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Foundational Investigation of an Acoustic Sensor for the Detection of Lumps in 2D Breast of Lactating Mother

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Abstract

Lactation refers to the process of producing and secreting milk from the mammary glands, typically occurring in mammals, including humans. There are some diseases that relate to breastfeeding, such as mastitis, blocked milk duct, nipple pain, and low milk supply. This project aims to investigate of breast lumps in lactating mothers by using Comsol Multiphysics 6.1. An acoustic sensor is a suitable sensor that can sense blocked ducts in mammary glands. This project model the anatomy of the breast in 2D geometries that involves creating and defining the spatial structures that represent the physical system of the breast in real life. The 2D model of a breast with lump milk surrounded by an acoustic sensor is being simulated. Two configurations of sensors are being investigated, two and four sensors. For each of the sensor configurations, four types of milk are being investigated, which are 37% of solid milk, 49.5% of solid milk, 59.6% of solid milk, and 72.4% of solid milk. The findings from this study will aid in determining whether the mother has a milk lump or not. The result shows that the more solid milk exist at the breast, the less acoustic and voltage received at the acoustic receiver. It also reveals that the low frequency penetrates more to the milk lump which result on higher acoustic received by the receiver. The results demonstrate a promising future for acoustic sensors in sense lump milk, although further investigation is necessary to explore different acoustic sensor arrangements and counts in real-world implementation.

1. Introduction

Breastfeeding is a natural process that provides essential nutrients and antibodies to infants, promoting their growth and development. However, nursing can encounter issues such as engorgement, mastitis, blocked ducts, nipple pain, and low milk supply [1]. Blocked ducts are particularly problematic and can be categorized into two types: duct ectasia and carcinoma.

Blocked duct ectasia involves the abnormal widening of milk ducts with chronic inflammation and fibrosis but is non-cancerous [2]. Blocked duct carcinoma, on the other hand, involves abnormal cells in the milk duct and is considered an early form of breast cancer, potentially curable if detected early [3].

A study involving 25 lactating mothers treated with ultrasound revealed that 16 had no prior history of blocked ducts, while 9 did. Out of these, only five had serious issues, with just two reporting pain [4]. Treatment with therapeutic ultrasound was effective in resolving these problems.

Various imaging techniques, including breast ultrasound, mammography, MRI, and photoacoustic imaging, are used to identify blocked ducts. Ultrasound is prevalent due to its ability to produce detailed images of tissues, blood vessels, and other structures using sound waves. This method captures echoes from tissue density changes, creating detailed images of internal structures, aiding in both diagnosis and treatment.

This project aims to detect milk lumps in lactating mothers by modeling breast anatomy and simulating the interaction between acoustic sensors and the model, enhancing future research and hardware development.

2. Literature Review

Each treatment approach for breast cancer has its advantages and disadvantages, with a common challenge being the need to position a probe or ultrasound beam accurately within the target tissue for effective ablation and monitoring. This task is particularly difficult when tumors are near large blood vessels or organs [5]. To address this, patient-specific image-based 2D modeling for thermal ablation simulation has been developed to optimize treatment protocols and enhance efficacy. Software such as Phantom, ScanIp, and Comsol Multiphysics can model breast anatomy in 2D.

These models aim to provide a precise depiction of breast cancer characteristics, including temperature distribution relative to the lesion's size, shape, and depth. Targeted parametric analysis is used to gather characteristics that help predict the location of breast cancer, thus aiding clinical detection and treatment [6].

Specifically, the 2D model generated by Comsol Multiphysics can simulate the penetration of skin, fat, and tissues to detect milk vessel lumps. By configuring material properties within the software, it is possible to visualize lumps in breast tissue, serving as a preliminary assessment before actual procedures.

