



Faculty of Engineering

**Modified Metamaterial Lens Structure for Non-invasive Hyperthermia
Breast Cancer Procedure**

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Master of Engineering

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Modified Metamaterial Lens Structure for Non-invasive Hyperthermia Breast Cancer Procedure

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A thesis submitted

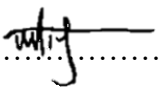
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DECLARATION

I declare that the work in this thesis was carried out in accordance with the regulations of Universiti Malaysia Sarawak. Except where due acknowledgements have been made, the work is that of the author alone. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

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ABSTRACT

Hyperthermia treatment procedure (HTP) is an alternative treatment for cancer, where it induces heat and forms a biological effect. The efficiency of the hyperthermia procedure depends significantly on the focusing distance position of the electromagnetic energy to elevate the temperature of the cancerous tissue until 41°C to 45°C within 60 to 360 minutes. However, the current non-invasive HTP for cancer has limitations in its penetration depth (PD) and focusing distance position (FPD) on human tissues, which may contribute to less effective treatment on the targeted cancer tissue. Thus, this research is mainly to develop a modified metamaterial-split ring resonator (MTM-SRR) lens structure for enhancing the FPD of different stages of breast cancers. To achieve the mentioned objective, five research phases are performed. First, the development of breast phantom. Second is microstrip antenna development, which follows metamaterial (MTM) lens development, then water bolus addition and the fifth, in which the final phase is the validation of the outcomes. These experiment components are developed using the SEMCAD X 14.8.4 software simulator. With SEMCAD X 14.8.4, an electromagnetic (EM) simulation is conducted to obtain the Specific Absorption Rate (SAR) distribution towards the developed breast phantom, which consists of breast fat and breast cancer tissue. From the SAR, the PD and FPD are measured. As the results, the integration of MTM has performed in a significant effect by enhancing the FPD of HTP and existed lesser unwanted hotspots area. The FPD coverage percentage of HTP execution with selected MTM-SRR designs reached 95.32%, 87.48%, 81.08% and 89.45% for early stage, stage 1, stage 2 and stage 3 of breast cancer respectively. In addition, different stages of cancers required different suitable operating frequencies and different D_0 of MTM. Then, with the addition of water bolus, the unwanted hotspots are reduced further and reshaped

the SAR distribution to attain the effective field size of SAR for HTP. In summary, with a modified MTM structure applicator with the addition of water bolus, the PD and FPD on the treated cancer tissue can be enhanced and improved further. However, further work is required to perform laboratory experimentation on a real proposed HTP applicator prototype with mimicked breast cancer tissue to observe the SAR distribution of PD and FPD.

Keywords: Metamaterial, Hyperthermia, Breast Cancer, Focus Position Distance, Penetration Depth

***Pengubahsuaian Struktur Kanta Metamaterial untuk Prosedur Kanser Payudara
Hipertermia Tidak Invasif***

ABSTRAK

Prosedur rawatan hipertermia (HTP) adalah rawatan alternatif untuk kanser, di mana prosedur ini mendorong haba dan membentuk kesan biologi. Kecekapan prosedur hipertermia bergantung dengan ketara pada kedudukan jarak fokus tenaga elektromagnet untuk meningkatkan suhu tisu kanser daripada 41°C–45°C selama 60 hingga 360 minit. Walaubagaimanapun, HTP bukan 'invasive' yang terdapat kini, mempunyai had dalam kedalaman penembusannya dan memfokuskan kedudukan jarak kearah tisu manusia, yang mungkin menyumbang kepada rawatan yang kurang berkesan pada tisu kanser yang disasarkan. Oleh itu, penyelidikan ini dijalankan untuk meminimumkan had HTP dengan menyepadukan aplikator kanta bahan metamaterial (MTM) untuk HTP. Lima fasa penyelidikan dijalankan. Pertama, perkembangan model payudara. Kedua ialah pembangunan mikrostrip antena, seterusnya pembangunan kanta MTM, kemudian penambahan bolus air dan kelima, di mana fasa terakhir adalah pengesahan output. Komponen eksperimen ini dibangunkan menggunakan simulator perisian SEMCAD X 14.8.4. Dengan SEMCAD X 14.8.4, simulasi EM dijalankan untuk mendapatkan taburan Kadar Penyerapan Spesifik (SAR) kearah model payudara yang dibangunkan, yang terdiri daripada lemak payudara dan tisu kanser payudara. Daripada SAR, kedalaman penembusan (PD) dan jarak kedudukan fokus (FPD) diukur. Penyepaduan MTM telah menghasilkan kesan yang ketara dengan mempertingkatkan FPD HTP, dengan kawasan pemanasan yang tidak diingini yang lebih rendah, ia boleh membawa kepada kesan kesihatan yang buruk pada tisu sihat di sekelilingnya. Kajian mendapati peratus peliputan FPD kepada tahap permulaan, tahap 1, tahap 2 dan tahap 3 kanser payudara, masing-

masing mencapai 95.32%, 87.48%, 81.08% dan 89.45% .Di samping itu, peringkat kanser yang berbeza bergantung kepada frekuensi operasi yang sesuai dan D_0 MTM yang berbeza. Oleh itu, FPD yang sesuai untuk pelbagai saiz kanser yang dirawat boleh dicapai. Kemudian, dengan penambahan bolus air, titik panas yang tidak diinginkan dikurangkan lagi dan membentuk semula taburan SAR untuk mencapai saiz medan SAR yang berkesan untuk HTP. Secara ringkasnya, dengan aplikator struktur MTM yang diubahsuai dengan penambahan bolus air, kedalaman penembusan (PD) dan jarak kedudukan fokus (FPD) pada tisu kanser yang dirawat boleh dipertingkatkan. Walaubagaimanapun, kerja lanjut diperlukan untuk menjalankan eksperimen di makmal untuk prototaip aplikator HTP sebenar yang dicadangkan dengan tisu kanser payudara yang dibangunkan untuk memerhatikan taburan SAR, PD dan FPD.

Kata Kunci: Metamaterial, Hipertermia, Kanser Payudara, Jarak Kedudukan Fokus (FPD), Kedalaman Penembusan (PD)

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LIST OF ABBREVIATIONS

CEM	Computational Electromagnetic
CC	Cranio-Caudal
CT	Chemotherapy
DNG	Double-negative
DICOM	Digital Imaging and Communications in Medicine
DoE	Design of Experiment
EFS	Effective field size
EM	Electromagnetic
EMF	Electromagnetic Field
ENG	Epsilon-negative
FQ	Frequency
FDTD	Finite-difference time domain
FPD	Focus position distance
FM	Frequency modulation
GPS	Global-positioning System
HTP	Hyperthermia Treatment Procedure
ID	Inner Depth
MLO	Medio-Lateral Oblique

MNG	Mu-negative
MTM	Metamaterial
MTM-SRR	Metamaterial-Split Ring Resonator
MTM-ZOR	Metamaterial-zeroth order mode
MW	Microwave
NRI	Negative Refractive Index
PD	Penetration depth
RF	Radiofrequency
RT	Radiotherapy
SAR	Specific Absorption Rate
SD	Surface Depth
SRR	Split Ring Resonator
TH	Thickness
TPE	Treatment Periods Estimation
UNIMAS	Universiti Malaysia Sarawak
US	Ultrasound
WB	Water Bolus

CHAPTER 1

INTRODUCTION

1.1 Introduction

This chapter consists of a research overview as well as the motivation of the research, problem statement, research objectives, contributions of research, research scopes, research gaps and thesis outlines. Details of the discussion are presented accordingly in **Sections 1.2 to 1.10**.

1.2 Research Overview

This research involves a study in developing of modified hyperthermia treatment procedure (HTP), which consists of a microstrip antenna and metamaterials (MTM) lens. This modified structure aims to improve focus position distance on the treated tissue and simultaneously reduce unwanted hot spots on the surrounding healthy tissue.

In recent years, numerous types of research on HTP applicators for non-invasive HTP applications have been carried out. This hyperthermia treatment is currently known as an alternative therapy for cancer (Vogl et al., 2018). It is often used with chemotherapy and radiotherapy, which is known as adjuvant therapy (Koo et al., 2014).

In addition, hyperthermia is a new technique to expose cancerous tissue to electromagnetic radiation in order to increase tissue temperatures around 41°C to 45°C for one (1) hour or more (Behrouzkia et al., 2016). Based on previous research, this hyperthermia technique is able to convert the cancerous tissue into necrotic tissue and destroy the cancerous tissue with minimal side effects (Beck et al., 2022; Lias et al., 2022).

Generally, HTP applications can be an invasive and non-invasive treatment. It is either the HTP applicator applies towards the human body internally or externally, respectively. Practically, invasive HTP can be much more effective than a non-invasive HTP, as the HTP applicator is inserted into the target region and heats the cancerous cell directly (Wang et al., 2014). However, the process of inserting this HTP applicator into the human body can be invasive and may cause several adverse health effects, such as major bleeding.

Meanwhile, as for non-invasive HTP, since it is applied outside of the human body, adverse health effects can be minimized as surgery can be avoided. In addition, this non-invasive HTP is simpler to handle if compared to invasive type HTP because it can be used as an in-situ applicator (Lias et al., 2014).

Nevertheless, both types of HTP are effective and applicable to cancer therapy. However, this research will focus on non-invasive HTP applicator development since it provides less adverse health effects and is safer than invasive HTP. This research study improves and stimulates non-invasive hyperthermia, where the HTP applicator is investigated and modified further in order to obtain the results that show the capability to perform the required depth and focus position distance on the treated tissue.

Based on the previous study, G.A. Deschamps initially introduced the idea of a microstrip antenna in the year 1953, and it was practically produced in the 1970s by Robert E. Munson and his fellow researchers using a low-loss substrate. Microstrip antenna has commonly used in many applications, such as broadcast satellite service, mobile satellite communications, a global positioning system (GPS), medical hyperthermia usage and such (Karthikeyan & Vijayalakshmi, 2014).

Meanwhile, the concept of Metamaterial (MTM) was first proposed by Veselago in the year of 1968 when he introduced the existence of materials whose permittivity and permeability were simultaneously negative (Vrba et al., 2016). Due to the negative refractive index (NRI) characteristics of MTM, Pendry introduced the perfect lens in 2000, which was known as left-handed materials (LHM). It has a great electromagnetic (EM) energy-focusing capability on the treated tissue (Pendry, 2000). However, poor wave propagation distance was found in Pendry's research. As of today, experimental results have proved that moving the microwave (MW) sources with respect to the MTM lenses based on tumour position can affect the concentration of heating within the biological tissue (Leggio et al., 2015).

When water bolus is added to the treatment procedure, it contributes to lessening the adverse health effects due to heat applied toward the treated tissue. It is mainly to provide cooling conditions during HTP execution (Juang et al., 2004).

With the integration of microstrip and MTM lens structure, it is expected the required penetration depth and focus position distance on the treated tissue can be achieved. Then, when water bolus is added to the treatment procedure, it aims to reduce unwanted hot spots on surrounding healthy tissue.

1.3 Research Motivation

There are three main factors which motivate to carry out this research.

First, the capability that was shown by the MTM lens in the previous research, where it was able to adjust the EM energy pattern (Vrba et al., 2016). Thus, when a microstrip antenna is integrated with an MTM lens to form a modified HTP applicator, it is

expected that the focus position distance on the treated tissue can be improved and enhanced to cater to different sizes and locations of cancer tissue.

