prepared within this study for the quantitative and qualitative evaluations. The samples for the quantitative evaluation are cylinders and dog-bone shaped samples; the samples for the qualitative evaluation mimic the shape of the soft tissues such as the bile duct and the tissues in which it is embedded. The samples are created by casting the silicone into 3D printed moulds.

When preparing silicone samples, the two parts of the silicones are mixed together which generates the formation of air bubbles. The samples can be vacuumed to remove the air bubbles; however, the influence of having air bubbles in the samples is also tested by not vacuuming half of the samples.

3.3 Evaluation protocol

The different samples are evaluated both quantitatively and qualitatively. To qualitatively evaluate the materials, they are compared to the images of ultrasound captured during a procedure.

For the quantitative evaluation, two of the physical parameters that influence the propagation of the sound waves which are the density or the speed of sound in the tissues are measured for the different types of silicones. The measures are compared to the properties of the soft tissues found in the literature. The mechanical properties of the samples are also tested to evaluate how well it would mimic the tactile feedback during a suturing task. The mechanical property evaluated is the Young modulus.

3.3.1 Measure of the density

To measure the density d of the samples, we first measure the weight *w* of the sample using a precision balance. Then we measure the volume *V* of the sample by immerging it in water and evaluating the variation of volume. At last, we deduce the density *d* with the following formula:

$$d = \frac{w}{V} \tag{1}$$

3.3.2 Sound celerity

The protocol to measure the speed of sound is inspired by [13] because all ultrasound imaging machines are calibrated to assume the propagation speed is 1540m/s in the materials; then the following procedure can be followed to measure the celerity of the sound wave in the sample:

1. Scan the material (of known thickness) with an ultrasound machine
2. Using the on-screen calipers measure the depth of the material on screen
3. The speed of sound in the material can be calculated with the following formula:

$$\text{Speed of sound in material} = \frac{actual\ depth\ of\ material}{on\ screen\ measured\ depth} \times 1540\ \mathrm{m/s} \tag{2}$$

3.3.3 Young modulus

The Young modulus is measure using a X350-20 tensiometer. This testing machine can record the stress and strain of the materials, allowing to deduce the Young modulus. The tensile tests were performed on dog-bone shaped samples. The geometry was obtained by scaling down by 50% the geometry of the ASTM D412 standard specimens used for elastomers and vulcanized rubber testing, as seen in the Figure below.

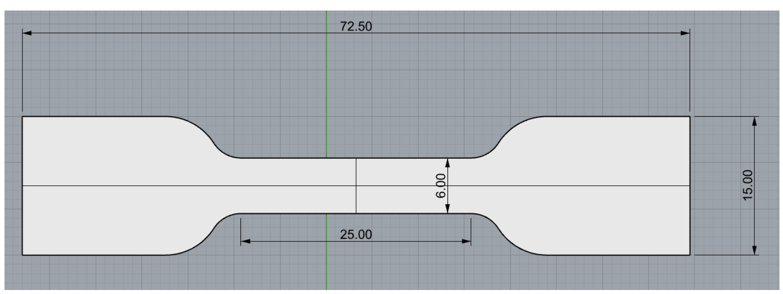

Figure 1: Dog-bone shaped samples (a); Mould designed on the Computer Assisted Design Software Rhino (b)

The mechanical tests were run at a constant rate of 50 mm/min with a maximum displacement of 1050 mm and a load cell of 100kgf. The strain and stress in the material were controlled by the WinTest Analysis software. The software records the stress and strain, then calculates the Young modulus of the material. The stress and the strain have a linear relationship in the elastic range. This relationship is the Hooke's law, as shown below. Each test was repeated several times for more precision of the results.

$$\sigma = \varepsilon \times E \tag{3}$$

4. RESULTS

4.1 Quantitative evaluation

The quantitative evaluation shows that the speed of sound in the silicone fluctuates between 9.0×10^2m/s and 1.0×10^3m/s in the silicone samples. The speed of sound in the soft tissues is typically of 1450 to 1590m/s, which is significantly higher than the speed of sound in the samples [14].

The measure of the density shows that the density of the samples varies between 9.6×10^2kg/m^3 and 1.1 $\times 10^3$kg/m^3. The density of the soft tissues usually varies between 950-1060 kg/m^3 [14]; the density of the samples is in the right order of magnitude. The density also appears to be connected to the hardness of the silicone; the softest silicones have a low density, while the hardest silicones tested have the highest density.

