waveguide width variation for biosensing application	Semiconductor Electronics (ICSE)	
Architecture of micro energy harvesting using hybrid input of RF, thermal and vibration for semi-active RFID tag	Engineering Journal (Eng. J.)	2017
2D material on 1D Photonic Crystal (PhC) nanowires	eProceedings Chemistry	2017
Higher Sensitivity RF-DC Rectifier for Ultra-Low Power Semi-Active RFID Tags	Proceedings of the International Conference on High Performance Compilation, Computing and Communications	2017

C(xi). Executive Summary of Research Proposal

(Please include the problem statement, objectives, research methodology, expected output/outcomes/implication, and significance of output from the research project)

Pulmonary embolism (PE) is a threatening condition that occurs due to the blockage of blood clot (embolus) in the pulmonary artery. PE is frequently underdiagnosed and the condition is highly mortal if untreated. Despite the advance in diagnosis and treatment over the past 30 years, PE has high early mortality rate with 70% of the patients ultimately die within the first hours of presentation. Accurate and rapid lung ultrasound diagnostic system is vital to diagnose PE with excellent specificity and efficiency. However, such system requires highly sensitive ultrasonic transducers that operate at certain frequency range, allowing deep veins scanning and embolus detection. In this work, we propose the implementation of multiple capacitive micromachined ultrasonic transducers (CMUT) arranged into 6x6 array as a chest scanning tool to detect embolus in deep pulmonary vessels. In order to achieve this, the transducers will be designed using micromachining process to have high sensitivity (~10 mVpp/Pa) within the operating frequency range (2 MHz - 18 MHz). The dimensions and material characteristics of the transducer's membrane will be studied and optimised. Ultrasonic measurement of the transducer array will be carried out and the influence of one transducer to other neighbouring transducers will be studied. We expect to measure clear output signals from the designed CMUT with high sensitivity and within the desired frequency range. Ultrasound-based diagnosis is a non-invasive modality that can be benefited by PE patients who could not undergo formal radiographic evaluation. From this study, we hope to create an accurate and rapid lung ultrasound diagnostic system for urgent/emergency evaluation of patients with PE symptoms

C(xii). Detail Planning

(a) Research background

1. Problem Statement

PE is a clinical emergency that needs rapid and accurate identification [1][2]. Ultrasound is a non-invasive PE diagnostic examination that uses sound wave transmission and gives quick visualisation of the lung venous system without injection and radiation exposure [3-6]. The developed algorithm uses multiple ultrasound signals measured from different positions on the chest to diagnose PE with high accuracy and efficiency. However;

1) transducers with low sensitivity could not detect small embolus and generally produce poor output signals. The scanning of pulmonary embolus in the arteries may be missed, giving false negative diagnosis results. Dire consequences to the patients may include the increase of recurrent PE risk or even possible death.
2) transducers with higher operating frequency could not penetrate deep into the tissue as it is more readily absorbed by skin and tissue but can give better image quality. In contrast, lower frequency can penetrate deeper but the image quality is inferior. A compromised working frequency region for PE ultrasound diagnostic system is needed.

2. Hypothesis

We propose the fabrication of multiple capacitive micromachined ultrasonic transducers (CMUT) in 6x6 array coordination system that can cover the whole chest area. These transducers consist of micromachined membranes that produce ultrasonic waves when an alternating current (AC) voltage is applied. Contrariwise, if the reflected ultrasound waves echo is applied onto the membranes, they will generate AC voltage (Figure 1) [3]. The energy transduction is due to the change of capacitance. Commonly, the sensitivity and operation frequency of the transducers depend on the membrane's geometrical dimensions and material properties. The best solution would be to aim for the highest sensitivity within the desired frequency range.