Second, non-invasive hyperthermia has the potential to kill cancer. However, requirements to improve penetration depth (PD) and focus position distance (FPD) on the treated tissue are significantly necessitated. This is to ensure the success rate of HTP can be increased with minimal side effects on surrounding healthy tissue (Gas & Kurgan, 2018). An overview study made by Kok et al. (2020) mentioned that current clinically used non-invasive hyperthermia treatment procedures could attain PD from 15mm to 70mm, but these are very dependent on the applied frequency and size or diameter of cancer.

Last but not least, the third factor is the increasing number of cancer incidences, especially breast cancer incidences. It is the most common cancer among women worldwide with 2.1 million new cases and caused 627 000 of cancer death in year 2018. (Wild et al., 2020).

In conjunction with this increment in cancer incidences, it is a requirement to introduce various improvement techniques to a potential alternative treatment for cancer. In this research, HTP is emphasized with MTM-Split Ring Resonator (SRR) design as it has proved able to improve the HTP efficiency (Slimi et al., 2022; Yusri & Muldarisnur, 2021).

1.4 Problem Statement

Concern for non-invasive therapy requirement has encouraged research for non-invasive HTP, as it is able to provide safer treatment procedures with minimal adverse health effects during treatment execution if compared to other conventional therapy such as

chemotherapy, radiotherapy, and surgery. However, the requirement for focusing capability is very crucial for hyperthermia procedures to reduce the excessive unwanted hotspots surrounding normal or healthy tissue and minimize the adverse health effect that contributes to the unwanted hot spots during hyperthermia execution. Thus, the applicator that needs to deliver the radiation or heat towards the treated tissue should be able to focus the radiation or heat at the necessitated area to be radiated or heated.

In addition, based on previous research, only specific sizes and locations are investigated. It is a limitation to reach different sizes and locations of the cancer tissues. Practically, the size and location of cancer incidences are different. A specific concern, whereby an improvement and enhancement on HTP applicator that is able to cater to different sizes and locations are significantly required to be investigated.

1.5 Research Objectives

This research is conducted to introduce a new HTP applicator that can provide the required PD and FPD on the treated tissue. Moreover, this HTP research is involving early stage until stage 3 breast cancer model to develop the most suitable HTP designs for each cancer stage. With regard, the main objectives for this research are stated as follows:

- (i) To develop a microstrip antenna as an HTP applicator that can penetrate a sufficient penetration depth for each cancer stages using SEMCAD X 14.8.4.
- (ii) To modify the MTM-SRR lens structure and integrate it in (i) for enhancing the FPD for different stages of breast cancers using SEMCAD X 14.8.4.
- (iii) To validate the outcomes in (ii) with thermo-simulation environment using SEMCAD X 14.8.4.

1.6 Contribution of Knowledge

Several contributions to knowledge are obtained from this research. The contributions are listed as follows:

- (i) Two (2) different thicknesses of microstrip antenna substrate provide different SAR distributions, where thicker substrate showed better PD and FPD in both 915MHz and 2450MHz HTP applicators.
- (ii) Two (2) different sizes of SRR MTM lens structures ($\lambda/34$ and $\lambda/46$) have shown that smaller-sized SRR ($\lambda/46$) performed higher heat concentration toward cancer tissue.
- (iii) Different distance arrangements for $\lambda/34$ and $\lambda/46$ sized MTM-SRR cells have presented those arrangements of SRR cell contributed to shifting of heat pattern.
- (iv) Different thicknesses of water bolus have affected the effective field size of the breast cancer-treated area.

1.7 Research Scope

Research scopes for this research are presented as **Figure 1.1**.

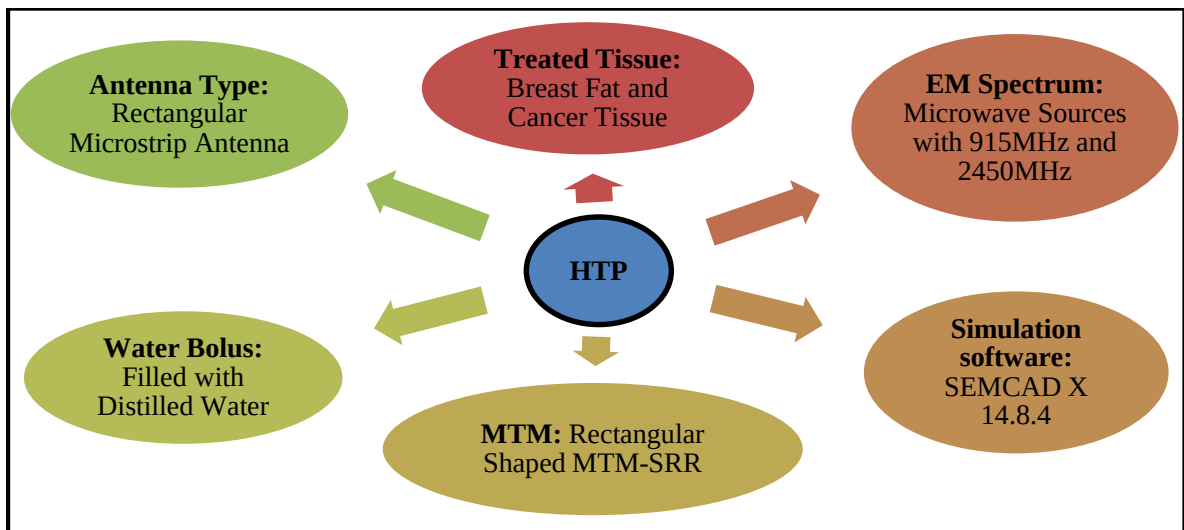


Figure 1.1: Research Scope of The Study

Based on **Figure 1.1**, this research is mainly carried out with SEMCAD X 14.8.4 simulator software and the breast phantom, which consists of breast tissue and breast cancer, is used as the treated tissue. Two operating frequencies are investigated, which are provided under Industrial, Scientific, and Medical frequencies: 915MHz and 2450MHz with microwave (MW) electromagnetic (EM) spectrum. Besides, rectangular SRR typed MTM is the type of MTM structures that will be compared. The water bolus is filled with distilled water, other solvents or liquids are not included in the investigation.

1.8 Research Gap

The research gaps applied in each component involved are presented in **Table 1.1**. Detailed discussions of the research gaps are discussed in the **Chapter 2**.

Table 1.1: Research Gaps of The Study

Research Components	Research Gaps
Breast Phantom	Four cancer stages are investigated to obtain the suitable HTP design for each cancer stages. This is because mostly recent researches are using one type of cancer data only, for example Woo et al. (2020) used kidney cancer data with 50 until 70 mm deep while Lias (2019) developed breast cancer phantom with depth 50mm until 100mm.
Microstrip antenna	Investigated with different thickness which mostly ignored by recent researchers such as Elsaadi et al. (2019) developed a HTP with RO 5880 substrate with thickness 1.57mm while Naimullah et al. (2022) simulated effects of different substrate in HTP in 1mm thickness.
MTM	Different sized SRR cell and various cell distance are involved in this research. Compared with another recent major MTM research directions such as multi-compartment SRR and MTM ZOR (Yusri, 2021; Vrba, 2016).
Water Bolus	Compared with research by (Lias, 2022), the water bolus developed in this research involved 2mm, 5mm and 10mm thickness variations .

1.9 Thesis Outlines

This report consists of five (5) chapters, which are Chapter 1: Introduction, Chapter 2: Literature Review. Chapter 3: Research Methodology, Chapter 4: Results and Discussion and Chapter 5: Conclusion and Recommendations.

Chapter 1 discusses the introduction of the research. This chapter consists of the research overview, research motivations, problem statement, project objectives, contribution of knowledge, research scope and research gap.

. Chapter 2 presents the literature review made on this study. This chapter consist of the review HTP in cancer treatment, microstrip antenna applicator in HTP, metamaterial lens as HTP enhancement and water bolus in HTP.

Chapter 3 provides the research methodology of this thesis. Research approaches, research tools, research process and design of experiments (DoE) are presented in this chapter. The research processes are planned in five (5) phases while a total of six (6) DoEs are designed to achieve the research objectives.

Chapter 4 shows the results and discussion for each DoE and the best design for each experiment steps are selected for each breast cancer stages. The simulation results obtained also compared and validated with other researchers' findings within this chapter.

Chapter 5 is the chapter for conclusion and recommendation. The research findings are concluded in this chapter and some research limitations and future recommendations are stated in chapter 5.

1.10 Summary of Chapter

In conclusion, the hyperthermia procedure is a technique that exposes the tissues to electromagnetic radiation to raise the regional temperatures around 41°C to 45°C in order to convert the cancerous tissue into necrotic tissue and destroy the cancerous tissue with minimal side effects. This research is mainly focused on MTM-SRR development to improve the PD and FPD of HTP on breast cancer-treated tissue. A research background has been presented in **Section 1.2**. Meanwhile, the research motivation, research problem statement, research objectives, contribution of knowledge, research scope, research gaps and thesis outlines have been provided in **Sections 1.3 to 1.10**, respectively.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Chapter 2 presents the comparison of hyperthermia to other cancer treatment procedures, such as chemotherapy, radiotherapy, immunology and physical surgery. In addition, this chapter also provides the fundamentals of hyperthermia for cancer treatment and various types of hyperthermia applicators, either invasive or non-invasive applicators. A comprehensive review of current non-invasive hyperthermia applicators is presented as well. Finally, recent research on Metamaterial (MTM) applicators in HTP, especially for split-ring resonator (SRR) and water bolus as HTP coolant, are also provided.

2.2 Hyperthermia in cancer treatment

Hyperthermia is an alternative treatment for cancer treatment procedures by inducing heat to form a biological effect towards the treated tissue (Yagawa et al., 2017). The hyperthermia procedure is used to elevate the temperature of the cancerous tissue to 41°C–45°C without affecting the surrounding healthy tissue (Nizam-Uddin & Elshafiey, 2017). Hyperthermia procedures have been proven to increase the efficacy of conventional cancer treatment. Currently, successful therapy method in a combination of HTP with radiation therapy and/or chemotherapy has increased (Jha et al., 2016).

Currently, there are three common cancer treatment therapies, which are known as chemotherapy (CT), radiotherapy (RT) and surgery. However, the side effects of these well-known therapies on human health have raised massive concerns among the public. In conjunction with that, alternative therapies for cancer, such as hyperthermia, targeted

therapy, hormone and immuno-therapy, have been proposed and investigated to increase the cancer treatment efficacy and simultaneously reduce the side effects (Kaur et al., 2011; Yagawa et al., 2017). A comparison between chemotherapy, radiotherapy, surgery, and hyperthermia is shown in **Table 2.1**.

Table 2.1: Comparison between CT, RT, Surgery and HTP (Demirci et al., 2010; Kok et al., 2020)

Cancer Procedure	CT	RT	Surgery	HTP
Treatment Procedure	Using a chemical drug to destroy cancerous cells.	Utilize energized waves or particles to kill the cancer cells.	Remove the cancerous tissue or cell via physical contact.	Inducing heat until 41°C to 45 °C to exposed cancerous tissues externally
Advantage(s)	It can be delivered as an outpatient procedure, increasing the success rate of other treatments.	Fast treatment (a few minutes) can be focused on the cancer regions.	High efficiency, removed the damaged organ to stop spreading.	Lower EM frequency applied compared with RT and able to increase the efficacy of conventional cancer treatment.
Side Effect(s) or Limitation(s)	Infertility, hair loss, nausea and vomiting	Possibility of causing radiation injury	Serious bleeding and the risk of left cancerous tissue.	Low penetration depth and hard-to-control FPD, which may damage the surrounding healthy tissues.