3. Methodology

COMSOL Multiphysics is a powerful software used for simulating and solving complex Multiphysics problems. It employs the finite element method to numerically solve systems of coupled physics equations. With its user-friendly interface, it allows users to create and customize simulation models, define materials and boundary conditions, and set up Multiphysics coupling. The software supports a wide range of physics interfaces and provides advanced solvers and algorithms for efficient computations. This application allows for the simulation of interconnected physical phenomena, empowering users to model and examine the interplay among diverse physical processes. Additionally, it provides robust features for crafting and importing intricate 2D geometries, enabling users to construct complex shapes tailored to their studies. Lastly, the software incorporates sophisticated meshing algorithms designed to discretize the geometry into elements suitable for finite element analysis.

Fig. 1 illustrates the flow of the project where it started with commencing the research on breast anatomy, focusing on the exploration of skin, fat, and milk duct properties. Later, the anatomy of the breast will be modeled using Comsol Multiphysics 6.1. If the model is correct, it shows no error, and subsequently, the acoustic sensor will be modelled and attached to the breast anatomy. The sensor will be configured around the breast model to identify milk lumps.

The materials from the milk need to be analyzed in relation to the properties of an acoustic sensor. This will ensure that the sensor detects only the target object. The simulation output is examined to verify if voltage can be generated. If not, adjustments in designing the acoustic sensor are required. Subsequently, the milk condition is change according to low, normal, saturated, and cyst milk by changing the property of each milk condition. The acoustic sensor produced the result based on conditions of milk. The location of sensor and number of sensors also will investigate to increase sensitivity. Lastly, the data received from all of them is analyzed.

3.1 Software Requirements

A model anatomy breast is designed in 2D geometries to involve creating and defining the spatial structures that represent the physical system of the breast. The design consist of three layers, which are skin, fat, and lump milk.

In this design, the material of skin is located at Comsol library. The properties of the skin in the Comsol library mirror those of regular human skin. Basically, the dermis, it is composed of an association of fibres, which is collagen. It capable of holding a large amount of water to maintain skin moisture. Skin thickness varies across different parts of the body, ranging from 0.3 to 2.6 mm, with an average thickness of 2 mm [7]. This project used approximately 1116 kg/m3 as the dermis density. While the fat layer encompasses triglycerides, cholesterol, and other essential fatty acids. The primary components of milk are fat, protein, carbohydrates, and water. Then, the density of adipose tissue was determined using the proportions of each of its constituent densities (fat: 900 kg/m3, water: 1012 kg/m3, and fat-free solids: 1400 kg/m3). Thus, the average density of adipose tissue was 900 kg/m3, and the mass of adipose tissue was computed [8]. Lastly, milk is main components that will observe in this project. The milk come in some conditions either liquid (37.0%), normal (49.5%), saturated (59.6%), and cyst (72.4%). The human milk consists of carbohydrates, protein, fat, vitamins, minerals and hormones. The density of human milk is 1030kg/m3[9]. Fig. 2 shows the breast model with two sensors, while Fig. 3 shows the breast model with four sensors. The green colour is a transmitter of an acoustic pressure sensor, while the blue colour is the receiver of the acoustic pressure sensor. The acoustic sensor is use to detect the differential between each conditions of milk.