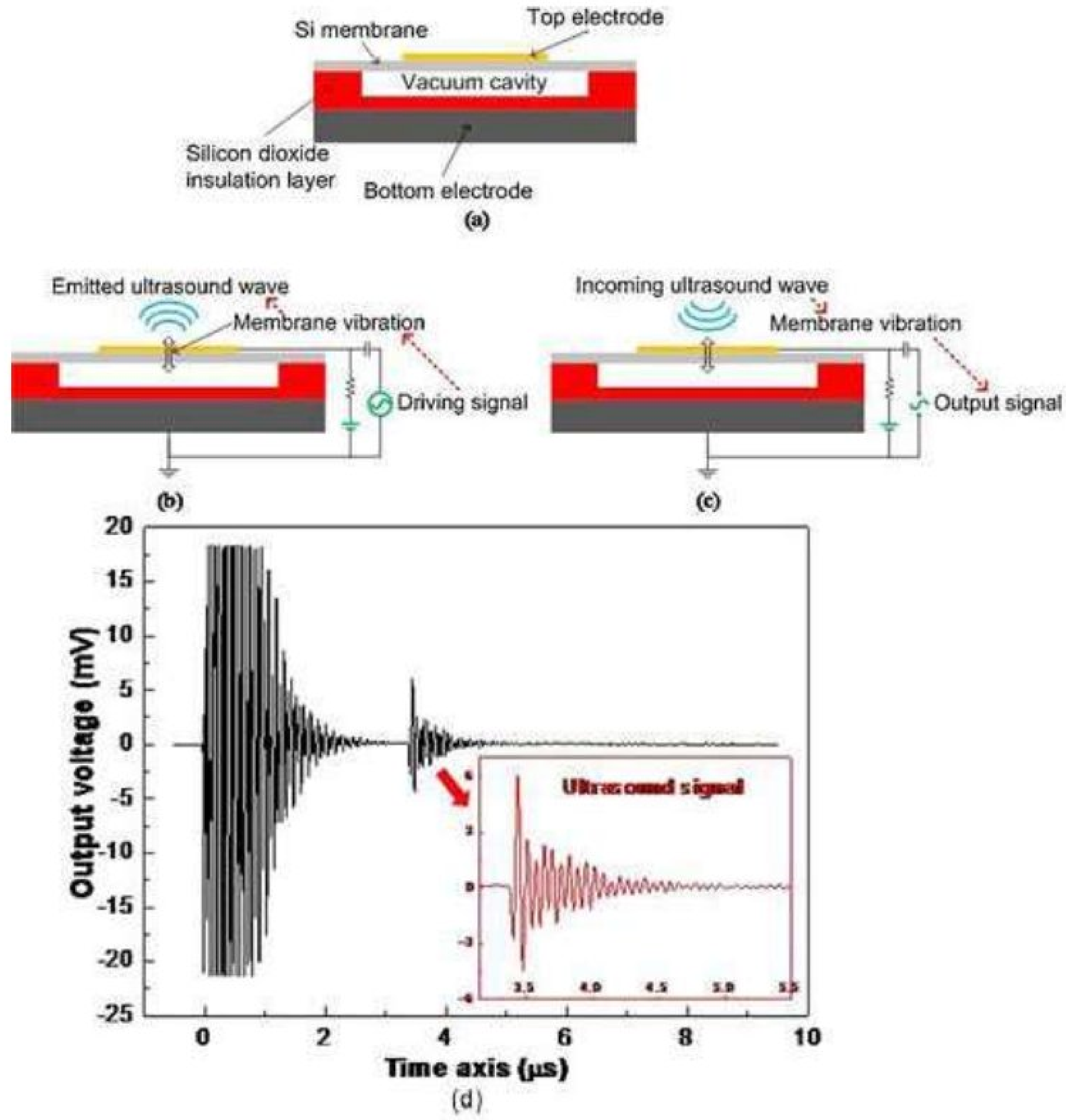

Figure 1: (a) The schematic of an ultrasonic transducer and its operation in (b) transmitting mode and (c) receiving mode. (d) The measured pulse-echo ultrasound signals in time domain when the transducer is immersed in DI water [3].