The measure of the Young modulus shows that the Young modulus of the silicone varies between 1 and 300kPa. The Young modulus of the soft tissues also varies within this range. The silicones tested in this study can mimic a wide range of soft tissues, ranging from very soft tissues like the fat and the liver, to hardest tissues like the bile duct, the artery, the gallbladder, or the skin. Because of their similar mechanical properties, the hardest silicones from this study are appropriate to mimic the bile duct in a suturing task.

Vacuuming the samples or adding a scattering agent do not seem to have an influence on the speed of sound into the sample, the density of the samples, nor the mechanical properties.

4.2 Qualitative evaluation

Before testing the samples, the parameters of the ultrasounds probe are set as in Table 2. These parameters are the same as the ones of the laparoscopic probe used in real surgery. The samples are evaluated in the B-mode. The aim is to mimic the images achieved in real surgery like in Figure 2(a).

Table 2: Parameters for ultrasound testing

Frequency	7.5MHz
SRI	Off
Graymap	D or E
Gain, DR, and TGC	Medium, but to be adjusted

When the samples are in the water like in Figure 2(d,e,f), the surface of the sample reflects most of the ultrasound wave because of the difference of impendence in between the two media. To avoid such reflection, the silicone vessels are put in another silicone matrix; similarly, during an ultrasound examination on a patient, the vessels are also embedded inside other soft tissues; for this reason, it makes more sense to analyze the silicone vessels in context too.

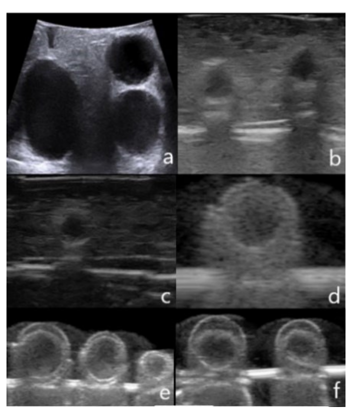

Figure 2: Ultrasound images of: the bile duct, cystic artery, and hepatic vein in real surgery (a); the tube samples in another silicone matrix (b) and (c); the silicone tubes samples in water (d), (e), and (f)

Because of the difference between the speed of sound in the silicone and the speed of sound in the tissues, the image is deformed and the dimensions of the tube appear bigger on the image. The speed of sound in the samples is around 2/3rd of the speed of sound in the tissues, resulting in a sample appearing 1.5 times bigger.

4.2.2 Influence of the scattering material

On the ultrasound images, the silicone takes different shades of grey. The hardest materials used to make the vessels because of their mechanical properties are anechoic and appear black on the image (Figure 2 (e) and (f)). Adding a scattering agent increase the reflection of the ultrasound wave in the silicone, and make them visible using the ultrasound; they then appear in grey on the ultrasound image (Figure 2 (d))

Rising the percentage of scattering agent results in more reflection from the sample, making it brighter on the ultrasound image (Figure 3). When the percentage of scattering agent is above 1%w, the images gets dark at the bottom because there was too much reflection on the scattering agent, limiting the penetration of the wave.

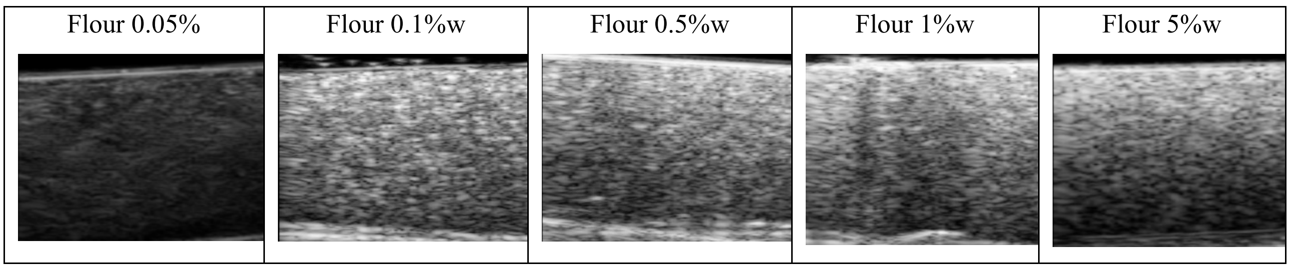

Figure 3: Effect of increasing the percentage of scattering agent

The influence of the size of the scattering agent is shown in the Figure 4; however, the influence is not apparent because the particles do not spread well into the silicone matrix, making the particles agglomerate together. For this reason, the particles appear bigger on the ultrasound image and the image look similar. The particles do not spread well into the matrices because their density and refractive index are too different from those of the silicone; and because their surface chemistry makes them agglomerate rather than disperse. Because of the high viscosity of the silicone, it is difficult to force the particle to disperse homogeneously into the sample.