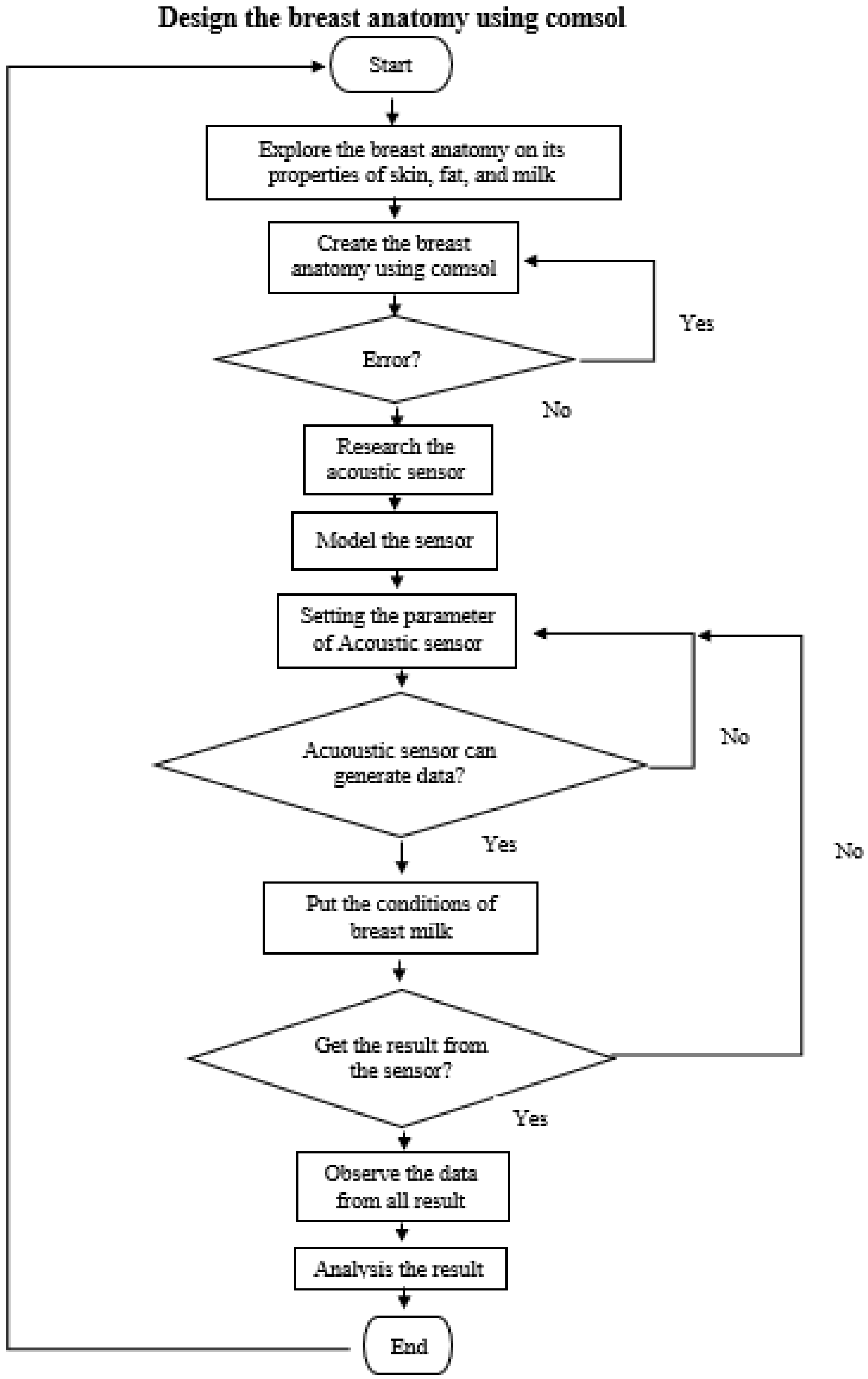

Fig. 1 *The overall process of the project.*

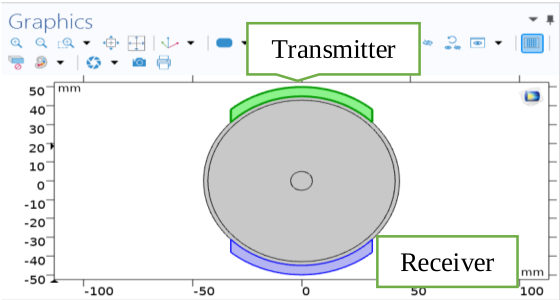

Fig. 2 *The breast model with two sensors.*

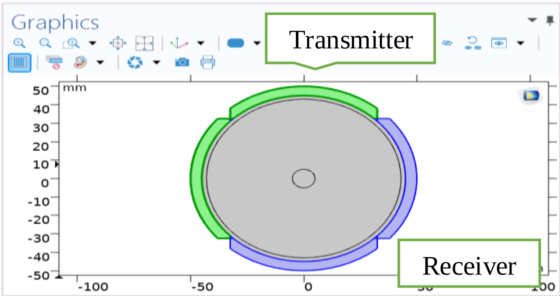

Fig. 3 *The breast model with four sensors.*

Acoustic employs high-frequency bursts of sound waves, typically ranging from 2.5 to 10 MHz, commonly used in general medical applications. Typically, a standard 7.5 MHz linear array probe is primarily used to visualize superficial structures [10]. Fig. 4 shows the setting of frequency for this project in Comsol which the sensor acoustic was used lead zinc titanate (PZT-5H), an acoustic pressure sensor, was the acoustic sensor utilised for this project [11].

Parameters

Name	Expression	Value
f0	7.5[MHz]	7.5E6 Hz
fmax	2*f0	1.5E7 Hz
T0	1/f0	1.3333E-7 s
t	1[s]	1 s
cp_water	1481[m/s]	1481 m/s

Fig. 4 *The frequency of acoustic sensor.*

The primary subject of study in this project is milk. This can occur due to incomplete emptying of the breast or less breastfeeding. Based on the study, the composition of milk mothers will change over time by adapting themselves to the changing needs of the growing child. There are two types of protein in human milk, which are whey and casein (curds) [12]. Whey proteins are liquid and very easy to digest, while casein proteins are larger, more complex protein molecules that are harder to digest. The concentration of milk will depend on the percentage of whey