1) CMUTs with higher sensitivity can be fabricated by making the membrane's area larger and the thickness smaller. In [7]. a corrugation profile was introduced to the membrane to enhance its sensitivity in ultrasonic sound detection. The material used for the membrane should possess small Young's modulus value. In addition, a lubricating gel is applied on the skin to ensure continuous contact and reduces acoustic impedance between the transducers and skin.

2) The ultrasound's frequency for diagnostic purposes is usually between 2 MHz to 18 MHz. The higher/lower working frequency for CMUTs system can be achieved by making the membrane's area smaller/larger and higher/smaller thickness while the membrane's material should exhibit high/low Young's modulus and low/high density.

3. Research Questions

1. How much influence the transducer's geometrical dimensions and material properties have on its operating frequency range and sensitivity?
2. What are the optimised specifications of the transducers in order to attain the desired sensitivity and operating frequency range?
3. How does the signal from each transducer in the array affect one another?

4. Literature Reviews

The two most common manifestations of venous thromboembolism (VTE) are deep vein thrombosis (DVT) and pulmonary embolism (PE). DVT is a condition in which a blood clot, or thrombus, develops in a deep vein of the leg, groin or arm. DVT can be life-threatening when this blood clot breaks off and travels to the lungs where it becomes lodged in the pulmonary artery/vein and blocks blood flow (Figure 2). This is known as pulmonary embolism (PE) and if it is not treated, it can lead to sudden death. The blockage is called an embolism (or more than one embolus).