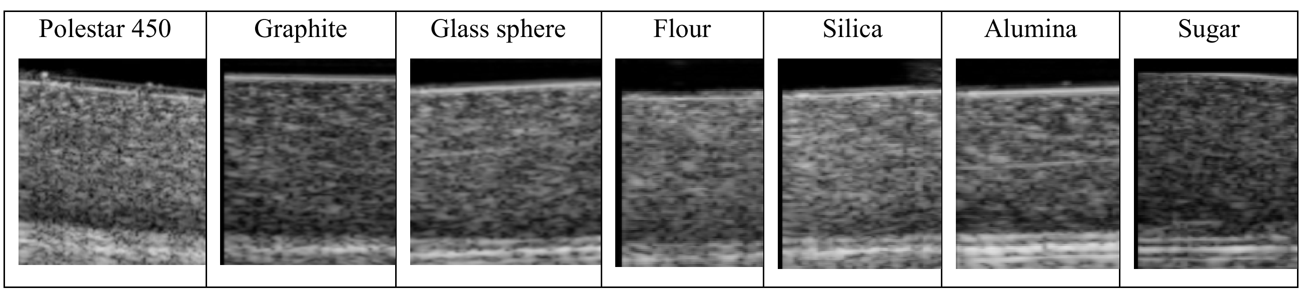

Figure 4: Effect of the different types of scattering particles

4.2.1 Influence of the vacuuming

The aim of the vacuuming is to remove the air bubbles from the samples. The air bubbles act similarly as a scattering material for the ultrasound wave during the ultrasound examination, making the sample more visible; this is shown in Figure 5.

From this study, it also seems that the softest silicones trap more air bubbles than the hardest materials, making them more visible on the ultrasounds.

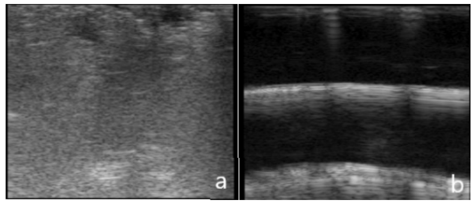

Figure 5: Ultrasound image of a sample of Ecoflex gel without vacuuming (a); ultrasound image of a sample of vacuumed Ecoflex gel (b)

5. DISCUSSION

One of the results from this study is that the dimensions of the samples on the images are deformed. This could be a limitation for the simulation of the ultrasound imaging of the bile duct in the context of laparoscopic bile duct exploration, because one of the tasks during the ultrasound examination is to measure the size of the bile duct to decide if the surgeon can go ahead with the procedure.

Furthermore, the colours of the ultrasound image are not very realistic. A solution could be to perform image processing on the ultrasound images in real time, creating a hybrid simulator. Style-transfer is an image processing technique that combines a style image and a content image to create an output image with the style of the first image and the content of the second image [15]. This technique has already demonstrates its potential for surgical simulation in the past [16]. In this application, it can be applied to add the style of an image of real ultrasound on the image of the simulator, as shown in the Figure 6.

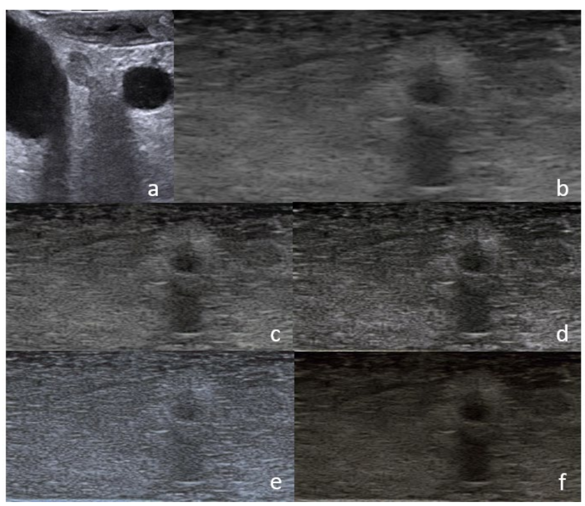

Figure 6: Style image from surgery (a); content image from the simulator (b); result of the style transfer algorithm using various style/content ratio (c)-(f)

Figure 6 shows that image processing can modifies the aspect of the ultrasound image of the simulator and modify the color and appearance which could lead to more realism; however, the generalization of this technique can be limited in real-time because of technology used to perform the ultrasound examination. If the ultrasound probe is connected to a computer, then the image can be processed; but if the image is displayed on a monitor made especially for the ultrasound, then processing the image could prove to be more difficult and challenging because the software of the ultrasound monitor would need to be modified directly.

