FEASIBILITY STUDY ON DETECTING LUNG TUMOUR IN MULTILAYER THORAX MODEL USING ULTRA-WIDEBAND MICROWAVE IMAGING

by

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A thesis submitted in fulfilment of the requirements for the degree of

Master of Science in Communication Engineering

School of Communication and Computer Engineering

UNIVERSITI MALAYSIA PERLIS

2015

DECLARATION OF THESIS

To I AM; the Beginning and the End; the Alpha and the Omega; Ancient of days; Lord God Almighty. Amen.

ACKNOWLEDGEMENT

Special thanks to the Malaysian Government and her Ministry of Education for the provision of scholarship and funding under the Commonwealth Scholarship and Fellowship Plan (CSFP) to which I am beneficiary.

This is to use this medium to acknowledge the advice and supervisory role of Associate Professor Dr Faizal Jamlos in the course of this research work, and to all my colleagues at the Advanced Communication Engineering Center of Universiti Malaysia Perlis, thank you for being worthwhile friends. Your contributions are appreciated.

To all fellow patriots from Nigeria, I appreciate the tips you gave to a brother during this time of the research work, thank you all. Worthy of mention is the congregation of Perlis Grace Centre, Kangar. I appreciate the hand of fellowship and the love of God with which you accepted me as a brother. May the good Lord bless you all.

Dad, Mum, Oluwatobi, Toluwalope, Jesuloluwa and you Olabimpe, thank you for being there as a family despite the miles apart we are. I am richly blessed having you around and knowing you are praying for me. *E seun.*

TABLE OF CONTENT

DECLARATION OF THESIS .... **ii**

DEDICATION .... **iii**

ACKNOWLEDGEMENT .... **iv**

TABLE OF CONTENT .... **v**

LIST OF FIGURES .... **viii**

LIST OF TABLES .... **xii**

ABSTRAK .... **xiii**

ABSTRACT .... **xiv**

CHAPTER 1 .... **1**

1.1 Overview 1

1.2 Problem Statement 7

1.3 Objectives 8

1.4 Scope of Study 8

1.5 List of Contributions 10

1.6 Thesis Outline 10

CHAPTER 2 .... **12**

2.1 Chapter Introduction 12

2.2 Anatomy of the Lung 12

2.3 Overview of Lung Cancer 14

2.4 Microwave Technology in Lung Diseases Diagnosis 15

2.5 Microwave Interaction with Biological Tissues 18

2.6 Dielectric Properties of Biological Tissues 26

2.7 Microwave Imaging Techniques 40

2.8 Ultra-Wideband Radar Imaging 44

2.9 Ultra-wideband Antennas 55

CHAPTER 3 59

3.1 Chapter Introduction 59

3.2 Microwave imaging setup 59

3.3 Choice of Frequency 60

3.4 Modified Delay and Sum (mDAS) Imaging Algorithm 62

3.5 Ultra-Wideband Antenna Design and Fabrication 66

3.6 Simulation Setup 73

3.7 Experiment Setup 80

3.8 Signal to Clutter Ratio (SCR) and Localisation Error Analyses 87

CHAPTER 4 88

4.1 Chapter Introduction 88

4.2 UWB Antenna performance testing 89

4.3 Simulation Results 93

4.4 Experiment Results 96

4.5 Effectiveness of the modified Delay and Sum (mDAS) Algorithm 99

4.6 Localisation Error Analysis in the Microwave Images 101

CHAPTER 5 104

5.1 Conclusions from the Research Work 104

5.2 Recommendations for Future Work 105

REFERENCES 107

APPENDIX A 116

APPENDIX B 118

APPENDIX C 120

LIST OF PUBLICATIONS 123

GLOSSARY 124

LIST OF FIGURES

Figure 1.1: Microwave imaging setup for lung tumour detection 7

Figure 2.1: Organs of the respiratory system (CCS, 2015) 13

Figure 2.2: The structure of the lungs (CCS, 2015).. 13

Figure 2.3: A transmission line model for reflection from Medium m to Medium n (Taylor, 2012) 19