HTP is classified as thermal therapy in a medical procedure. There are three types of thermal therapies, which are known as diathermy, hyperthermia and thermal ablation.

These thermal therapies are compared in **Table 2.2**.

Table 2.2: Comparison of Thermal Therapy

Thermal Therapy	Characteristics	Advantages and Disadvantages
Diathermy	Diathermy is a treatment modality used to reduce pain through localized heating by utilising EM energy to induce heat inside the patient's body. This method is used for injuries such as sprains and strains and muscle and tendon tears (Joyner, 1987).	Advantage: Increased blood circulation for inducing faster healing. Able to used in electro-surgery in cutting modality or stop bleeding. (Boyd & Macg Palmer, 2013). Disadvantage: Temperature can reached up to 1000°C, not suitable in denaturated the cancer tissue.
Hyperthermia	Inducing heat within 41°C–45°C to exposed cancerous tissues internally or externally to convert into necrotic tissues (Nizam-Uddin & Elshafiey, 2017).	Advantage: Can be used externally or internally. Lower applied temperature compared with the thermal ablation method. Disadvantage: A developing technology with issue of poor penetration depth (Hassan et al., 2021).
Thermal Ablation	Thermal ablation is a treatment by overheating the targeted cancerous tissue until it turns to necrotic tissue. The range of applied temperature is 55°C to 100°C.	Advantage: High efficiency in cancer treatment with overheating approach. Disadvantage: Overheating the tissue to high levels can cause the destruction of various physiological and biological phenomena, especially not suitable in major organs such as the heart and brain (Gas & Szymanik, 2018; Mellal et al., 2017)

Table 2.2 clearly shows hyperthermia thermal therapy with lower applied heat is a more suitable modality for cancer tumour treatment procedures since it is a safer treatment

for cancer procedures. According to the heat deposition mechanism in tissues by Electromagnetic Filed (EMF), heat is produced by a process analogous to friction when the electric dipoles of the tissue vibrate in response to the EMF of applied sources. As free-charged electrons or ions in the tissue are oscillated by the EM field, heat is generated from the collision process (Lias, 2019).

HTP causes complex effects on cancer, which are significantly disrupted the ability of tumour cells to divide and lead to the shrinkage of tumours (Cabuy, 2011). HTP is also able to prevent cancer cell repair after adjuvant therapy with chemotherapy or radiotherapy (Behrouzkia et al., 2016). As it is able to de-nature the cancer cell to necrotic tissue, then the human antibody system destroys the necrotic tissue as it is detected as a foreign substance for the human body.

2.2.1 Type of Hyperthermia Procedure

There are three main types of HTP, which are classified by the organ targeted, cancer stage, and distribution technique of energy. They are referred to as Local, Regional and Full-body or Whole-body HTP, respectively (Mellal et al., 2017).

Local HTP applies heat to a small area, using various techniques that transfer heat energy to the cancerous tissue (Choi et al., 2020). There are different approaches of Local HTP, which are External, Intraluminal or Endo-cavitary and Interstitial (Jha et al., 2016). The comparison of different approaches is shown in **Table 2.3**.

Meanwhile, regional HTP used to treat cancer by removing some of the patient's blood, heated and then delivered back to the patient's body into the organ or limb, generally used together with anticancer drugs. It is commonly used to treat complicated

tumours located in the pelvis, thighs, or abdomen. However, regional HTP is more complex than local HTP due to the different properties of different tissues (Behrouzkia et al., 2016; Rahpeima & Lin, 2022).

Then, whole-body hyperthermia executes radiation heat or extracorporeal technologies to elevate the body temperature to 41 °C or above. The most frequent used method for whole-body thermotherapy is heat transmission via skin contact. Inductive coils, hot wax, warm water blankets, and thermal rooms or chambers are used to elevate the body temperature to the desired level (Jha et al., 2016).

Because a human breast is selected as a targeted organ which is mentioned in **Section 1.2**, thus, local HTP is selected to be used further in this research as it is suitable to treat small cancer that is basically near the skin.

There are three main applicators which are used for local HTP. They are known as external, intraluminal and interstitial. The external applicator is considered a non-invasive HTP applicator, while the other two local HTP applicators are classified as invasive HTP applicators. Further explanations of these local HTP applicators are presented in **Table 2.3**. Examples of invasive and non-invasive HTP applicators are shown in **Figure 2.1** (Eltigani et al., 2022) and **Figure 2.2** (Minnaar et al., 2020), respectively.

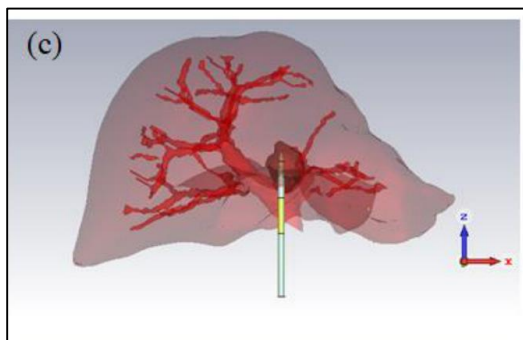


Figure 2.1: Invasive HTP- Interstitial Slot Antenna



Figure 2.2: Non-invasive Hyperthermia: EHY-2030

Table 2.3: Different Approaches of Local HTP (Jha et al., 2016)

Local HTP	External	Intraluminal or Endo-cavitary	Interstitial
Treatment Procedure	Uses to destroy cancer within or below the skin. External applicators are targeted on or around the targeted space to boost its temperature.	Uses to destroy the tumours inside the body or close to body cavities. Antennas were placed within the cavity and inserted into the tumours to transfer energy and warmth to the area directly.	Uses to treat a tumour that is deep within the body, like brain tumours in which high temperature is needed.
Advantage	No minor surgery is involved to avoid bleeding, a non-invasive method that is safer.	Heat can be induced directly into the targeted tissue.	Heat can be induced directly into the targeted tissue.
Disadvantage	Poor penetration of EM energy.	A probe is inserted into the human body. Surgery for open a hole is required for this invasive method.	Several holes are needed to insert the probes from a suitable array in this invasive method, and high heat is needed.

Based on Table 2.3, external local HTP is a safer treatment procedure compared with intraluminal and interstitial as no surgery is needed. Therefore, research on external local HTP applicator to overcome its poor penetration disadvantages is required.

Microwave (MW), radiofrequency (RF) or ultrasound are used as HTP energy sources. It can be classified by the applied frequency, treatment regions and the required PD (Dobšíček Trefná et al., 2019).

MW energy source is chosen as applied EM spectrum for this research. This is because MW HTP is suitable as external non-invasive HTP for superficial malignancies such as breast cancer (Dobšíček Trefná et al., 2017). MW antenna generally operated within 434MHz until 2450MHz (Beck et al., 2022; Naimullah et al., 2022). MW energy source also proved with suitable PD performance in breast cancer HTP researches (Wong & Lias, 2021).

RF energy source are frequently applied in deep region hyperthermia with interstitial antenna with frequency 30MHz to 140MHz. RF based antenna can reach PD until 20cm. Mostly RF antenna are functioned as regional type HTP for cervix, bladder, rectum cancer with deep-seated cancer tissue (Crezee et al., 2020; Dobšíček Trefná et al., 2019; Eltigani et al., 2022).

US HTP uses high-frequency sound waves above the upper limit of human hearing (higher than 10 kHz) to generate heat in tissues. US energy can be focused to a precise location, allowing for heating without affecting surrounding healthy tissues. However, RF and MW typed energy have higher efficiency when covering large size cancer that larger than 40mm (Zhu et al., 2019).

2.2.2 Antenna Structure for HTP

An escalating number of research and works have been conducted to obtain the efficacy of hyperthermia procedures from the aspects of antenna design, optimization techniques focusing techniques and cooling techniques recently by different researchers. The antenna enhancement for hyperthermia is significant as heat produced by EMF is used for cancerous treatment.

Various antennas, such as microstrip, coaxial, dipole, and spiral, have been developed for HTP investigation (Lias, 2019). **Table 2.4** summarises recent research in hyperthermia based on 72 references, which are retrieved from various journals and conference technical proceedings between 2013 to 2023.

Table 2.4: Antenna Used in Recent HTP Research

Type of Antenna	Microstrip	Coaxial	Dipole	Bowtie	Helical	Spiral	Triaxial	Total
Frequency	33	18	13	1	4	6	1	76

As shown in **Table 2.4**, the microstrip antenna is the most popular antenna used in the HTP research investigation. Further characteristics of different types of antennas and its response towards a treated tissue in HTP are presented in **Table 2.5** while, **Figure 2.3** and **Figure 2.4** show different antenna types, which were used as HTP applicators by Sethi and Nijhawan (2016), Yuce and Dissanayake (2013).

Table 2.5: Comparison Between Type of Antenna Used in HTP (Lias, 2019)

Antenna	Advantages	Disadvantages
Dipole Antenna	It can be made of simple wire. It can be used as an implanted antenna in the breast or brain.	Excessive unwanted hotspots.
Monopole Antenna	Half the size of a dipole antenna	Omni-directional radiation may lead to wider propagation and cause low focusing, and damage healthy tissue.
Microstrip Antenna	Easy to manipulate the thickness and obtain the size via different frequencies.	Narrowband radiation pattern that causes inconsistency in focusing on cancerous tissue.
Coaxial Antenna	Most used clinically for hyperthermia treatment. It can be used as both interstitial and external HTP. Mostly utilised in 2450MHz. With higher power input, it can perform to better penetration depth.	Mostly used in invasive antenna for better heat distribution. It can be caused massive health effects as surgery is required.
Spiral Antenna	Performed well in penetration depth of hyperthermia and significantly reduced the hot-spots and consistently performed in focusing on cancerous tissue.	Limited to a multi-band antenna.

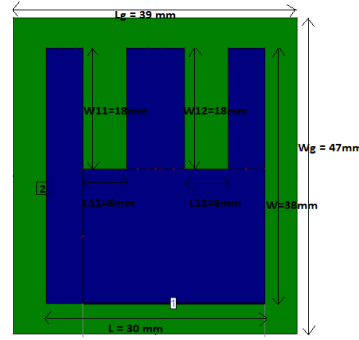


Figure 2.3: Example of Microstrip Antenna (Sethi & Nijhawan, 2016)

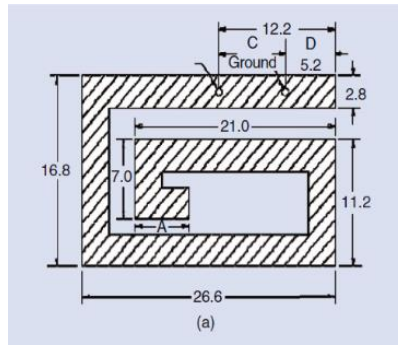


Figure 2.4: Example of Spiral Antenna (Yuce & Dissanayake, 2013)

Based on **Table 2.5**, a microstrip antenna has been chosen to be improved and modified further in this research. This microstrip antenna has the advantages such as easy-to-modify size, various array types of enhancement and miniaturization factor.

Microstrip antenna consists of a metal strip on a substrate to the ground plane. The strip can be in different forms to satisfy various design requirements. Generally, commonly used shapes are square, rectangular, circular ring and circular (Alam et al., 2018; Deshmukh et al., 2018).

The microstrip antenna is low-profile, compatible with planar and non-planar areas, easy and low-cost to conduct by the latest printed-circuit technology, compatible with monolithic microwave integrated circuit design and mechanically pragmatic (Dey et al., 2011). In addition, further analysis of the microstrip antenna is tabulated in **Table 2.6**.