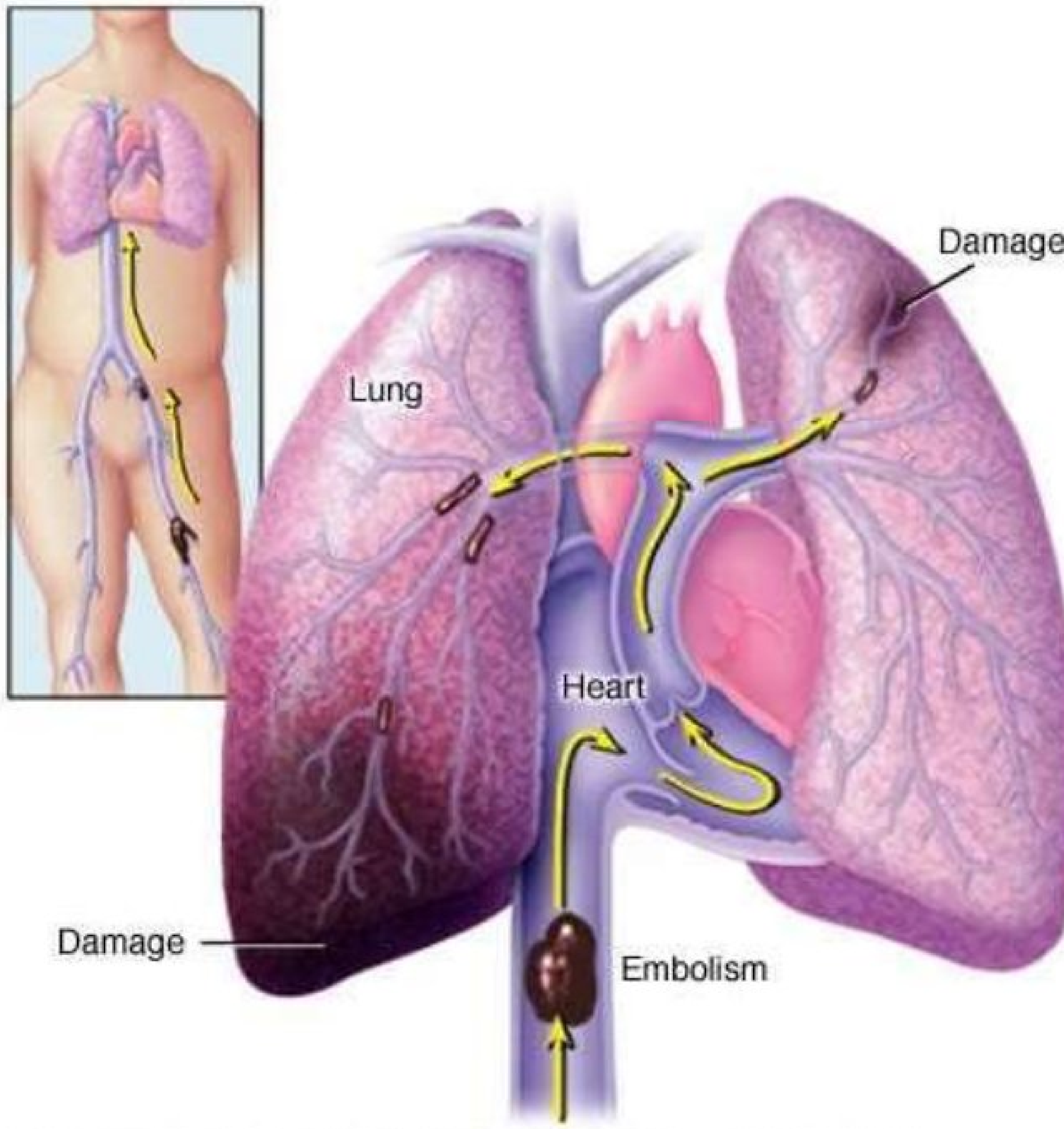

Figure 2: A blood clot from a deep vein thrombosis in a leg vein breaks off and travels through the body to the lungs can cause pulmonary embolism (PE)

Anything that obstructs the pulmonary arteries (clot, tumour, fat or air) can be considered as PE [8]. PE/DVT affects 300 000 – 600 000 individuals in the United States (US) with PE causing considerable mortality [9][10]. The risk factors may include ageing, cancer, pregnancy and the postpartum period, genetic mutations, postoperative/surgery states and immobility due to paralysis, prolonged confinement to bed or long-haul travel [11]. PE has been reported to be the leading cause of maternal mortality in Malaysia [8][12]. Many of the critical Covid-19 patients are placed under medically induced coma for a few days to help them recover faster but too long of bedridden condition can promote blood clot formation. WHO Research into Global Hazards of Travel (WRIGHT), found out that the risk of VTE increases 2- to 3-fold after long-haul flights of more than 4 hours [11].

Computerised tomography pulmonary angiogram (CTPA) is the gold standard for diagnosis of PE [13]. Recently with better technology, multidetector row CTPA is able to detect pulmonary emboli that were previously missed with good sensitivity and specificity [10]. CTPA is not a quick procedure and the verification process also takes time in order to be certain that the detected filling defects are genuine pulmonary emboli [14]. Ventilation-perfusion (V/Q) scan is reported to be more sensitive in diagnosing chronic PE than CTPA with less radiation exposure and avoidance of contrast injections [9]. There is also an evolution in nuclear medicine and imaging technique to diagnose PE with single photon emission/computed tomography (SPECT/CT). Overall, V/Q SPECT/CT has been found to result in significantly higher diagnostic accuracy than a typical V/Q scan [15]. Imaging methods like X-ray scan, CTPA scan and V/Q scan require large and complex equipment. These methods are expensive, time consuming and may not be available especially in rural and developing areas. Children, pregnant women and elderly population are particularly radiosensitive, therefore, non-radiation imaging modalities such as ultrasound should be utilised if possible.