Figure 2.4: A two port network showing components of the electric field at each port. 23

Figure 2.5: Scattering parameters measurement of the mammary (breast) with a vector network analyser (Barnes, 2007) 26

Figure 2.6: Coaxial probe technique for measuring dielectric properties (Alabaster, 2004) 36

Figure 2.7: Free space technique for measuring dielectric properties (Alabaster 2004) 36

Figure 2.8: Waveguide technique for measurement of dielectric properties (Alabaster 2004) 37

Figure 2.9: Resonant technique for measurement of dielectric properties (Alabaster, 2004) 38

Figure 2.10: Passive microwave imaging technique showing a radiometer and tissue with embedded tumour(Abdul-Sattar, 2012; Zhurbenko, 2011) 41

Figure 2.11: Active microwave imaging technique showing the transmitter and receiver antennas. E^{inc} and E^{scat} represent incident electric field and scattered electric field respectively (Zhurbenko, 2011). 42

Figure 2.12: Hybrid microwave imaging technique showing ultrasound transducers, microwave transmitter and tissue with embedded tumour (Zhurbenko, 2011). 43

Figure 2.13: Microwave Imaging Techniques (Nikolova, 2012) 44

Figure 2.14: Architecture of a UWB radar transceiver (X. Wang, Dinh, & Teng, 2012) 46
Figure 2.15: Cross-section of the human thorax from Duke Anatomy (Cavagnaro, Pittella, et al., 2013) 51
Figure 2.16: Multilayer Tissue Representation of the Human Thorax (Cavagnaro, Pittella, et al., 2013) 52
Figure 2.17: Finite Difference Time Domain Simulation Setup for Detection of Lung Tumour (Camacho-Velazquez, 2004) 54
Figure 2.18: An illustration of a circular printed circuit monopole antenna (Liang, Chiau, Chen, & Parini, 2005) 57
Figure 3.1: Flow chart of the modified delay-and-sum (mDAS) imaging algorithm 63
Figure 3.2: Antenna A showing dimensions of the front and back views 67
Figure 3.3: Design of Antenna B showing dimensions of the step notches on the patch and the slot on the ground plane 68
Figure 3.4: Design of Antenna C, (a) shows the main antenna and (b) is image of the planar reflector positioned behind the ground plane 68
Figure 3.5: Antenna D, (a) showing fork-like shape patch and (b) ground plane 69
Figure 3.6: Reflection coefficient versus Frequency graphs for; (a) Antenna A (b) Antenna B (c) Antenna C (d) Antenna D 70
Figure 3.7: Simulation result of the radiation patterns for Antennas A, B, C and D 71
Figure 3.8: Flowchart for antenna fabrication and testing 72
Figure 3.9: Dielectric properties of Tumour as modelled in Microwave Studio in the frequency range of 1-20 GHz 75
Figure 3.10: Derivation of a 3D multilayer thorax model from the thorax slice of the Duke anatomy 76