and casein. When the percentage of casein is higher, so the milk is more viscous. The casein will turn curds when in a low PH environment. Galactocele (cyst milk), also referred to as lactocele or lacteal cyst, is an uncommon benign retention cyst found in the breast, characterized by being filled with milk [13]. Milk solids determine the quality of milk. Low-quality milk contains 37% milk solids, normal milk has 49.5%, saturated milk has 59.6%, and cyst milk has 72.4%. These percentages indicate the amount of milk solids present in the milk.

4. Result and Analysis

4.1 Sensor acoustic emitted to the anatomy breast model

Fig. 5 shows the two acoustic sensors located at the breast model with milk. Sensor that acting as transmitter, transmit the acoustic pressure to the receiver side. The pressure signal spread to the entire breast area. While Fig. 6 shows the four acoustic sensors surrounded the breast model with milk where two sensors acting as transmitter, emitted the pulse towards receiver side. For two sensor simulation, it takes around 15 minutes until 20 minutes to run the simulation, while for four sensor simulation take between 20 minutes until 30 minutes to run the simulation. In this project, simulations are also conducted on a breast without milk to compare the results with those obtained from a breast with milk.

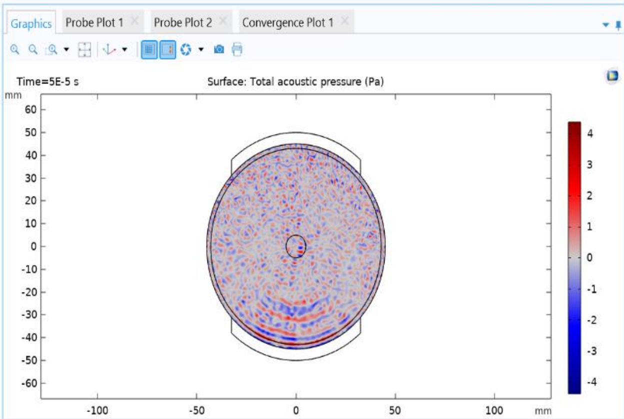

Fig. 5 *Condition when one acoustic sensor was emitted a pulse towards the breast.*