Chest ultrasound produces images of the structures and organs within the chest. It is a non-invasive diagnostic examination that gives quick visualisation [16]. A chest ultrasonic transducers classification system for automatic diagnosis of PE may differentiate different lungs medical conditions of specific symptoms for example low-risk PE, submassive PE or massive PE [9]. Density or other reflection properties (wave intensity/wave speed) of the emboli/embolus can be used to classify PE. This lung ultrasonography diagnostic system requires high performance of the ultrasound transducers with high sensitivity of ~10 mVpp/Pa and working frequency range of 2 MHz to 18 MHz [17-19]. In this work, we propose the capacitive micromachined ultrasound transducers (CMUT) that offers wide bandwidth, operates in low voltages, ease in batch fabrication and good integration with electronics (Figure 3a). Various different design of the transducer's membrane could be implemented, using different materials for the membrane structure. In [7], a corrugation profile was introduced to the membrane to enhance its sensitivity in ultrasonic sound detection (Figure 3b). In Figure 3c, a piezoelectric material layer is employed for the membrane and the frequency of the membrane can be tuned by applying a voltage on the membrane [20]. In transmitter mode, the frequency changed 8.7 Hz per volt while in receiver mode, the frequency shifted at 7.8 Hz per volt. An array of CMUTs sealed in vacuum works in the 3D ultrasound imaging frequency band (Figure 3d) [21]. Each element of the array transmits ultrasound signals at 3 MHz (-211 dB) and receives signals at 4 MHz (-213 dB). In our work, we propose the fabrication of CMUTs with high sensitivity and specific working frequency range for lung ultrasound system. The proposed chest ultrasonic transducers are expected to be able to penetrate deep veins and detect small embolus, supporting the development of a comprehensive, real-time, inexpensive, fast and high accuracy lung ultrasonography diagnostic system for PE.