Table 2.6: Selected Microstrip Antenna Research from 2013- 2022

Shape or structure	Treated body tissue (s)	Observation	Reference
Microstrip Spiral Antenna	Breast	The desired temperature in the tumour region can be obtained within 60 minutes of exposure, while the superficial heating can be compensated by water circulation.	(Korkmaz, Isik, & Kara, 2013)
Embedded Electromagnetic Band Gap (EBG) Microstrip Antenna	Breast	The EBG-Microstrip antenna was able to provide acceptable PD and also reduce excessive hot spots, which may affect other surrounding healthy tissue.	(Lias et al., 2014)
Rectangular Microstrip Antenna with Hemispherical Ground Plate	Breast	The increase in the number of antenna elements can improve the penetration depth.	(Curto et al., 2015)
Slotted Circular Shaped Microstrip Antenna	Not mentioned specifically	The two-slotted circular microwave patch antenna presented a good focus with low return loss and high directivity compared with a normal circular microwave patch antenna.	(Sethi & Nijhawan, 2016a)
C-Shaped Microstrip Antenna with Water Bolus	Muscles tissues	The size of the radiating path is greatly decreased when using a high dielectric substrate and reactive loading with shorting pin.	(Chakaravarthi & Arunachalam, 2014)

Table 2.6 continued

Shape or structure	Treated body tissue(s)	Observation	Reference
Rectangular Microstrip Antenna with Hemispherical Ground Plate	Breast	Simulations showed that an antenna with 915MHz applied frequency achieved a better power absorption ratio and focusing ability.	(Garcia-Miquel et al., 2016)
Rectangular Microstrip Antenna in Array Structure	Not mentioned specifically	Array structure can enhance the efficiency of microstrip antenna and able to achieve the performance like invasive HTP.	(Debnath et al., 2015)
Multi Patch and Grid Structure Array Antenna	Breast	The combining of array antenna and grid antenna able to change the radiation pattern	(Salimi et al., 2019)
Microstrip Antenna with 434 MHz, 915MHz and 2450MHz	Breast	2450MHz antenna showed the best PD and achieved return loss - 15dB.	(Hassan et al., 2021)
Microstrip Antenna with Y-slot lens and 2mm Breast Shape Water Bolus	Breast	With the integration of a 2mm thickness breast-shaped water bolus, the FPD was able to control within 20-50mm.	(Lias et al., 2022)

Based on **Table 2.6**, there are several microstrip antenna shapes or structures, including microstrip-spiral, embedded EBG and slotted circular shaped microstrip antenna.

Table 2.6 shows that the microstrip antenna has presented good penetration depth and acceptable focus position distance to the treated tissue. However, a further requirement on improving focus position distance on various sizes and positions of cancers is significant.

This limitation was observed from the existing HTP applicators, where it was only focused on a particular focus position distance of cancer and mentioned by Wong et al. at year 2021. Therefore, this research is carried out to improve the limitation by presenting the modified MTM lens structure to the microstrip antenna to cater for different sizes and positions of cancer.

Furthermore, this research also investigated the efficiency of HTP with different thicknesses of antenna, as a lot of recent studies are applied one substrate thickness only (Lias et al., 2022; Naimullah et al., 2022).

Based on the datasheet of RO4000 Series Datasheet by Rogers Corporation released in 2018 as in APPENDIX C, two of the commonly used substrate thickness are selected, which are 1.524mm and 0.762mm.

2.3 Metamaterials

Metamaterials (MTM) are artificial components which consist of electromagnetic properties that are unable to be found in natural materials. This is because MTM with properties of negative permittivity and permeability simultaneously (Caloz & Itoh, 2002).

The term metamaterial was given by Rodger M. Walser, from the University of Texas at Austin, in 1999 (Caloz & Itoh, 2002 and Walser, 2001). From his definition, metamaterial is a “Macroscopic composite that has a synthetic, three-dimensional, periodic cellular architecture designed to produce an optimized combination, not available in nature, of two or more responses” (Caloz & Itoh, 2002). Details on MTM lenses in HTP are presented in **Section 2.3.1**.

2.3.1 Metamaterials Lens as Hyperthermia Enhancement

MTM with both negative permittivity and permeability is known as left-handed material and acts as a negative refractive index (NRI) lens that is able to enhance the EMF induced by an energy source (Jaffar et al., 2019; Wojciech & Thanh, 2019). Due to NRI characteristics, Pendry introduced the perfect lens in 2000, which was known as left-handed materials (LHM). It has a great EM energy focusing capability on the treated tissue (Pendry, 2000).

Recent microwave hyperthermia applicators are not perfectly in uniform large tissue regions heating, while experimental results have proved that moving the microwave sources with respect to the MTM lenses based on cancer position can affect the concentration of heating within the biological tissue (Vrba et al., 2016; Wong & Lias, 2021).

In conjunction with that, this research is carried out further to investigate the ability of this MTM lens to improve the focus position distance to the treated tissue, especially when it is integrated with the microstrip antenna, the base antenna for the HTP applicator.

Table 2.7 presents an overview of MTM slabs or lens research ascending by years from 2009 to 2023.

Table 2.7: Overview of MTM Slabs or Lens Research

Reference	Type of Structure	Targeted Organ	Research Finding(s)
(Gong & Wang, 2009)	LHM slabs	Muscle	When the source was moving towards the LHM lens, the heating depth was increased. Higher input power was required to archive the necessary therapeutic temperature. The temperature reached 42°C and sustained for one hour for tissue 1.0 cm in width and 1.2 cm in depth with the source amplitude of 43.44 V/cm.
(Karathanasis et al., 2009)	Combination of dielectric filling and MTM layer	Brain	The combined structure has increased the system response to relative movements of the head around the geometrical focal point with 1GHz antenna. Significant enhancement of the EM field in the presence of the dielectric filling.
(Tao & Wang, 2010)	Γ -Shaped LHM Lens	Breast	Incoming sources were applied to horizontal, vertical or both sides of the Γ-Shaped LHM Lens. The condition with single-sided sources has contributed to worsening HTP performance. The temperature can reach 43 °C with source amplitude of 9.4V/cm

Table 2.7 continued

Reference	Type of Structure	Targeted Organ	Research Finding(s)
(Velazquez-Ahumada et al., 2011)	Metallic slabs with broadside-coupled SRR	Breast	The SAR has focused on the targeted tissue region. a peak of temperature in the tumour reaching 46 °C. However, the peak of temperature is restricted to a region smaller than the tumour size with higher conductivity.
(Vrba et al., 2016)	MTM-ZOR mode resonator (lumped LC circuit)	Muscle	The composition of ZOR array structures has radiated EM waves that were nearly plane waves in the structure. For 2×2 and 2×3 array configurations, the EFS achieve 25% of maximum SAR in the 3.5 cm deep plane is 100% and 91% of the array aperture area, respectively.
(Yusri & Muldarisnur, 2021)	Complementary MTM-SRR with gaps from 0.5 to 3.5 mm	Not mentioned	The heat concentration increased significantly with MTM-SRR The temperature can reach 58°C after 60 minutes.
(Sharma et al., 2023)	Double spiral antenna, artificial magnetic conductor and frequency selective surface (FSS) as lens.	Not mentioned	Analysed with irregular shaped tumour placed at 16 mm from the skin surface. The temperature hit 44°C with 2.5W input power. The applicator is capable of heating deep-seated tumours.

As shown in **Table 2.7**, an integration of MTM-SRR can be performed well in both research of Velazquez-Ahumada et al. (2011) and Yusri and Muldarisnur (2021).

In order to further investigate the development of MTM-SRR, this research implemented the concept of different cell sizes mentioned by Slimi et al. in the MTM breast cancer detection enhancement research in 2022 and cell gaps or cell distance approach used by Yusri and Muldarisnur for HTP enhancement in 2021.

The implementation of these two concepts are discussed in next chapter, **Section 3.6.3** and **3.8.2**.

2.4 Water Bolus for HTP

In previous studies (Juang et al., 2004; S. P. Singh & Singh, 2015), water bolus (WB) was used to control the effect of skin burning during treatment. In other research (Drizdal et al., 2021; Korkmaz, Isik, & Nassor, 2013), WB was provided as a cooling material and used with the proposed applicators.

Furthermore, the addition of WB in the hyperthermia treatment procedure was observed to be able to enhance the effective field size (EFS) of the EMF in the targeted tissue (Stauffer et al., 2017).

Figure 2.5 and **Figure 2.6** show examples of WB, which are known as water bolus vest by Juang et al. in 2004 and rectangular single-input single-output water bolus by Stauffer et al. in 2017, respectively. While Trefná and Ström also introduced the hydrogel typed WB such as agarose and xanthan gel in year 2019 (**Figure 2.7**).

However, in this research, did not significantly emphasise WB development, as the main Research Objectives are focused on the antenna and MTM development. The addition of WB in this research is to complete the HTP execution.

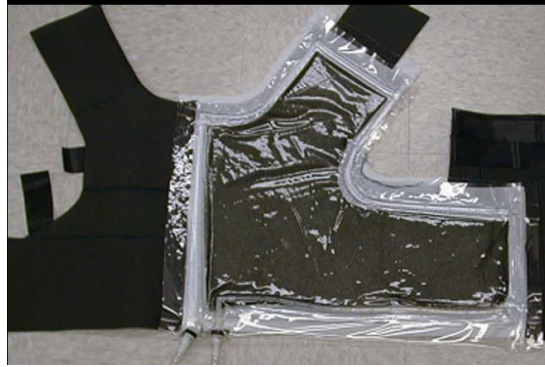


Figure 2.5: Water Bolus Vest (Juang et al., 2004)



Figure 2.6: Rectangular Water Bolus (Stauffer et al., 2017)

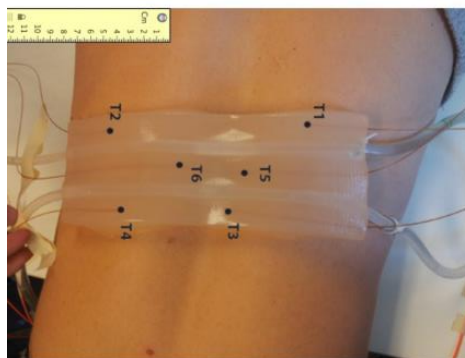


Figure 2.7: Hydrogel Typed WB (Trefná & Ström, 2019)

2.5 Comparison of Computational Electromagnetic Solver

This research experimentation is mainly conducted through simulation, there are various types of computational electromagnetic (CEM) solvers, which are called SEMCAD X 14.8.4 by SPEAG, XFDTD by REMCON, ANSYS high-frequency EM field simulation (HFSS) solver and Microwave Studio by Computer Simulation Technology (CST). **Table 2.8** presents the characteristics of the mentioned frequent implemented CEM solvers (Lias, 2019).

Table 2.8: Frequent Implemented CEM solvers (Lias, 2019)

CEM Solvers	Specifications
SEMCAD X by SPEAG	SEMCAD X is a thermal simulation platform and 3D full-wave electromagnetic simulation based on the FEM and FDTD methods. It is applicable for multiple ranges of applications, such as medical implant device design, safety assessment, antenna design, EMI/EMC, and dosimetry. Thermal simulations cover radiation absorption by antenna. An additional specification for thermal simulation is a thermal solver for hyperthermia.
XFDTD by REMCON	XFDTD release 7 is a 3D electromagnetic simulation solver for FDTD-based design and simulation. This program is enormously quick because of its compatibility with NVIDIA's most advanced CUDA-enabled GPUs. For thermal simulations, XFDTD covers radiation absorption toward human health by movable and magnetic resonance imaging coil.
CST by Microwave Studio	CST is an efficient, economical process resolution for electromagnetic design and analysis. CST could be a user-friendly 3D EM simulation software system program that allows the user to decide on the foremost acceptable technique for the planning and improvement of devices operating in various selections of frequencies. For thermal simulations, CST covers radiation absorption toward human health by portable devices.