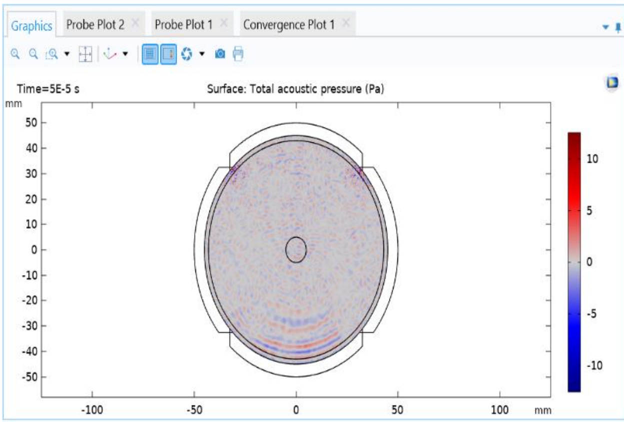

Fig. 6 *Condition when one acoustic sensor was emitted a pulse towards the breast.*

4.2 Result and analysis of milk condition with different sensor configurations

The maximum total output acoustic pressure (Pa), was measured across various percentages of solid milk using two sensors. The graphs of the output acoustic pressure indicate that all conditions exhibit a similar pattern, with only minor differences. Table 1 presents the highest peak of output acoustic pressure for each percentage of solid milk. Fig. 7 compares the highest peak of the output acoustic pressures across different solid milk percentages using a bar chart for two sensors. Therefore, it can be concluded that an increase in the percentage of solid milk results in a decrease in output acoustic pressure (Pa).

Table 1 *Effect types of solid milk on acoustic pressure output, Pa, by using two sensors.*

No	Percentage of solid milk	Output acoustic pressure, Pa
1	37.0%	1.663118
2	49.5%	1.661570
3	59.6%	1.660317
4	72.4%	1.658649

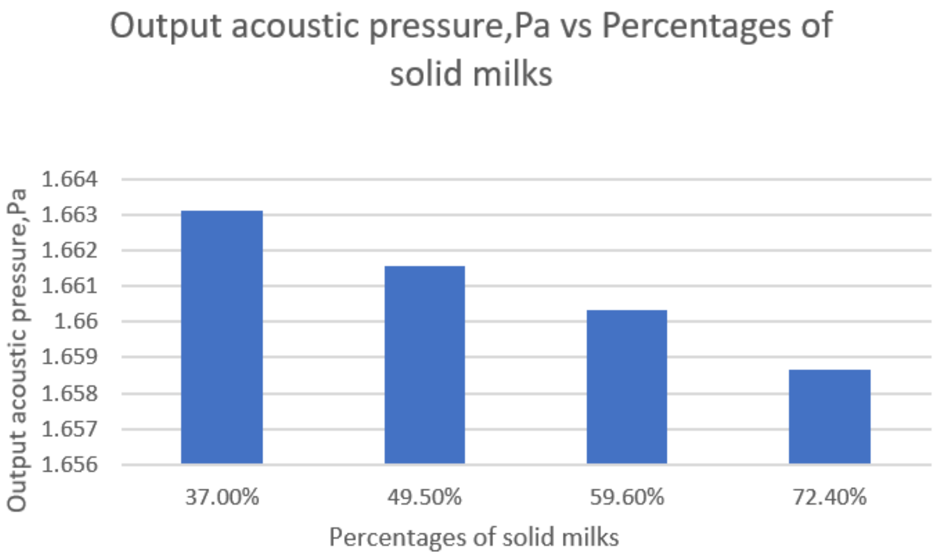

Fig. 7 *Comparison between percentages of solid milks with output acoustic pressure, Pa, by using two sensors.*

The maximum total output acoustic pressure (Pa), was measured across various percentages of solid milk using four sensors. The graphs of the output acoustic pressure indicate that all conditions exhibit a similar pattern, with only minor differences. However, the results of differ in the no milk condition due to the absence of solid milk in the breast. Table 2 presents the output acoustic pressure for each percentage of solid milk. Fig. 8 compares the output acoustic pressures across different solid milk percentages using a bar chart for four sensors. Therefore, it can be concluded that an increase in the percentage of solid milk results in a decrease in output acoustic pressure (Pa).