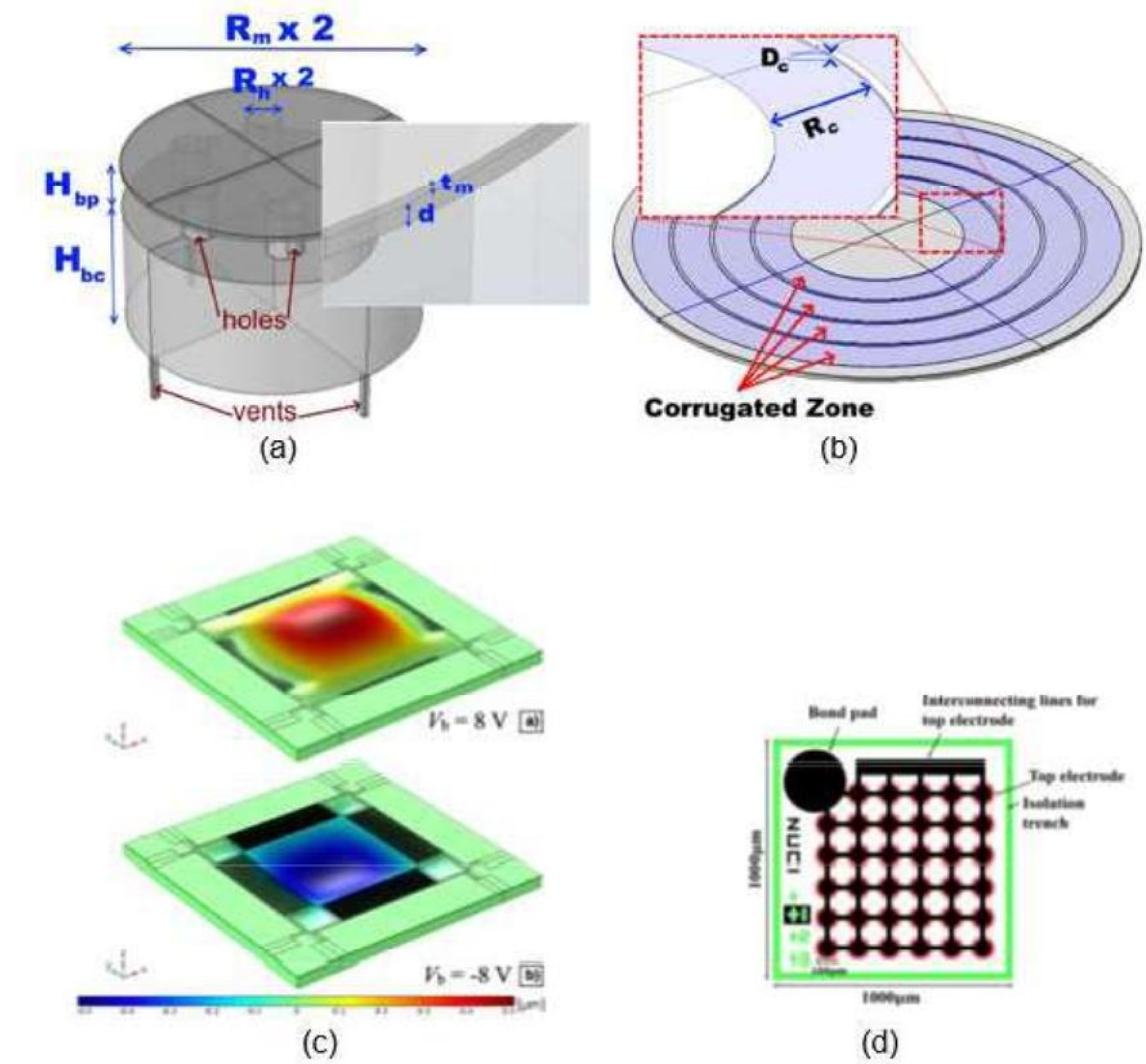

Figure 3: (a) The 3D design of a capacitive micromachined ultrasonic transducer (CMUT) with 6 acoustic holes and 4 vents. (b) The 3D view of the corrugated membrane with 4 corrugated zones. (c) A piezoelectric micromachined ultrasonic transducer varies in frequency depending on the applied voltage on the membrane. (d) CMUTs array for ultrasound medical imaging.

5. Relevance to Government Policy (if any)

From this study, we hope to create an accurate and rapid lung ultrasound diagnostic system for urgent/emergency evaluation of patients with PE symptoms. Point-of-care ultrasound testing allows medical diagnostic test to be carried out on patients in challenging situations. Overall, the research project supports the Key Economic Growth Area (KEGA) under the new Shared Prosperity Vision (SPV) 2030 that envisages the enhancement of medical technology in the nation and improving the local community healthcare system.

(b) References

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(c) Objective(s) of the Research

In this project, we propose an array of MEMS transducers, specifically CMUTs that can penetrate deep veins and detect small embolus. The research embarks into the following specific objectives;

1) To correlate the transducer's geometrical dimensions and material properties with its operating frequency range and sensitivity.
2) To formulate and fabricate the transducer's structure with high sensitivity of ~10 mVpp/Pa within 2 MHz - 18 MHz of working frequency range.
3) To examine the capability of the transducer array in transmitting and receiving ultrasound signals at the desired specifications and study the signals interaction between the transducers in the array.

(d) Methodology:

1. Description of Methodology

The research methodology has 4 phases as follows;

Phase 1: Numerical simulation (Objective 1)

In the first stage, the researcher will conduct the theoretical and computational simulation model based on Finite Element Method (FEM) using COMSOL Multiphysics to predict the response of the transducer toward the various pressure and frequency in order to optimize the geometrical dimension, material which could increase its sensitivity in ultrasonic sound detection. The developed numerical model using Solid Mechanics and Pressure Acoustic Modules will determine the level of sensitivity and resonance frequency of the transducer before the prototyping phase.

Phase 2: Prototype Fabrication (Objective 2)

The fabrication of transducers will be conducted in the clean room facilities in IMEN, UKM using the lithography process with metallic deposition of Aluminium, gold or copper acting as electrode. The minimum resolution of the transducer design using this technique is 5 micron. The etching of the substrate is ensured by RIE technique to create a suspending membrane in the CMUT transducer.

Phase 3: Characterization (Objective 2 and 3)

Next, we will evaluate the performance of our fabricated transducers using various electrical characterization such as current-voltage (IV) and capacitance-voltage (CV). The measurement will be conducted using LCR meter and source meter (SMU) available in IMEN. The CMUT transducer will be tested under varied pressure and frequency to determine its resonance frequency and sensitivity in order to optimize its material and geometrical properties for our ultrasonic application.