Figure 3.11: Dielectric properties of inflated lung and deflated lung 77
Figure 3.12: Dielectric properties of bone and muscle 78
Figure 3.13: Dielectric properties of fat and skin 78
Figure 3.14: Simulation Setup for the detection of Tumour in the Thorax model. Shown are the Multilayer Tissue Thorax, UWB Antenna, and Tumour 79
Figure 3:15 Front view of simulation setup showing positions the UWB antenna traverses in synthesising an array so as to cover the model surface area 79
Figure 3.16: Dielectric properties measurement setup. Insets are (a) the tissue simulating liquid and (b) tumour simulating semisolid 82
Figure 3.17: Permittivity of tissue simulating liquid for inflated lung and deflated lung 83
Figure 3.18: Permittivity of tissue simulating liquid for muscle and bone tissues 84
Figure 3.19: Permittivity of tissue simulating liquid for skin and semi-solid tumour 84
Figure 3.20: Plexiglass multilayer thorax model box; a) Side view showing different compartments of the tissue simulating liquids (TSL); b) Front view showing divisions to indicate where the antenna will be placed to synthesise an antenna array. 86
Figure 3.21: Experimental setup showing the Vector Network Analyser, Ultra-wideband Antenna and Plexiglass box with Tissue Simulating Liquids content. 86
Figure 4.1: Images of the fabricated UWB Antenna; a) Top view b) Elevated side view c) Side view showing the attached Reflector 90
Figure 4.2: Setup for antenna testing 91
Figure 4.3: Measured and simulated reflection coefficients compared 91
Figure 4.4: The Radiation Patterns of the UWB antenna at 3, 4 and 5GHz 93
Figure 4.5: Magnitude of the reflection versus frequency for simulation obtained from inhalation model- multilayer thorax with inflated lung tissue layer 94

Figure 4.6: Magnitude of the reflection versus frequency for simulation obtained from exhalation model- multilayer thorax with deflated lung tissue layer............................. 94

Figure 4.7: Simulation Result for Multilayer Thorax Model with Inflated Lung Tissue modelling inhalation in the lung 95

Figure 4.8: Simulation Result for Multilayer Thorax Model with Deflated Lung Tissue modelling exhalation in the lung 95

Figure 4.9: Magnitude of the reflection versus frequency obtained from experiment setup for inhalation model- multilayer thorax with inflated lung tissue layer................ 97

Figure 4.10: Magnitude of the reflection versus frequency obtained from experiment setup for exhalation model- multilayer thorax with deflated lung tissue layer 97

Figure 4.11: Reconstructed microwave image from experiment setup for multilayer thorax simulating liquids having inflated lung tissue layer representing inhalation in the lung 98

Figure 4.12: Reconstructed microwave image from experiment setup for multilayer thorax simulating liquids having deflated lung tissue layer representing exhalation in the lung 98

Figure 4.13: Reconstructed image from the experiment data in multilayer thorax with inflated lung depicting inhalation: a). shows the result when DAS algorithm was applied and b). shows when the mDAS algorithm was applied 99

Figure 4.14: Reconstructed image from the experiment data in multilayer thorax with deflated lung depicting exhalation: a). shows the result when DAS algorithm was applied and b). shows when the mDAS algorithm was applied 100

LIST OF TABLES

Table 3.1: Microwaves in Lung disease management ... 61

Table 3.2: Dimensions of the designed UWB Antenna ... 70

Table 3.3: Four term Cole-Cole Parameters for multilayer thorax tissues (Andreuccetti et al., 1997) ... 76

Table 3.4: Compositions of tissue simulating materials ... 83

Table 4.1: Signal to Clutter Ratio Analysis ... 100

Table 4.2: Location Error Analysis ... 102

Table B.1: Derivation of the dielectric properties of lung tumor (data for Fig. 3.11) ... 118

Table B.2: Plots data for Figures 3.13, 3.14 and 3.15 ... 119

Table C.1: Target value compared to measured value for the tissue simulating materials at 3GHz ... 120

Table C.2: Target value compared to measured value for the tissue simulating materials at 4GHz ... 121

Table C.3: Target value compared to measured value for the tissue simulating materials at 5Hz ... 122

Kajian kebolehlaksanaan pengesanan tumor paru-paru dalam model multilayer toraks dengan menggunkan teknik microwave pengimejan ultra-wideband