Table 2 *Effect types of solid milks on acoustic pressure output, Pa by using four sensors.*

No	Percentage of solid milk	output acoustic pressure, Pa
1	37.0%	1.511887
2	49.5%	1.507373
3	59.6%	1.505102
4	72.4%	1.502335

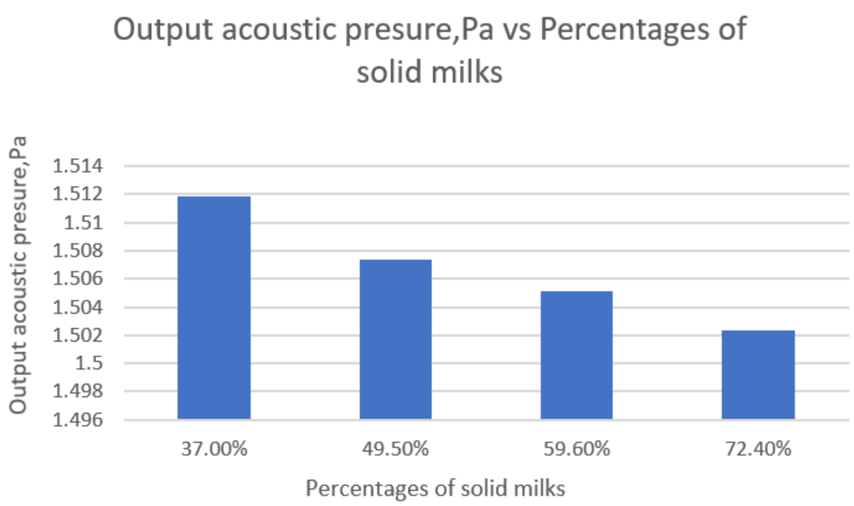

Fig. 8 *Comparison between percentages of solid milks with output acoustic pressure, Pa, by using four sensors.*

4.3 Result by changing the frequency of sensor acoustic

The frequency of acoustic pressure changes to 3 MHz, 7.5 MHz, and 10 MHz on two sensors and four sensors. The variation of frequency for this project due to analyse either high frequency or low frequency more suitable. This only focuses on conditioned milk, with 72.4% of solid milk, where it is easy for milk lumps to occur. Fig. 9(a) shows the setting of acoustic pressure for 3Mhz. Fig. 9(b) shows the setting of acoustic pressure for 7.5 MHz. Fig. 9(c) shows the setting of acoustic pressure for 10 MHz.