Phase 4: Ultrasonic recordings (Objective 3)

Multiple CMUT transducers will be arranged in the form of an array (30cm x 30cm) and positioned in the ultrasonic measurement setup. The transducer array transmits waves with frequency above the audible hearing frequency range. The short bursts of ultrasonic energy are transmitted and after each burst, the same transducer array will look for a return signal within a small window of time. The transmitted waves reflected back like an echo to the transducers that transduce the mechanical membrane vibrations into electrical signals. The acquisition system retrieves and stores data from the transducers. In the future, the received ultrasonic signals can be processed and classified by the lung ultrasonography diagnostic system.

2. Flow Chart of Research Activities	'FLOWCHART FRGS2022.pdf'

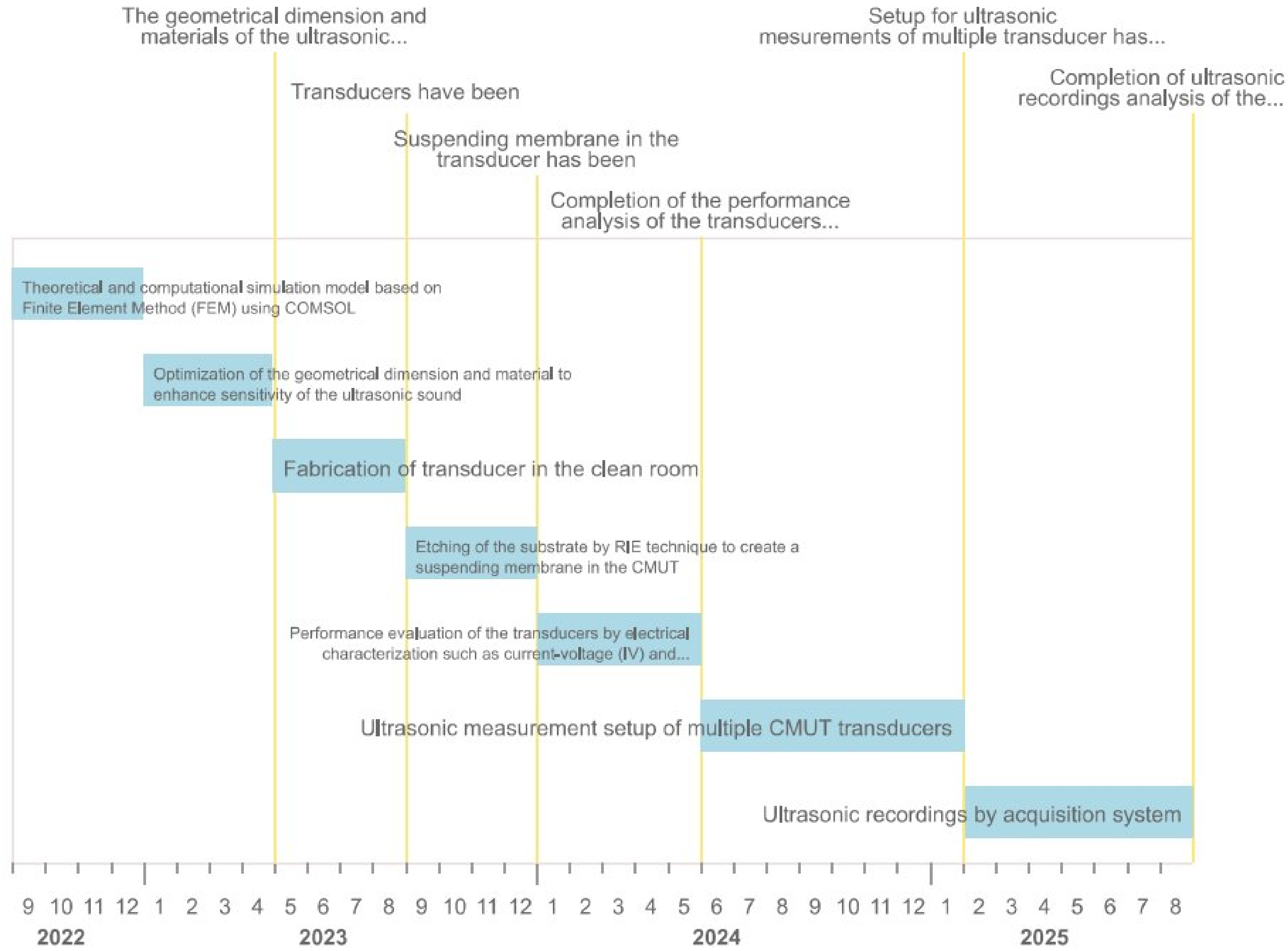
3. Research Activities

Activity	Start Date	End Date
Theoretical and computational simulation model based on Finite Element Method (FEM) using COMSOL Multiphysics	01/09/2022	31/12/2022
Optimization of the geometrical dimension and material to enhance sensitivity of the ultrasonic sound detection	01/01/2023	30/04/2023
Fabrication of transducer in the clean room	01/05/2023	31/08/2023
Etching of the substrate by RIE technique to create a suspending membrane in the CMUT transducer	01/09/2023	31/12/2023
Performance evaluation of the transducers by electrical characterization such as current-voltage (IV) and capacitance-voltage (CV)	01/01/2024	31/05/2024
Ultrasonic measurement setup of multiple CMUT transducers	01/06/2024	31/01/2025
Ultrasonic recordings by acquisition system	01/02/2025	31/08/2025

4. Milestones

Description	Date	Cumulative Project Completion Percentage(%)
The geometrical dimension and materials of the ultrasonic sound detection have been optimized to enhance the sensitivity	30/04/2023	20
Transducers have been fabricated	31/08/2023	30
Suspending membrane in the transducer has been created	31/12/2023	50
Completion of the performance analysis of the transducers by electrical characterization	31/05/2024	60