ABSTRAK

Pendedahan secara berterusan kepada patogen dan mikrob melalui gaas-gas yang disedut membuatkan paru-paru terdedah kepada penyakit. Kanser menjejaskan semua tisu-tisu, paru-paru juga tidak terkecuali. Terdapat 14.1 juta kes-kse kanser yang dilaporkan di seluruh dunia pada tahun 2012 dan daripada jumlah ini, 13% adalah disebabkan oleh kes-kes baru kanser paru-paru. Walaupun angka-angka tinggi kes-kes baru kanser paru-paru dikesan, banyak kes-kes lain yang telah berlalu tidak dapat dikesan kerana simptom-simptom peringkat awal kanser paru-paru sama seperti penyakit paru-paru yang lain seperti batuk kering. Kanser paru-paru adalah punca utama kematian berkaitan barah di seluruh dunia kerana sangat sukar untuk mengubati penyakit kanser. Pemeriksaan bagi kanser paru-paru jarang dilakukan dan walaupun imbasan tomografi sinar-x dan komputer boleh mengesan kanser bersaiz kecil didalam paru-paru, namun ianya tidak akan digunakan sehingga simptom-simptom telah jelas dan semakin teruk. Kaedah-kaedah yang lain untuk pemeriksaan kanser seperti *biopsies* dan *bronchoscopies* adalah kaedah yang invasif dan jarang digunakkan. Kebelakangan ini, teknik-teknik pengimejan gelombang mikro turut dicadangkan bagi mengesan pelbagai bentuk kanser. Pengesanan kanser dengan menggunakan gelombang mikro dalam julat frekuensi 300 MHz kepada 30 GHz adalah sebagai idea utama bahawa sifat-sifat dielectrik bagi tisu tumor adalah berbeza dengan tisu-tisu badan yang normal. Perbezaan dalam sifat-sifat dielectrik telah diekploitasi dalam tomografi gelombang mikro, pengimejan radar gelombang mikro *ultra-wideband* (UWB), *radiometry* dan tomografi thermo-akustik. Tesis ini membentangkan kajian yang menggunakan teknik pengimejan gelombang mikro *confocal* yang mana ianya adalah satu bentuk pengimejan radar gelombang mikro UWB untuk mengesan tumor bersaiz kecil didalam paru-paru manusia. Sistem pengesanan yang terdiri daripada thorax manusia yang dimodelkan dengan pelbagai lapisan tisu-tisu paru-paru, tulang, otot, lemak dan kulit; tumor bersaiz 10mm; antena UWB yang disambungkan dengan vektor penganalisa rangkaian; dan algoritma kelewatan yang diubahsuai dan jumlah imej (mDAS) yang telah dicadangkan bertujuan untuk pemprosesan isyarat dan pembinaan semula imej. Pembinaan semula imej gelombang mikro menunjukkan kemungkinan untuk mengesan tumor pada paru-paru dalam prosedur simulasi dan eksperimen. Menggunakan satu lokasi cadangan ralat penghampiran, ralat lokasi tumor dalam imej-imej gelombang mikro adalah kurang daripada 3 cm. mDAS yang dicadangkan telah dibandingkan dengan algoritma kelewatan biasa dan jumlah pengimejan (DAS) menggunakan isyarat kepada nisbah kekacauan, dan didapati bahawa mDAS mempunyai 2 - 3 dB resolusi yang lebih baik dalam imej-imej gelombang mikro. Teknik pengimejan gelombang mikro tidak semestinya boleh menggantikan piawaian lain yang dikenali dan juga berharga untuk mengesan kanser, tetapi pasti akan menjadi langkah pertama dalam diagnosis dan sebagai pelengkap kepada sistem-sistem pengesanan yang lain. Teknik pengimejan yang dibentangkan didalam laporan ini adalah pembinaan semula imej yang cepat hanya memerlukan 120 saat pada komputer biasa, selamat, bebas mengion, dan mudah untuk dilaksanakan.