Table 2.8 continued

CEM Solvers	Specifications
ANSYS high-frequency EM field simulation (HFSS)	ANSYS and Ansoft-HFSS are industrial solver tools supported by the finite-element method (FEM). ANSYS HFSS solver is the commercial standard for simulating high-frequency electromagnetic fields. HFSS offers progressive simulation technologies supported by the finite component, integral equation, straight line, and advanced hybrid ways to resolve vary types of microwaves, RF, and high-speed digital applications. For thermal simulation, it uses to acquire a thermal map, such as power loss distribution among any microwave package, to carry out mechanical and thermal analysis and to identify heat transfer constant.

As shown in **Table 2.8**, SEMCAD X is chosen to simulate this research due to the additional specification for thermal simulation, which is significantly used to validate the resulted SAR distribution of EM-simulation.

SEMCAD X is a thermal simulation platform and 3D full-wave electromagnetic simulation based on the FEM and FDTD methods. It is applicable for multiple ranges of applications, such as medical implant device design, safety assessment, antenna design, EMI/EMC, and dosimetry. The procedure of research simulation by SEMCAD X is based on three methods, whereas setting up the model, configuring the model and interpreting the simulation results.

Besides that, SEMCAD X software is a highly specialized full-wave EMF solver used to design an HTP applicator, as well as to obtain the radiation distribution, which presents the EM energy penetration depth and its energy focus distance.

2.6 Summary of Chapter

In this chapter, three main components have been explained, which are microstrip antenna, MTM lens and water bolus. Based on the reviewed study, a microstrip is selected to be used in this research as it has provided good penetration depth on the treated tissue. Meanwhile, a rectangular SRR MTM has shown a good focus on heat distribution, as stated in **Table 2.7**. The comparison of CEM solvers also discussed in this chapter. Thus, a microstrip antenna and MTM lens integration can provide sufficient PD and control the FPD for different cancers stages and sizes

CHAPTER 3

RESEARCH METHODOLOGY

3.1 Introduction

In this section, a research plan, research approach, research type, research variables, research process and extracting method of SAR are presented accordingly in **Section 3.2** to **Section 3.7**. Besides, the design of experiments is also presented in **Section 3.8**.

3.2 Research Plan

The primary goal of this research is to investigate the suitable designs of MTM-SRR as microstrip typed HTP enhancement in each breast cancer stages. A summary of research plan is presented as in **Figure 3.1**.

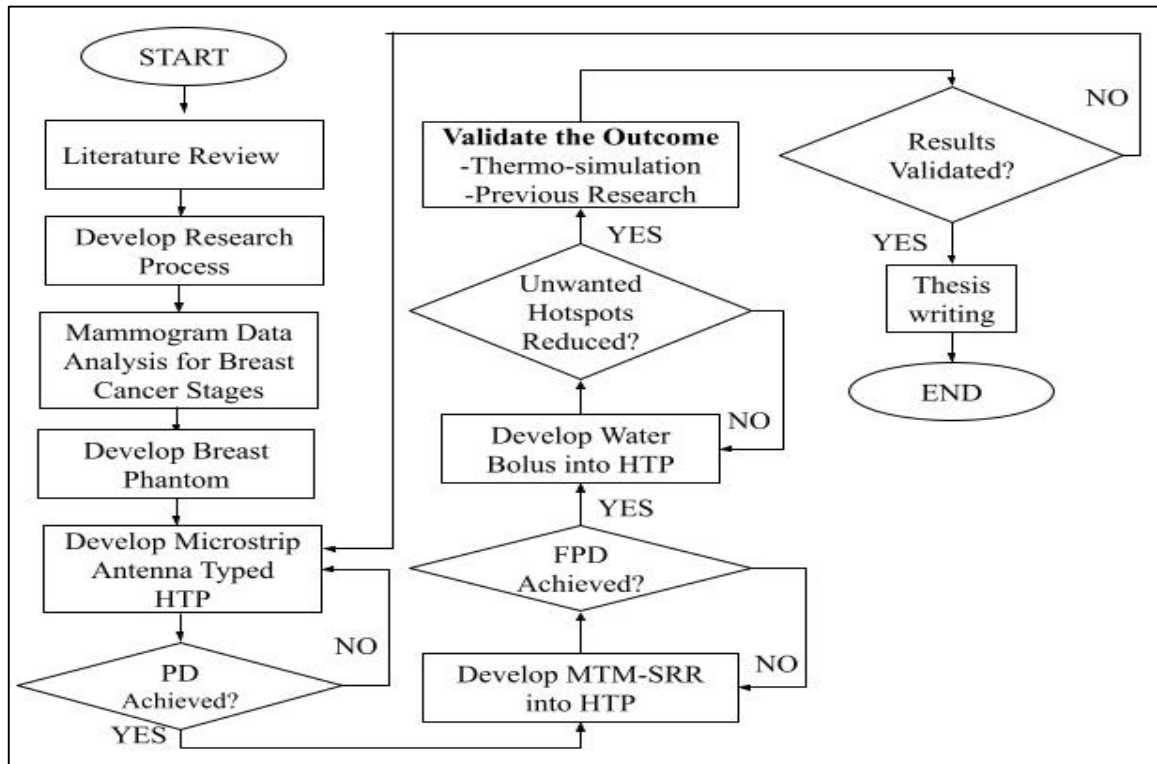


Figure 3.1: Summary of Research Plan

Based on **Figure 3.1**, this research started with literature reviewing of recent research trends of each component of HTP. This literature review process includes the overview of HTP in cancer treatment, antenna type, MTM and WB for HTP.

The next stage identifies the breast phantom and cancer size required with real patient data. The develop breast phantom simulates with microstrip antenna designed. The most suitable and performed designs for each cancer stage are further integrated with MTM-SRR lens and WB. Moreover, the final designs with MTM and WB are then validated with Thermo-simulation and compared the results with the previous research findings. Finally, a complete thesis is prepared.

The details of each research process and design of experiment involved are discussed in following sections of this chapter.

3.3 Research Approach

A quantitative experimental approach is used as the research approach for this research. According to Creswell, a quantitative experimental approach to determining a specific treatment affects an outcome. The researchers apply this approach to determine how different factors scored on the result (Creswell & Creswell, 2023).

Quantitative statistical data is involved when collecting patients' data. The data analysis is based on a breast cancer mammogram to identify the proposed focusing distance. The results of the data analysis are discussed in **Section 4.2**.

Moreover, this is a closed-ended experiment research. This simulation research is carried out to achieve the research objectives. In addition, enhancement of the current study is carried out in this research to improve the effectiveness of HTP.

3.4 Research Type

This research focuses on experimentation by simulation type of research. A simulation study is important as it is an initial step before further experiments are carried out. The simulation also allows concepts and ideas to be more easily verified, communicated, and understood. Therefore, the performance of the HTP applicator can be measured through this simulation study, and the resulting radiation distribution can be observed via the SAR measurement parameter.

The simulator software used in this experiment investigation is called SEMCAD X 14.8.4, which is produced by SPEAG. Details on SEMCAD X 14.8.4 are presented in the previous chapter, **Section 2.5** (Comparison of. CEM solvers).

3.5 Research Variables

In this research, there are three main research variables used. First is the independent variable, then the second variable is dependent, and the third variable is the intervening variable. Examples of independent variables for this research are microstrip antenna structure, MTM lens structure, water bolus structure and breast phantom design.

While the intervening variable of this research is the SAR, SAR provides the rate at which energy is absorbed by a human body when radiated to EM fields. As for dependent variables, two main measuring parameters are penetration depth and focus distance position.

3.6 Research Process

This research is divided into five phases, from the data collection to the validation process. The following are the five phases involved in the research:

Initial Phase: Patients' data collection, analysis and breast phantom development.

Phase 1: Microstrip antenna development under EM simulation environment

Phase 2: MTM lens development in focus distance position enhancement.

Phase 3: Water bolus development for reshaping EFS.

Phase 4: Validation by using thermo-simulation in SEMCAD X 14.8.4.

3.6.1 Initial Phase: Breast Phantom Development

Mammogram is an imaging method for screening breast cancer (Salimian et al., 2019). In this research, the breast phantom is constructed with the actual human breast cancer character parameters. This is obtained from the mammogram breast cancer images analysis collected from the referred hospital. **Sections 3.6.1.1, 3.6.1.2 and 3.6.1.3** present data collection, data analysis and breast phantom development, respectively.

3.6.1.1 Data Collections

Mammogram breast cancer images are obtained from one of the hospitals in Kuching, Sarawak. Before the collection can be made, ethical approval from the referred hospital is required to be attained. This procedure is important in order to uphold the research's ethics while practising the research with patient data.

Digital Imaging and Communications in Medicine (DICOM) software is used for data analysis. There are total of 57 images gathered, among the images there are 4, 10, 25 and 18 images for early stage, stage 1, stage 2 and stage 3 breast cancer mammogram respectively. The depth and size of the cancer tissue are measured and analysed with the provided software.

3.6.1.2 Data Analysis

After the mammogram breast cancer image is obtained, the images are categorized by two mammogram positioning views, which are known as medio-lateral oblique (MLO) and cranio-caudal (CC).

The CC and MLO represent the mammography positioning for the breast, where the CC is the upper view of the breast, while the MLO represents an oblique or angled view of the breast. The average surface depth (SD) and average inner depth (ID) of patients' data are analysed to obtain the targeted focus position distance and penetration for the proposed HTP. The details of the calculation to attain the SD and ID are presented in Appendix B. Meanwhile, one set of examples of MLO and CC is shown in **Figure 3.2**.

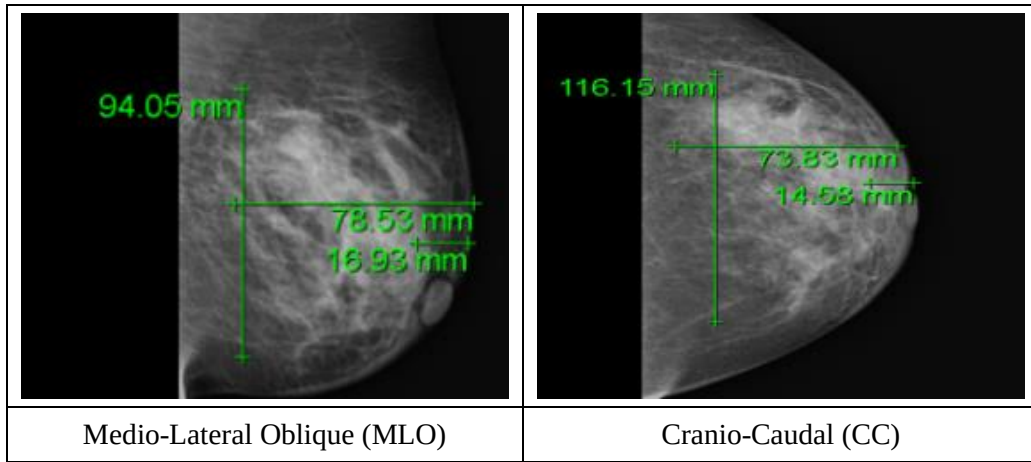


Figure 3.2: Mammogram positioning views; MLO and CC.