Setup for ultrasonic mesurements of multiple transducer has been completed	31/01/2025	80
Completion of ultrasonic recordings analysis of the multiple array transducers	31/08/2025	100

Gantt Chart of Research Activities with Milestones



(e) Expected Results/Benefit

1. Novel theories/New findings/Knowledge

To the best of our knowledge, Directed Transfer Function (DTF) method has never been implemented for ultrasound signals. It was previously used for brain signals (EEG) or muscle signals (EMG). This project will be the first to implement DTF to process and analyse the multiple ultrasonic waves signals.

2. Impact Statement on Quintuple Helix (please delineate/describe expected research deliverables on Society, Academia, Government, Industry and Environment)

Society: The potential to provide an accurate, non-invasive PE diagnosis tool, especially to the lower income group (B40) at a fraction of the current price.
Academia: The knowledge obtained by this project will contribute to more advance research in developing the PE diagnostic examination in Malaysia and also globally.
Government: Input for 10-10 Malaysia Science, Technology, Innovation and Economy (MySTIE) under Medical and Healthcare.
Industry: Job opportunity for local and international industry players.
Environment: The fabrication of this diagnostic tools is using the available MEMS fabrication techniques that gives a very minimal impact to the environment.

3. Research Publications (Each proposal must produce at least two (2) papers in indexed journals, one of which should be in Web of Science (WoS))

Indexing Body	**Indexed Journal**	
Number of Publication	**Name of Journal**	
WoS	2	1) Journal of Vibration and Control (IF:3.095 Q1) 2) Journal of Microelectromechanical Systems (IF:2.417 Q2)
SCOPUS	2	2 IEEE conference proceedings
ERA		
MyCITE		
	Total 4	

4. Specific or Potential Applications of the Research Findings

Lungs ultrasonography system for early PE diagnostics can assist with early detection and treatment to reduce the costs for healthcare. The point-of-care testing allows medical diagnostic to be done under emergency circumstances or even in rural areas.

Total Number of Applications: 1