Feasibility Study on Detecting Lung Tumour in Multilayer Thorax Model Using Ultra-Wideband Microwave Imaging

ABSTRACT

The constant exposure to pathogens and carcinogenic substances through inhaled gases makes the lungs very vulnerable to diseases such as asthma, tuberculosis and cancer. Available statistics revealed there were 14.1 million cases of cancer reported worldwide in the year 2012 and out of this figure, 13% were attributed to new cases of lung cancer. Despite the high figures of the new cases of detected lung cancer, many other cases would have passed undetected as symptoms of early stages of lung cancer are common with other diseases of the lungs such as tuberculosis. Lung cancer is the leading cause of death related cancers worldwide as the cancer of the lung is very difficult to cure. Screening for lung cancer is not routinely done and although X-ray and computer tomography scan can detect small sized cancers in the lungs, they are not required until symptoms have advanced in patients. Other methods for lung cancer screening like biopsies and bronchoscopies are only required when suspicious irregularities are observed in images generated from X-ray. In recent times however, microwave imaging techniques are being proposed for detection of various forms of cancer. The detection of cancer using microwaves in the frequency range of 300 MHz to 30 GHz is possible iin the premise that the dielectric properties of tumour tissues are different from the normal host tissues. These contrasts in dielectric properties are being explored in microwave tomography, ultra-wideband (UWB) microwave imaging radar, radiometry, and thermo-acoustic tomography. This thesis presents a study in using confocal microwave imaging technique which itself is a form of the UWB microwave imaging radar to detect millimetre sized tumour in the human lungs. The detection system comprises of a human thorax modelled as multilayer tissues of lung, bone, muscle, fat and skin; a 10 mm tumour; a UWB antenna connected to a vector network analyser; and a proposed modified delay and sum (mDAS) imaging algorithm for signal processing and image reconstruction purposes. Reconstructed microwave images show the possibility of detecting tumours in lung in both simulation and experimental procedures. Using a proposed location error approximation, errors of tumour location in the microwave images was less than 3 cm. The proposed mDAS was compared to the standard delay and sum (DAS) imaging algorithm using signal to clutter ratio, and it was found that the mDAS has a 2-3 dB better resolution in the microwave images. Microwave imaging techniques may not necessarily replace other known gold standards for cancer detection, but will definitely be a first step in diagnosis and will be complementary to other detection systems. The imaging technique presented in this report can be adjudged to be fast as the image reconstruction was about 120 seconds on a standard computer; it was safe from non-ionizing radiations and also, it was easy to perform.

CHAPTER 1

INTRODUCTION

1.1 Overview

The human body is organized at different levels. The complexity of these organizational levels increases from the simple cells to the complex organ systems. Cells are the most basic and functional parts of a human body, examples of cells are the neurons and red blood cells. A group of connected cells performing a similar function forms the tissue. There are four tissue types in the human body, namely connective tissue, muscle tissue, epithelial tissue and nervous tissue. A structure with two or more tissue types coming together to achieve the same task is known as the organ. Examples of organs are the brain, heart and lung. Organs are further organised into organ systems, this complex organization makes the organs work together to achieve more complex functions. Examples of systems are circulatory system, skeletal system and respiratory system. The respiratory system is of interest in this study and its overview shows that the system is comprised of trachea, bronchi, bronchioles, lungs and the diaphragm. Gas exchange takes place in the alveoli of the lungs, a vital process for staying alive.

Replication of cells of the various tissues is an indication of growth. But growth may be impaired by many factors ranging from nutrition, mutation and environment. Impaired growth in tissues result into tumour tissues, hence, tumours are masses of abnormal tissues from uncontrollable and abnormal growth of cells; and they can be classified broadly into benign (non-cancerous) tumours and malignant (cancerous) tumours. Tumours take a heavy toll on human health and most times result in death, especially if not immediately detected and treated. Considering the lung as an important organ in the respiratory system, Lam et al (Lam, White, & Chan-Yeung, 2004) pointed out that the constant exposure to pathogens and carcinogens like radon and asbestos through the process of inhalation and exhalation, makes the lung vulnerable to diseases like cancer. Also, from inhalation of tobacco smokes, vapours from cooking oil, and smokes from burning coal, the lung may become vulnerable. Further, infections from microbes such as *Mycobacterium tuberculosis*[1], human papilloma virus and *Microsporum canis*[2] are also potent causes of lung tumours. In non-smokers, health risks arise from 'passive' smoking or 'second-hand' smokes and from polluted environmental air.