3.6.1.3 Development of Breast Phantom

The microstrip antenna with 915MHz and 2450MHz and breast phantom of different breast cancer stages are modelled with SEMCAD X 14.8.4. A few parameters are required to be set in SEMCAD X before the simulation is run.

Table 3.1 shows permittivity (ϵ), electrical conductivity (EC, S/m) and specific heat capacity (c , J/kg°C) of 915MHz and 2450MHz that are obtained from Gabriel Database build-in SEMCAD X, finding by Hussien et al. (Hussein et al., 2019) and typical heat properties, which is used in the bio-heat transfer (Leggio et al., 2015; Miaskowski & Gas, 2023).

Table 3.1: Electrical and Thermal Properties of Elements Used

Elements	915MHz	2450MHz
Substrate (RO4350)		
Permittivity, ϵ	3.48	3.48
Electrical conductivity, S/m	0.00077	0.00077
Specific heat capacity, $J/kg^{\circ}C$	1×10^{-12}	1×10^{-12}
Patch Copper		
Permittivity, ϵ	1	1
Electrical conductivity, S/m	5.813×10^7	5.813×10^7
Specific heat capacity, $J/kg^{\circ}C$	1×10^{-12}	1×10^{-12}
Breast Tissue		
Permittivity, ϵ	3.11433	3.24886
Electrical conductivity, S/m	0.88985	0.80329
Specific heat capacity, $J/kg^{\circ}C$	3550	3550
Cancer Tissue		
Permittivity, ϵ	74.45	72.81
Electrical conductivity, S/m	1.88	2.72
Specific heat capacity, $J/kg^{\circ}C$	3510	3510

The operating power and mass of SAR average over the cube controlled at 10W and 1g during the simulation. The distance between the antenna and the breast phantom is fixed at 0mm, which means it is directly in contact with the skin.

3.6.2 Phase 1: Microstrip Antenna Development

As mentioned in **Section 2.2.2**, a microstrip antenna is chosen in this research due to its characteristics and is frequently used in HTP research. There are many types of microstrip antenna, but this research has emphasized the development of a rectangular shape as this shape is easier to manipulate under different frequencies.

The rectangular antenna is developed with SEMCAD X 14.8.4 to obtain the SAR distributions, which are then to be compared and analysed. Any rectangular microstrip antenna design that reaches the required EM energy penetration depth, which is basically up to 50mm and also has a good focus position distance, is selected to be modified further.

A microstrip antenna depends significantly on the frequency used. Based on a previous study (V. Singh, 2015), the relationship between the size and frequency can be observed and referred to as in the following equations. **Equations 3.1 to 3.7** provide the formula used for rectangular-shaped microstrip antenna design (V. Singh, 2015).

The width of the rectangular-shaped microstrip antenna, W is obtained by **Equation 3.1**, where C_o , f_o , and ϵ_r represent the speed of light, fundamental frequency applied and permittivity of the substrate, respectively.

$$W = \frac{C_o}{2f_o\sqrt{(\epsilon_r + 1)/2}} \quad \text{Equation 3.1}$$

The effective permittivity depends on the width, W , which is obtained from the thickness of the substrate used, h .

$$\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2} \left[\frac{1}{\sqrt{1 + \frac{12h}{w}}} \right] \quad \text{Equation 3.2}$$

The effective length of the microstrip antenna is calculated as in **Equation 3.3**. It is to obtain the actual length of the antenna as shown in **Equation 3.5** with identified ΔL , which represents the fringing effect. Then, L_{eff} and ε_{eff} are different because of the radiation of the EM wave at the outside of the strip.

$$L_{eff} = \frac{Co}{2f_o\sqrt{\varepsilon_{eff}}} \quad \text{Equation 3.3}$$

$$\Delta L = 0.412 \frac{(\varepsilon_{eff} + 0.3)(\frac{w}{h} + 0.268)}{(\varepsilon_{eff} - 0.258)(\frac{w}{h} + 0.8)} \quad \text{Equation 3.4}$$

$$L = L_{eff} - 2\Delta L \quad \text{Equation 3.5}$$

The length and width of a ground plate of the rectangular antenna are calculated with **Equation 3.6** and **3.7**, respectively.

$$Lg = 6h + L \quad \text{Equation 3.6}$$

$$Wg = 6h + W \quad \text{Equation 3.7}$$

Previous experimental results showed that, 915MHz and 2450MHz antenna are suitable for HTP in breast cancer as location of breast is near to the human skin which is located at approximately 20mm until 80mm from the human skin (Kok et al., 2020; Naimullah et al., 2022). Therefore, 915MHz and 2450MHz are selected as operating frequency in this research as they are the commonly used HTP frequency under Industrial, Scientific, and Medical band (Jha et. al., 2016).

3.6.3 Phase 2: Metamaterial Lens Development

The enhancement investigation of the EM energy focus position distance towards the treated area tissue is carried out by integrating an MTM lens into the modified

microstrip antenna. As mentioned in **Section 2.3**, moving the microwave sources with respect to the MTM lenses based on the cancer position can affect the concentration of heating within the biological tissue.

Based on Y Gong, H. Wang, and G. Wang, the distance of metamaterials is considered in **Figure 3.3**.

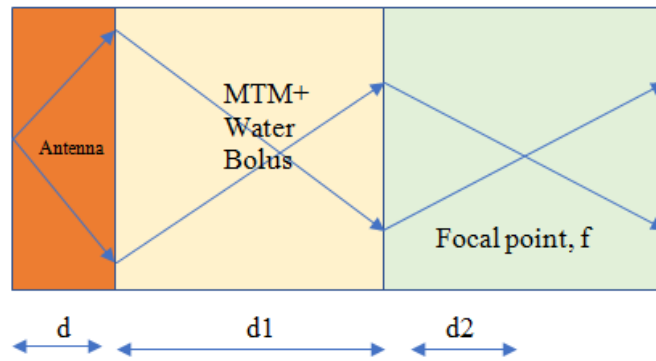


Figure 3.3: Relations of Metamaterials Lens to Focal Length

The distance between the antenna and metamaterial is required to take into account for obtaining the most suitable frequency (Yu et al., 2008). Therefore, the range between the antenna and breast phantom is at least bigger than the width of the metamaterial and water bolus.

According to David Vrba et al., the design of metamaterial can be determined as **Equation 3.8** and **3.9** in order to obtain the maximum height, width and thickness of the MTM lens (Vrba et al., 2016).

$$\lambda = \frac{c}{f} \quad \text{Equation 3.8}$$

$$h = \frac{1}{10\lambda} ; w = \frac{1}{3\lambda} ; d = \frac{1}{10\lambda} \quad \text{Equation 3.9}$$

Whereas c , f , h , w and d are represented as wavelength, speed of light, operating frequency, height, weight, and thickness of the MTM lens.

Currently, two MTM structures that are used the most are called electrical dipoles or thin wires array and the magnetic loops or split-ring resonators array (Wojciech & Thanh, 2019).

The thin wires array (**Figure 3.4(a)**) is also known as epsilon-negative (ENG) MTM or artificial magnetic conductors (AMCs). Through the parallel configuration of thin metallic wire mesh, it exhibits high-pass properties for the incoming plane wave. The wires are parallel with the electric field to perform a negative effect of permittivity below the plasma frequency. The wire can be made of silver, gold, aluminium or copper (Wojciech & Thanh, 2019).

While for split-ring resonators (SRR) (**Figure 3.4 (b)**), it is one of the most used structures to design mu-negative (MNG) MTM or artificial magnetic materials (AMMs). SRR cell, which is consisted of two concentric metallic rings (can be square or circle) formed an array structure by a specific gap, d . The gap between the inner and outer ring performs the capacitor properties, while each ring provides the inductors properties. Thus, the integration of the two rings forms an LC resonance circuit and thus performs a negative effect of permittivity (Leila & Omar, 2010; Wojciech & Thanh, 2019).

When ENG and MNG MTM are combined, this produces a double-negative (DNG) material (**Figure 3.4 (c)**), which is known as a negative refractive index (NRI) material. It contributes to the negative permittivity effect from the wire array and the negative permeability of the SRR array (Wojciech & Thanh, 2019).

DNG metamaterials are frequency-dependent, which results in the refractive index n . This is based on Drude-Lorentz models, which are indicated in **Equations 3.10, 3.11 and 3.12** (Wojciech & Thanh, 2019).

$$n \equiv n_{eff}(\omega) = \sqrt{\varepsilon_{eff}(\omega)\mu_{eff}(\omega)} \quad \text{Equation 3.10}$$

$$\varepsilon_{eff}(\omega) = 1 - \frac{\omega_{ep}^2 - \omega_{e0}^2}{\omega^2 - \omega_{e0}^2 - j\omega\gamma_c} \quad \text{Equation 3.11}$$

$$\mu_{eff}(\omega) = 1 - \frac{F\omega^2}{\omega^2 - \omega_{m0}^2 - j\omega\Gamma} \quad \text{Equation 3.12}$$

Where $\varepsilon_{eff}(\omega)$, $\mu_{eff}(\omega)$, ω_{ep} , ω_{mp} , ω_{e0} , ω_{m0} , γ_c , F and Γ are frequency-dependent effective permittivity, frequency-dependent effective permeability, electric plasma frequency, magnetic plasma frequencies, electric resonant frequency, magnetic resonant frequency, collision frequency, amplitude factor and damping factor, respectively.

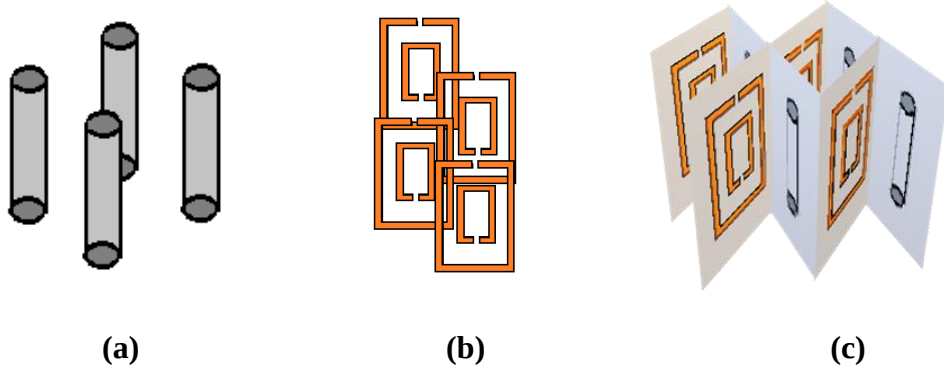


Figure 3.4: (a) ENG, (b) MNG and (c) DNG structure

One of the AMCs or AMMs applications is integrated metamaterials as the loading of the antenna (Liu et al., 2013). This research applies MTM as loading in the form of an SRR array to investigate its efficacy in HTP improvement, especially in terms of focus position distance for treated cancer tissue. The shape of the SRR is referred to Leila and Omar (2010), Wojciech and Thanh (2019) designs.

In Leila and Omar (2010) research, they found that a $\lambda/46$ MTM-SRR can attained lower frequency resonance, higher negative permeability properties and better wave propagation when compared with $\lambda/23$ sized SRR. Thus, this research is made the $\lambda/46$ sized SRR with a variation of $\lambda/34$ sized SRR and comparing their performance in HTP.