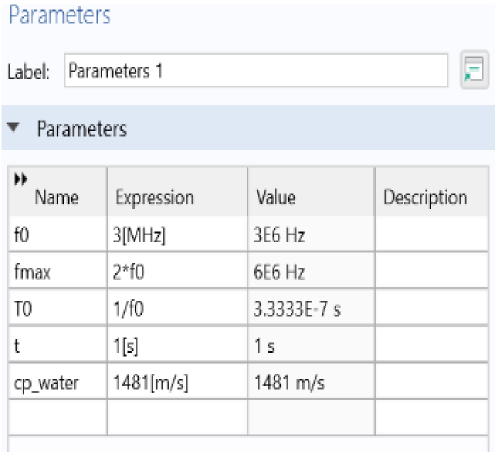

Fig. 9(a) *Setting the frequency of the acoustic sensor to 3 Mhz.*

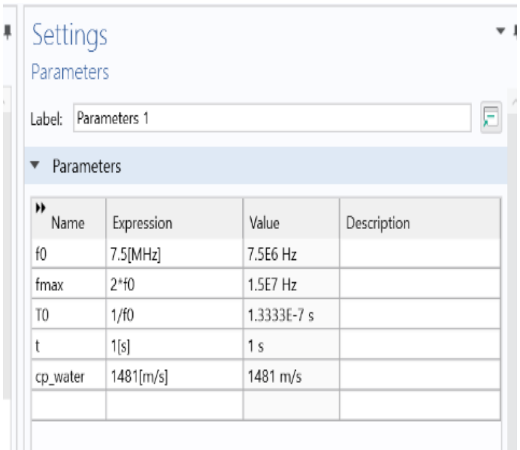

Fig. 9(b) *Setting the frequency of the acoustic sensor to 7.5 Mhz.*

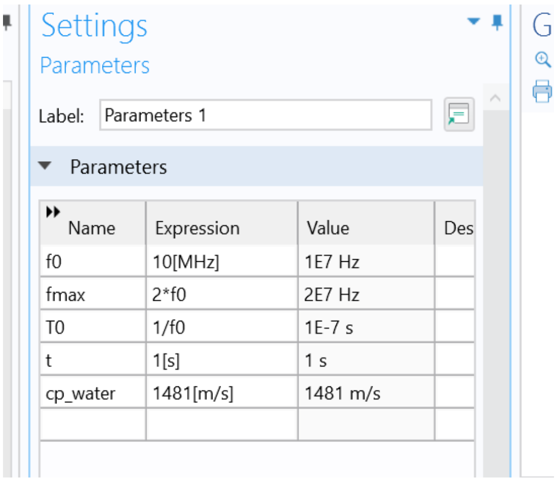

Fig. 9(c) *Setting the frequency of the acoustic sensor to 10 MHz.*

The highest total output acoustic pressure (Pa) was recorded at various sensor frequencies (MHz) using two sensors. The output acoustic pressure graphs show a similar pattern for frequencies of 7.5 MHz and 10.0 MHz, with only slight differences, while the graph for 3.0 MHz shows significant changes compared to the others. The highest peak of output acoustic pressure for each frequency are 3.0 MHz (10.612435), 7.5 MHz (1.658649), and 10.0 MHz (0.932064). Table 3 illustrates the impact of different sensor frequencies (MHz) on the output acoustic pressure (Pa). Fig. 10 provides a bar chart comparison of the output acoustic pressures across different sensor frequencies for the two sensors. Therefore, it can be concluded that increasing the sensor frequency (MHz) leads to a decrease in the output acoustic pressure (Pa).

Table 3 *Impact of sensor frequency on acoustic pressure output, Pa, by using four sensors.*

No	Frequency of sensor, Mhz	Output acoustic pressure, Pa
1	3.0	9.220869
2	7.5	1.502335
3	10.0	0.856781

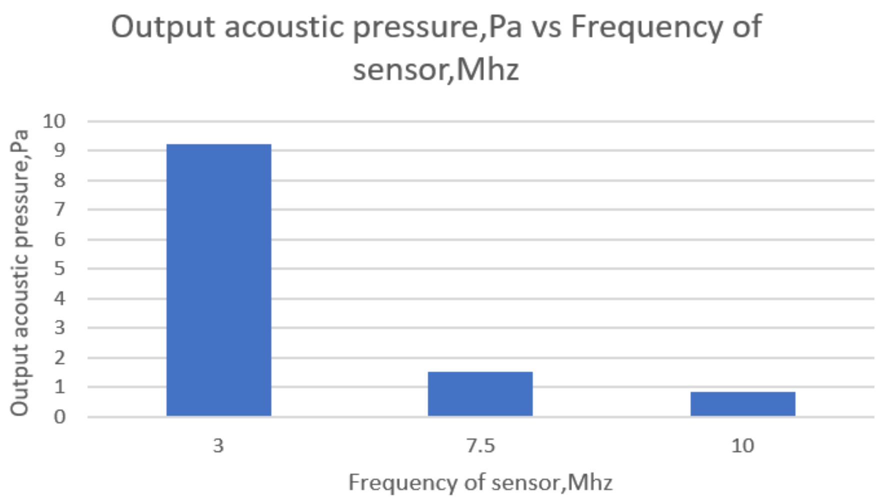

Fig. 10 *The comparison between the frequency of the sensor, MHz, against output acoustic pressure, Pa, by using four sensors.*