Many diagnostic measures are being taken to detect tumour in their early stages. These include medical imaging techniques like X-ray, magnetic resonance imaging (MRI) and recently, microwave imaging techniques. X-ray and MRI involve using varying doses of X-rays and magnetic fields respectively to produce images of internal organs while microwave imaging depends on the use of the varying electric properties of tissues and their responses to electromagnetic fields in the microwave frequencies. From the electrical point of view, all materials including biological tissues react to the passage of electrical current through them; a phenomenon that describes their electrical properties. Broadly, a material is either a conductor of electrical current or an insulator. Permittivity and conductivity are two parameters used to describe the electrical properties of most materials. The electrical properties of different tissues of the human body had been measured over the years (Gabriel, Gabriel, & Corthout, 1996; S Gabriel, RW Lau, & Camelia Gabriel, 1996). Electrical properties vary with different tissues because of the water content of the tissues, the frequency of the applied electrical field and the physiological state of the tissue being measured. This relation of electrical properties and tissue physiological states is being explored in microwave imaging for medical diagnosis of tumours.

Typically, a tumour has higher fluid (water) content than its host or normal tissue (Miklavčič, Pavšelj, & Hart, 2006). This higher amount has an influence on the electrical properties of the tumour. In comparison to host tissues, tumours have higher permittivity and conductivity values. This contrast in electrical properties is the underlying principle of tumour detection using microwave imaging methods.

Microwave imaging is defined by (Fear, Meaney, & Stuchly, 2003) as "seeing the internal structure of an object by means of electromagnetic fields at microwave frequencies (300MHz- 30GHz)". Microwave imaging produces maps of the electrical property distribution in the human body called microwave images. Several approaches have been proposed for microwave imaging, and they can be broadly divided into active, passive and hybrid microwave imaging techniques. In active microwave imaging, a set of antennas transmit low power microwave signals into tissues and backscattered signals acquired using another set of antennae are used to generate microwave images; while in passive microwave imaging, microwave images are generated by processing the measured changes in the temperature of tissue surfaces caused by the loss of thermoregulatory capabilities of tumour cells; and in hybrid microwave imaging, thermal, acoustic and microwave properties of tissues are explored to produce microwave images. When microwaves propagate from one medium into another, some waves are reflected while some are transmitted depending on the nature of the media. These reflected waves are called backscattered signals.

The detection system setup for active microwave imaging seems to be the simplest of all the three types of microwave imaging techniques. Passive microwave imaging is limited by the difficulty in estimating temperature distribution in the body while hybrid microwave imaging require microwave pulses with about tens of kilowatt of power to yield low decibel of acoustic waves that are difficult to detect (Zhurbenko, 2011), but active microwave imaging relies only on the electrical properties distribution and scattered fields in the body which can easily be detected by a low power antenna. Active microwave imaging can be further divided into ultra-wideband (UWB) radar microwave imaging and tomography microwave imaging. Tomography microwave imaging is the less attractive of the two because the setup and algorithm used is aimed at reconstructing the electrical field distribution in the imaged body which involves solving complex inverse scattering problems at the expense of computer resources and time. UWB radar microwave imaging technique was first introduced for breast tumour detection (Hagness, Taflove, & Bridges, 1998; Hagness, Taflove, & Bridges, 1999); and several approaches and configurations have emerged. Similar principles of the technique have been extended to stroke or tumour detection in the brain (Ireland & Bialkowski, 2011). This thesis presents a step taken further to detect tumour in the lungs using microwave imaging techniques.