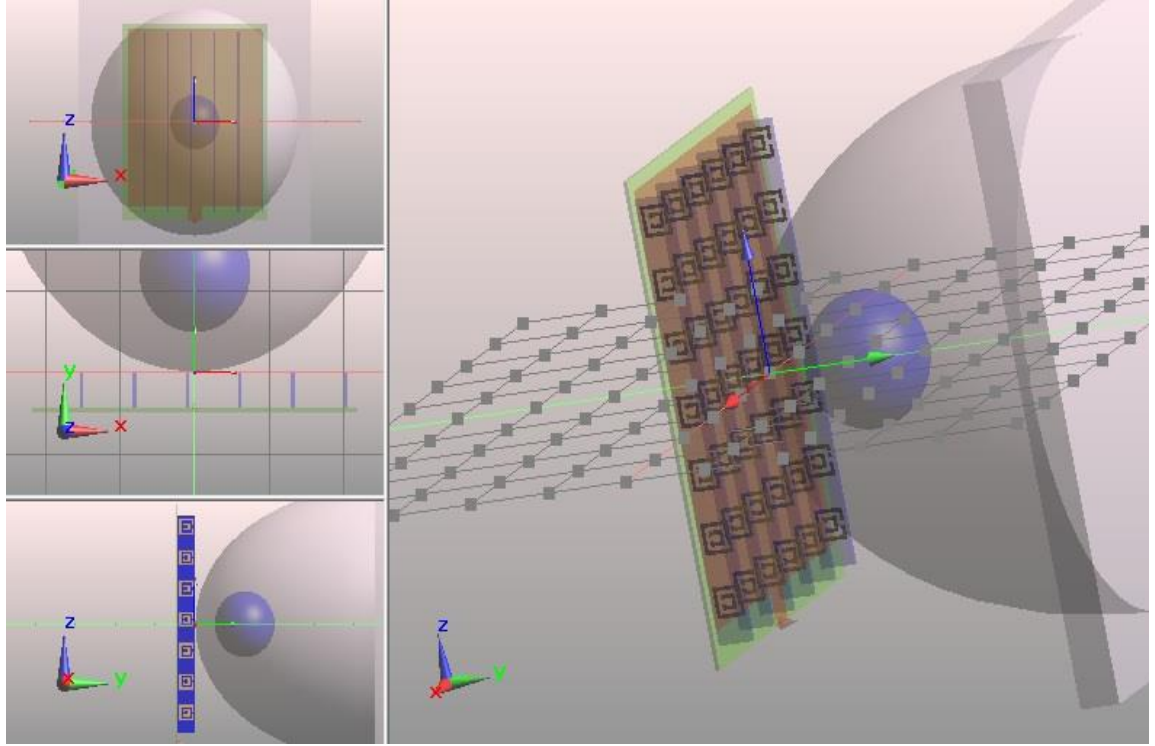


Figure 3.5: Development of MTM as Loading into HTP ($\lambda/46$, $D_0 = 1.2L_1$)

The MTM as loading or SRR array will be attached close to the surface of the selected antenna design, as shown in **Figure 3.5**.

3.6.3.1 Proved the MTM Designs by Retrieving Negative Electrical Properties

As mentioned in **Section 3.6.3**, split-ring resonators (**Figure 3.4(b)**) is one of the most used structures to design mu-negative (MNG) MTM or artificial magnetic materials (AMMs). In order to prove the development of MTM cells in this research showed negative permeability electrical properties, several calculations are applied.

According to (Orfanidis, 2016; Smith et al., 2005), a linear two-port network can be modelled into an equivalent circuit parameter, including the transfer matrix, impedance matrix, admittance matrix, and scattering matrix when retrieving negative electrical properties are required. **Figure 3.6** presents an equivalent circuit with its matrix parameter.

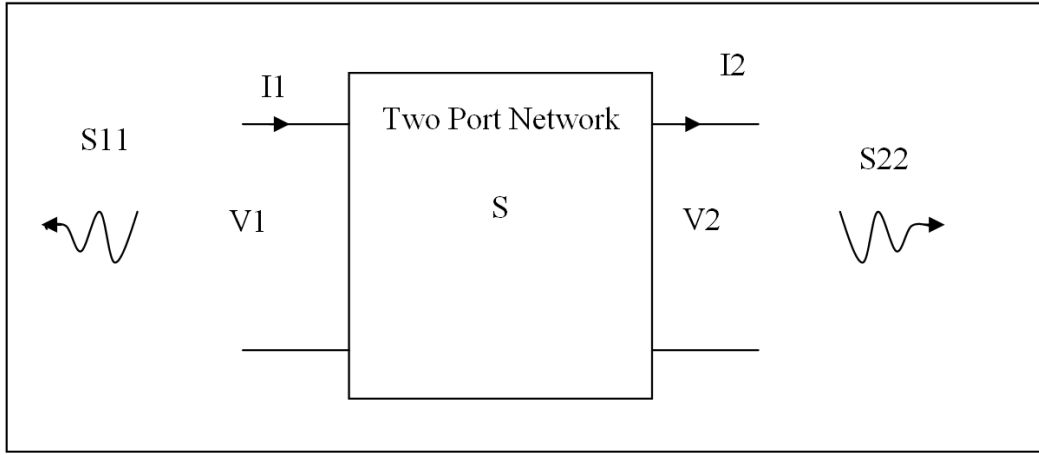


Figure 3.6: Equivalent circuit in S-Parameter

S_{11} , S_{22} , I_1 , I_2 , V_1 and V_2 in **Figure 3.6** represented the reflection coefficients of port 1, reflection coefficients of port 2, current supply in port 1, current supply in port 2, voltage port 1 and voltage port 2, respectively.

Based on (Orfanidis, 2016), the transfer matrix, or T matrix, relates the voltage and current at port 1 to those at port 2 (**Equation 3.13**), while the impedance matrix (Z matrix) relates the voltages and current with ohmic's law (**Equation 3.14**).

$$\begin{bmatrix} V_1 \\ I_1 \end{bmatrix} = [T] \begin{bmatrix} V_2 \\ I_2 \end{bmatrix} \quad \text{Equation 3.13}$$

$$\begin{bmatrix} V_1 \\ V_2 \end{bmatrix} = [Z] \begin{bmatrix} I_1 \\ I_2 \end{bmatrix} \quad \text{Equation 3.14}$$

The incoming waves and out-coming waves for port 1 (a_1 , b_1) and port 2 (a_2 , b_2) can be written as a scattering matrix with S_{11} , S_{22} and S_{21} , S_{12} , the transmission coefficients (S -Parameter).

$$\begin{bmatrix} b_1 \\ b_2 \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \end{bmatrix} \quad \text{Equation 3.15}$$

From the transient response of terminated line formula, the incoming and outcoming wave can be justified as **Equations 3.16** and **3.17**, and thus, a_1 , a_2 , b_1 and b_2 (travelling waves) can be calculated by solving **Equations 3.13**, **3.14**, (Orfanidis, 2016).

$$V1 = \sqrt{Z_0}(a1 + b1); V2 = \sqrt{Z_0}(a2 + b2) \quad \text{Equation 3.16}$$

$$I1 = \frac{1}{\sqrt{Z_0}}(a1 - b1); V2 = \frac{1}{\sqrt{Z_0}}(b2 - a2) \quad \text{Equation 3.17}$$

$$\begin{aligned} a_1 &= \frac{V_1 + Z_0 I_1}{2\sqrt{Z_0}} & a_2 &= \frac{V_2 - Z_0 I_2}{2\sqrt{Z_0}} \\ b_1 &= \frac{V_1 - Z_0 I_1}{2\sqrt{Z_0}} & b_2 &= \frac{V_2 + Z_0 I_2}{2\sqrt{Z_0}} \end{aligned} \quad \text{Equation 3.18}$$

Z_0 is referred to as antenna impedance which is commonly used as 50 ohms.

Equation 3.18 are future solved with **Equation 3.15** and obtained equation below.

$$\begin{aligned} b_1 &= S_{11}a_1 + S_{12}a_2 \\ b_2 &= S_{21}a_1 + S_{22}a_2 \end{aligned} \quad \text{Equation 3.19}$$

The S-parameter obtained from **Equation 3.15** will be future used to calculate the T-matrix of the antenna. According to (Smith et al., 2005) and (Pozar, 2012), by solving **Equation 3.19** into **Equation 3.16** and **Equation 3.13**, the transfer matrix for a transmission line has the analytic equation as below. The detailed derivation of the equation can be referred to (Pozar, 2012).

$$T_{11} = \frac{(1 + S_{11})(1 - S_{22}) + S_{21}S_{12}}{2S_{21}} \quad \text{Equation 3.20}$$

$$T_{12} = \frac{(1 + S_{11})(1 + S_{22}) - S_{21}S_{12}}{2S_{21}} \quad \text{Equation 3.21}$$

$$T_{21} = \frac{(1 - S_{11})(1 - S_{22}) - S_{21}S_{12}}{2S_{21}} \quad \text{Equation 3.22}$$

$$T_{22} = \frac{(1 - S_{11})(1 + S_{22}) + S_{21}S_{12}}{2S_{21}} \quad \text{Equation 3.23}$$

Smith et al. (2005) mentioned that the magnetic field could be calculated into the reduced magnetic field, which was suggested by (Pendry, 2000) with the optical path

theory ($\omega = \alpha d = nkd$), where ω , n , k , d represented wavelength, refractive index, wave vector and slab thickness.

$$\cos(\alpha d) = \frac{1 - S_{11}S_{22} + S_{21}^2}{2S_{21}} \quad \text{Equation 3.24}$$

Smith also derived the equation from calculating the relative impedance, Z_{red} , for inhomogeneous slabs such as SRR as **Equation 3.25**.

$$z_{red}^2 = \frac{T_{12}}{T_{21}} \quad \text{Equation 3.25}$$

The Z_{red} calculated will be needed for permittivity and permeability identification as **Equation 3.26** and **3.27**.

$$\mu_{av} = z_{av} n_{av} \quad \text{Equation 3.26}$$

$$\epsilon_{av} = \frac{n_{av}}{z_{av}} \quad \text{Equation 3.27}$$

However, Smith also warned in his research that an inhomogeneous periodic structure does not have a well-defined impedance, as the ratio of electric field and magnetic field would change throughout the structure. This change becomes negligible for very small unit cell sizes relative to the wavelength.

Besides, current research and knowledge were unable to define Z_{red} precisely, and this can cause the values of permittivity and permeability retrieved to be not generally assignable, although they can be applied in an artificial manner if the MTM is always to be located in the same location of the unit cell (Smith et al., 2005; Wojciech & Thanh, 2019).

3.6.4 Phase 3: Water Bolus Development

A water bolus is designed to provide a cooling condition effect. The water bolus is able to reduce the skin burn effects during HTP treatment execution. Distilled water is used as coolant fluid with ζ , ϵ_r , and ρ values of 5e-005, 76.7, and 1000, respectively.

The effects of water bolus on effective field size (EFS) are observed in this research. Although this research did not emphasised in water bolus development as mentioned in the Research Objectives which are focused on the antenna and MTM development. But the addition of water bolus is a must in HTP execution, primarily to provide a cooling environment as well as to reduce massive skin burn problems due to high heat applied to the skin.

Therefore, the water bolus developments are referred to the previous publication of our research team in the year 2022, which is the breast-shaped water bolus (**Figure 3.7**) (Lias et al., 2022). Compared with the previous publication, the only variation applied in this research is the thickness of the water bolus (2mm, 5mm and 10mm).