6. CONCLUSION

This study shows the potential of using silicone in the context of simulation of bile duct exploration to perform tasks such as ultrasound imaging and suturing. Silicone has many benefits in the context of simulation because it is easy to use, has a long shelf-life, and has a softness range similar to the one of soft tissues, resulting in a realistic tactile feedback, notably for suturing tasks.

However, silicone has limitations for the simulation of ultrasounds because it required the addition of a scattering material to be visible using ultrasound; moreover, the speed of sound in the silicone is too slow resulting in deformed images. Image processing technique can improve the realism of the simulation of ultrasounds, making silicone suitable for the simulation of this procedure.

7 ACKNOWLEDGMENTS

Funded by the Horizon 2020 programme of the European Union. Grant number 814158 ”Appearance Printing - European Advanced Research School” (ApPEARS).

REFERENCES

[1] Joshua S. Winder and Eric M. Pauli (2016) Common Bile Duct Stones: Health Care Problem and Incidence. Springer Int Publ Switz. https://doi.org/10.1007/978-3-319-22765-8_2

[2] Beckingham I, Macutkiewicz C, Toogood G, Maynard N (2014) Pathway for the Management of Acute Gallstone Diseases. Assoc Up Gastrointest Surg 1–12

[3] Vagholkar K, Nachane S, Vagholkar S (2021) Comparative study between laparoscopic and open cholecystectomy (Study of 50 cases). Int J Med Rev Case Reports 33:1. https://doi.org/10.5455/ijmrcr.comparative-study-between-laparoscopic-and-open-cholecystectomy

[4] Helmy MZ, Ahmed AE (2018) Safety and efficacy of laparoscopic versus open surgery in management of common bile duct stones: experience at the Sohag University Hospital, Egypt. Int Surg J 5:3727. https://doi.org/10.18203/2349-2902.isj20184652

[5] Redwan A, Omar M (2017) Common bile duct clearance of stones by open surgery, laparoscopic surgery, and endoscopic approaches (comparative study). Egypt J Surg 36:76. https://doi.org/10.4103/1110-1121.199895

[6] Stather DR, MacEachern P, Rimmer K, et al (2011) Assessment and learning curve evaluation of endobronchial ultrasound skills following simulation and clinical training. Respirology 16:698–704.

[7] Freschi C, Parrini S, Dinelli N, et al (2015) Hybrid simulation using mixed reality for interventional ultrasound imaging training. Int J Comput Assist Radiol Surg 10:1109–1115. https://doi.org/10.1007/s11548-014-1113-x

[8] Bernardo A (2017) Virtual Reality and Simulation in Neurosurgical Training. World Neurosurg 106:1015–1029. https://doi.org/10.1016/j.wneu.2017.06.140

[9] S. Ahmad M, Suardi N, Shukri Mustapa Kamal A, et al (2020) Chemical Characteristics, Motivation and Strategies in choice of Materials used as Liver Phantom: A Literature Review. J Med Ultrasound 28:.

[10] Viglialoro RM, Esposito N, Condino S, et al (2019) Augmented Reality to Improve Surgical Simulation: Lessons Learned Towards the Design of a Hybrid Laparoscopic Simulator for Cholecystectomy. IEEE Trans Biomed Eng 66:2091–2104. https://doi.org/10.1109/TBME.2018.2883816

[11] Smooth-On I Smooth-On: Mind Blowing Materials for a World of Applications. https://www.smooth-on.com/. Accessed 12 Jul 2021

[12] Chanda A, Unnikrishnan V (2016) Human tissue simulants for study of traumatic brain injury (TBI) 31st technical conference. Proc Am Soc Compos - 31st Tech Conf ASC 2016

[13] Chiu T, Xiong Z, Parsons D, et al (2020) Low-cost 3D print–based phantom fabrication to facilitate interstitial prostate brachytherapy training program. Brachytherapy 19:800–811. https://doi.org/10.1016/j.brachy.2020.06.015

[14] Soni NJ (2015) Point-of-Care Ultrasound

[15] Gatys L, Ecker A, Bethge M (2016) A Neural Algorithm of Artistic Style. J Vis 16:326. https://doi.org/10.1167/16.12.326

Luengo I, Flouty E, Giataganas P, et al (2019) Surreal: Enhancing Surgical simulation Realism using style transfer. Br Mach Vis Conf 2018, BMVC 2018 1–12