The ultra-wideband radar microwave imaging method is used in this study because it is not as cumbersome as the tomography microwave imaging. UWB radar microwave imaging simply aims as using backscattered signals to construct microwave images that show areas with high scattering values which are due to the presence of different permittivity in the imaged body. The radar system could be configured as multistatic which involves the use of an array of antenna or as monostatic which involve the use of a single element antenna. The monostatic configuration is not prone to mutual coupling effects in antenna arrays as present in multistatic, and this is highly suitable for this feasibility study. Hence, the imaging setup uses a single antenna to transmit pulses and receive backscattered signals, here in terms of scattering parameters (S_{11}). The delay-and-sum imaging algorithm otherwise known as confocal microwave imaging algorithm is used in signal processing and image generation. The algorithm is simple and straightforward in application compared to algorithms used in tomography (Fear, Meaney, et al., 2003). Backscattered signals arise from the aforementioned differences in dielectric properties of normal and tumour tissues when microwaves propagate through them. Theoretically (Fear, Meaney, et al., 2003), a tumour will scatter signal energy back to the transmitting antenna due to the difference in the dielectric properties of the tumour compared to the surrounding healthy tissue and this can be selectively processed to detect the presence and location of the tumour.

The approaches in this thesis started out with a simulation of the scenario of a tumour embedded in a thorax[3] model comprising of lung, bone, muscle, skin and fat tissues. The thorax was represented as a multilayer of the tissues stacked upon each other. In both scenarios, deflated and inflated lungs were considered. The simulations were performed in CST Microwave Studio, a full wave electromagnetic solver. Next, experimental feasibilities of simulated scenarios were performed. A thorax phantom with embedded tumour was created and similar procedure as used in the simulation was used in the experiments; the procedures for the simulations and experiments are discussed in Chapter 3. Human phantoms would have been suitable for use in the experiments, but they are not readily available for much range of frequencies, not flexible enough for this study and the dielectric properties of the materials phantom are not always exact as would be required for a microwave imaging system setup. Hence, novel tissue simulating liquids were used to represent the tissues of the thorax and they were prepared from inexpensive materials of Polysorbate 20 (Tween 20) and water. Polysorbate 20 is a stable and non-toxic surfactant that is easily soluble in water and its use shows that it can effectively lower the permittivity value of water to the desired values of the tissues of the thorax. Polysorbate 20 also outperforms sucrose when used to prepare tissue simulating liquids as it does not get saturated in water easily, also the realised solution of Polysorbate 20 and water has longer shelf life than the solution of sucrose and water. Simulating liquids were prepared for inflated and deflated lung, bone, muscle, skin and fat. The liquids have satisfactory dielectric properties of the tissues when measured using a dielectric probe. The complete imaging system comprises of the imaged body which is a thorax phantom with an embedded tumour, an ultra-wideband antenna which was designed and fabricated, and a vector network analyser (VNA) as the hardware related part, while on the software related part, the major equipment was a workstation on which the acquired data was post processed, imaging algorithm program was executed and the result was displayed. The imaging setup is as outlined in Fig. 1.1.

Results from both simulation and experiments agree well and the studies have shown that microwave imaging can be used in lung tumour detection. The tissue simulating liquids are cheap and not harmful for handling, and hence, can be used in a variety of applications involving the tissues of the thorax.