The highest total output acoustic pressure (Pa), was recorded at various sensor frequencies (MHz) using four sensors. The output acoustic pressure graphs show a similar pattern for frequencies of 7.5 MHz and 10.0 MHz, with only slight differences, while the graph for 3.0 MHz shows significant changes compared to the others. The highest peak of output acoustic pressure for each frequency are 3.0 MHz (9.220869), 7.5 MHz (1.502335), and 10.0 MHz (0.856781). Table 4 illustrates the impact of different sensor frequencies (MHz) on the output acoustic pressure (Pa). Fig. 11 provides a bar chart comparison of the output acoustic pressures across different sensor frequencies for the four sensors. Therefore, it can be concluded that increasing the sensor frequency (MHz) leads to a decrease in the output acoustic pressure (Pa).

Table 4 *Impact of sensor frequency on acoustic pressure output, Pa, by using four sensors.*

No	Frequency of sensor, Mhz	Output acoustic pressure, Pa
1	3.0	9.220869
2	7.5	1.502335
3	10.0	0.856781

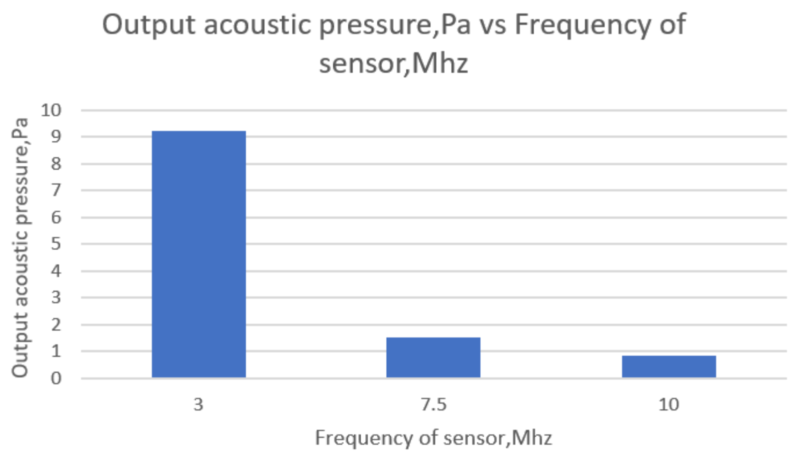

Fig. 11 *The comparison between the frequency of the sensor, MHz, against output acoustic pressure, Pa, by using four sensors.*

5. Conclusion

This project designed a two-dimensional breast model to investigate milk lumps using ultrasound. Goals included developing breast model software, creating a sensor on the COMSOL platform, and analyzing results. The study found that lower percentages of solid milk yield higher output acoustic pressure and voltage, and lower frequency sensors enhance these outputs. This model aids breastfeeding diagnostics in hospitals by identifying milk lumps.

However, simulating varying solid milk content is challenging and time-consuming, requiring mastery of COMSOL Multiphysics. Understanding these limitations is crucial for future advancements in gynecological technology.

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***study conception and design:*** *Afiq Humaidi Mohamad Zalani;* ***data collection:*** *Afiq Humaidi Mohamad Zalani ;* ***analysis and interpretation of results:*** *Afiq Humaidi Mohamad Zalani;* ***draft manuscript preparation:*** *Afiq Humaidi Mohamad Zalani, Siti Zarina Mohd Muji. All authors reviewed the results and approved the final version of the manuscript.*

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