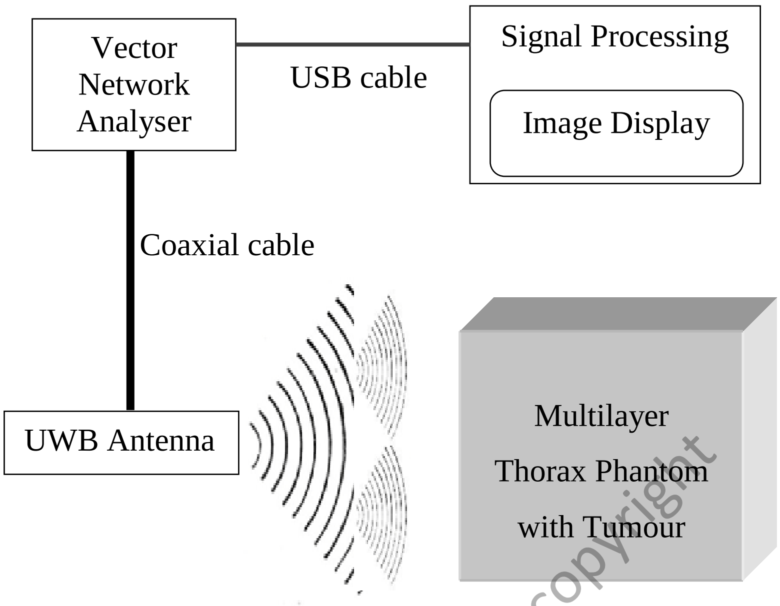

Figure 1.1: Microwave imaging setup for lung tumour detection

1.2 Problem Statement

Available statistics for the prevalence of cancer for the year 2012 estimated cases of 14.1 million, out of which lung cancer was estimated to be 13% of the new cases. This value puts lung cancer to be the leading cancer disease and the commonest cause of cancer related death, a value that is on the increase (2015). Clinical sciences have come up with many means of detecting cancer in the human body. Some of which are biopsy, bronchoscopy, cytology, chest x-ray, magnetic resonance imaging (MRI), computed tomography scan (CT), and positron emission tomography scan (PET). X-rays are ionising rays, and quite harmful with repeated exposure while strong magnetic fields are used in generating magnetic resonance images which are as well dangerous in large quantities. Availability of X-ray and MRI equipment are also limited to large hospital settings due to the costs of procurement, size of equipment and expertise of operating personnel. Summarily, all these means can detect tumour but with some limitations and health risks. Hence, needs for alternatives; which will be readily available, cost less, and easier to operate and still be efficient in detecting and localising tumour in the human body. An alternative with great potentials is the microwave imaging technique and its feasibility of detecting tumour in the lungs is studied in this research. To the best of the author's knowledge this is the first attempt to detect tumour in the lungs using ultra-wideband radar microwave imaging technique.

1.3 Objectives

The research work aims at investigating the capability of microwave imaging techniques in diagnosing the presence of tumour in the lung model and hence, produce microwave images that can be interpreted to indicate tumours. In the course of the research work, objectives highlighted as follows will be met:

i. Design and fabrication of an ultra-wideband antenna suitable for use in ultra-wideband microwave imaging technique for detecting lung tumour.
ii. Fabrication of a multilayer thorax model with tissue simulating materials to mimic the human thorax and have dielectric properties of the constituent tissues.
iii. Assess the accuracy of lung tumour detectability in microwave images using a localisation approximation.

1.4 Scope of Study

A conceptual simulation to validation in experiment approach is followed in the research work. The measured dielectric properties of the tissues of the thorax as available in literature were used in the simulation. A proposed multilayer thorax model was designed in the simulation and fabricated in the experiment. The multilayer thorax was only limited in terms of the physical structure of the human chest. The simulation and experiment had similar setup, where a phantom box filled tissue simulating materials represented the multilayer thorax model. Further considerations were given to represent the varying dielectric properties of the lung during exhalation and inhalation. This was done by representing exhalation with lung model and tissue simulating liquid that has the dielectric properties of deflated lung in both simulation and experiment; and inhalation with similar lung model and tissue simulating liquid with dielectric properties of inflated lung. The physical dimensions or change in volume of the lung as observable during respiration were not considered, that is, the dimension of the lung was fixed for both inhalation and exhalation, the dielectric properties were changed to reflect respiration.

Tumour response was extracted using a differential approach; this involves performing measurement for when there was no tumour in the thorax model, the acquired backscattered signals are used as reference. With the tumour in the thorax model, another measurement is performed and the tumour response is realised by subtracting the previously acquired reference signals. The differential approach is otherwise known as calibration, where the calibrated signal is the tumour response. More work is needed to be done in translating the research work to a more realistic scenario.