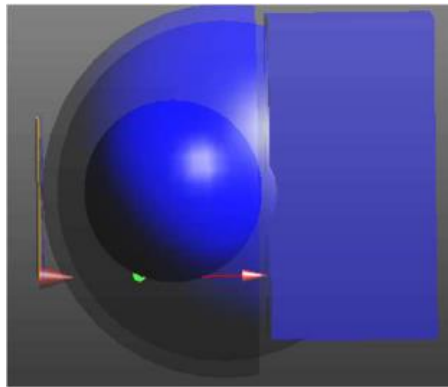


Figure 3.7: Breast-Shaped Water Bolus (Lias et al., 2022)

3.6.5 Phase 4: Validation with Thermo-Simulation Environment

Thermo-simulation in SEMCAD X can be used to validate the thermal distribution of the HTP designed. The thermo-simulation findings can reveal a good correlation

between the SAR and thermal distribution applied by the intended applicator to the tissue that has to be heated or treated. When the operating region is between 41 and 45 °C, the thermal distribution and temperature are drastically altered when the operating power is adjusted to a certain level.

As mentioned by (Kim et al., 2015), the bioheat-equation defines the temperature elevation with SAR, blood perfusion, and thermal conductivity and is expressed in **Equation 3.28**.

$$C\rho\frac{\partial T}{\partial t} + CbW(T - Tb) = k\nabla^2 T + \rho SAR \quad \text{Equation 3.28}$$

Where C , ρ and k represent specific heat capacity, mass density and thermal conductivity, respectively, while W is the blood perfusion rate with or without the indications of body materials characteristics, b .

3.6.6 EM Simulation Setting

The modified HTP model, which consists of breast phantom, breast cancer, microstrip antenna, MTM lens and water bolus, is designed as mentioned in **Section 3.6.1** to **3.6.4**. The properties of muscle and breast fat are determined by Gabriel Database, while the properties of metal and dielectric components are referred to as Material Database in the SEMCAD X software simulator (**Table 3.1**).

After the component's properties are determined, the HTP model is simulated under EM Simulation mode. The operating power of HTP is fixed for 1W, and two different operating frequencies (915MHz and 2450MHz) are investigated. The results are validated using Thermo-simulation in SEMCAD X to observe the heat transfer within treated tissues. **Figure 3.8** shows the experimentation set-up in SEMCAD X.

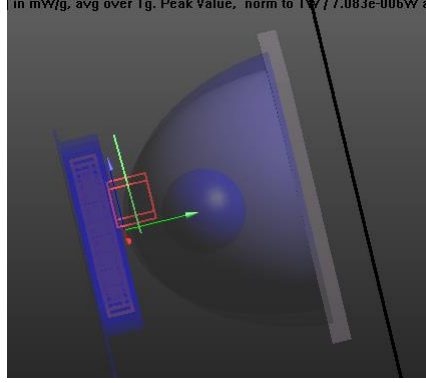


Figure 3.8: Example of HTP Experimentation Set-up

3.7 Extracting Results of SAR and Time Period Estimations (TPE)

SAR is a measurement for the rate of energy absorbed by biological tissues when radiated by radiofrequency (RF) or microwave (MW) EMF. Besides, SAR also determines the amount of power absorption per unit mass of a biological system under an EM field. SAR parameters are normally presented in units of milli-watts per gram (mW/g or W/kg) (Brizi et al., 2018; Chakaravarthi & Arunachalam, 2014; Lias et al., 2016).

According to the standard of the International Electrotechnical Commission (IEC) and Institute of Electrical and Electronics Engineers (IEEE), IEC/IEEE 62704-1, SAR can be calculated as **Equation 3.29**. When the electric field is considered, **Equation 3.30** is referred.

$$SAR = \frac{\delta}{\delta t} \left(\frac{\delta W}{\rho \delta V} \right) \quad \text{Equation 3.29}$$

$$SAR = \frac{\sigma E^2}{2\rho} \quad \text{Equation 3.30}$$

Moreover, the SAR is also can be written as **Equation 3.31** when temperature and period are considered.

$$SAR = \frac{c\Delta T}{\Delta t} \Big|_{t=0}, \quad \text{Equation 3.31}$$

W , t , V , E , ρ , T , σ and c stand for the energy absorbed (Watt), time taken (sec), the volume of the element (m^3), peak electric field vector (V/m), the density of element (kg/m^3), temperature ($^{\circ}\text{C}$), the conductivity of tissue (S/m) and specific heat capacity ($\text{J}/\text{kg}^{\circ}\text{C}$), respectively. According to **Table 3.1**, the c of cancer tissue is $3510 \text{ J}/\text{kg}^{\circ}\text{C}$.

The simulation is carried out using SEMCAD X 14.8.4 to obtain SAR distribution that is used to determine the penetration depth and focus position distance to the treated tissue. There are various colour regions represented in the SAR simulation, where the yellow colour shows the hottest area, and the dark blue colour represents the coldest area.

The contour of yellow colour is required at the cancerous breast tissue to ensure the temperature range for hyperthermia is reached and executed. An example of the colour range is represented in **Figure 3.9**.

Therefore, different modified HTP applicator SAR simulation results are then calculated as **Equation 3.31** to estimate the proper time periods in different cancer stages treatment as HTP required 41°C to 45°C heating.

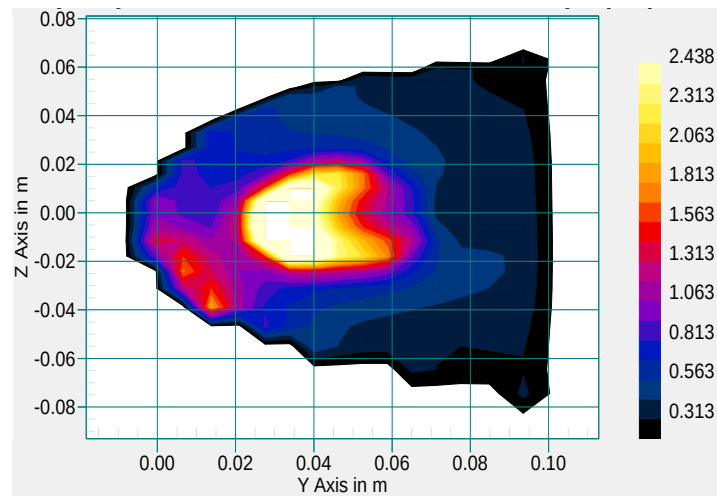


Figure 3.9: Colour Range in SAR Simulation

3.8 Design of Experiment (DoE)

In conjunction with Research Process in **Section 3.6**, a few DoEs are required to be performed to attain the outcomes for the stated Research Objectives in **Section 1.5**. Therefore, for this research, it has six (6) DoEs. **Figure 3.10** shows the summarization of the DoE.

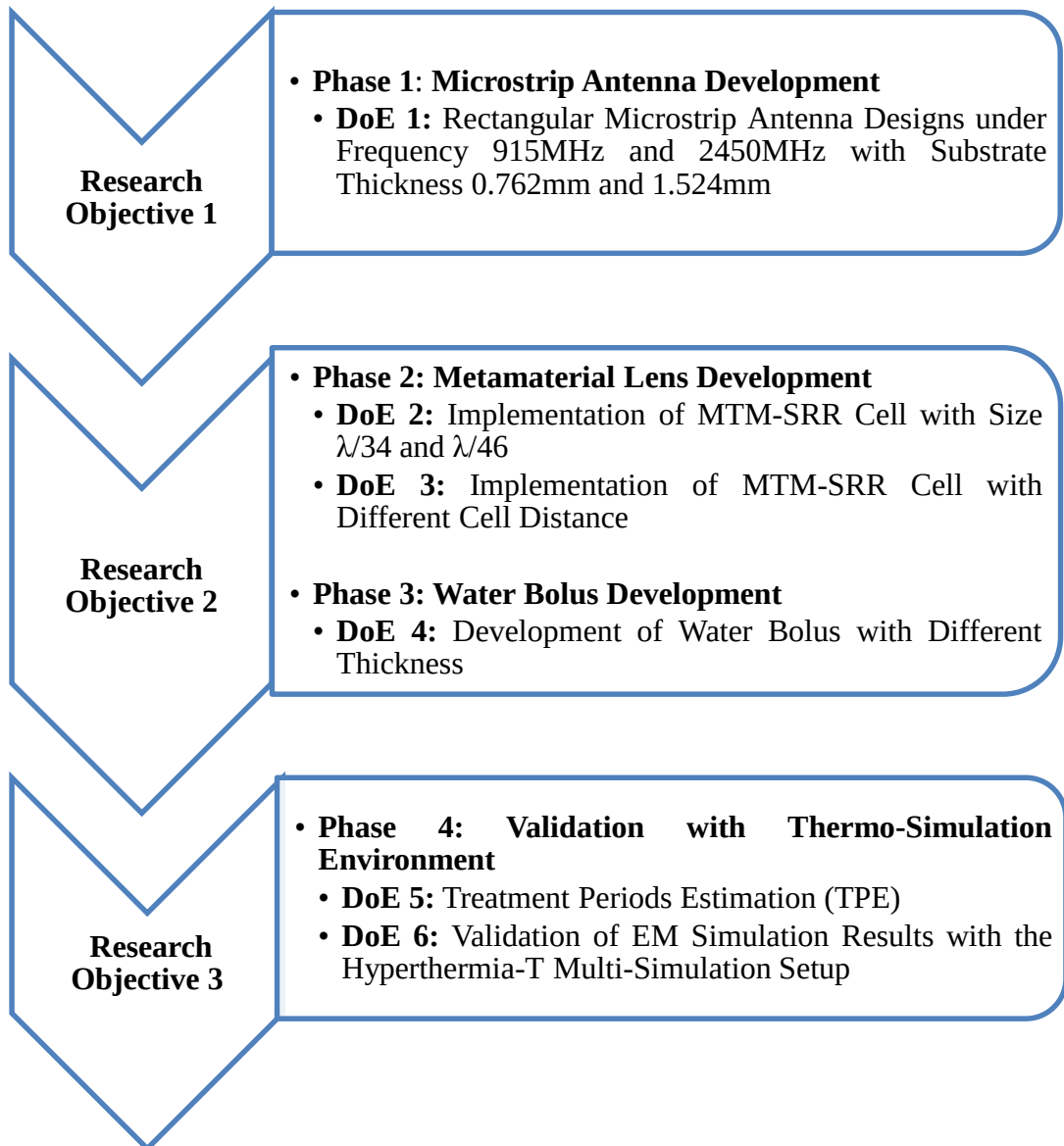


Figure 3.10: Summarization of the DoE

The first of DoE is to develop the most suitable microstrip antenna for different stages of breast cancer. The antennas are designed under two (2) operating frequencies, which are 915MHz and 2450MHz. In addition, this experiment also developed the antenna with substrate thicknesses of 0.762mm and 1.524mm

The second DoE involved the implementation of MTM-SRR cells with various sizes, which are $\lambda/34$ and $\lambda/46$. Then, it followed by the third DoE with different cell distances of MTM-SRR. In this stage, the MTM-SRR cell design with the most efficient effect in terms of FPD has been selected for the next experimentation stages.

The fourth DoE is the development of water bolus into HTP. The objective of this experiment is to design a suitable water bolus that is able to lower the unwanted hotspot and reshape the EFS of the treated area.

The next DoE involved the calculation of treatment periods. This is to avoid the HTP design unsuitable with the commonly used HTP treatment. This experiment retrieves the SAR value from the simulation results and is calculated with IEEE/IEC 62704 standard.

The last DoE is to validate the outcomes from DoE 4. Thermo-simulation is performed in SEMCAD X to attain the heat distribution on the treated tissue.

The details steps involved for all DoEs are shown in the flowchart **Figure 3.11** to **Figure 3.13**.

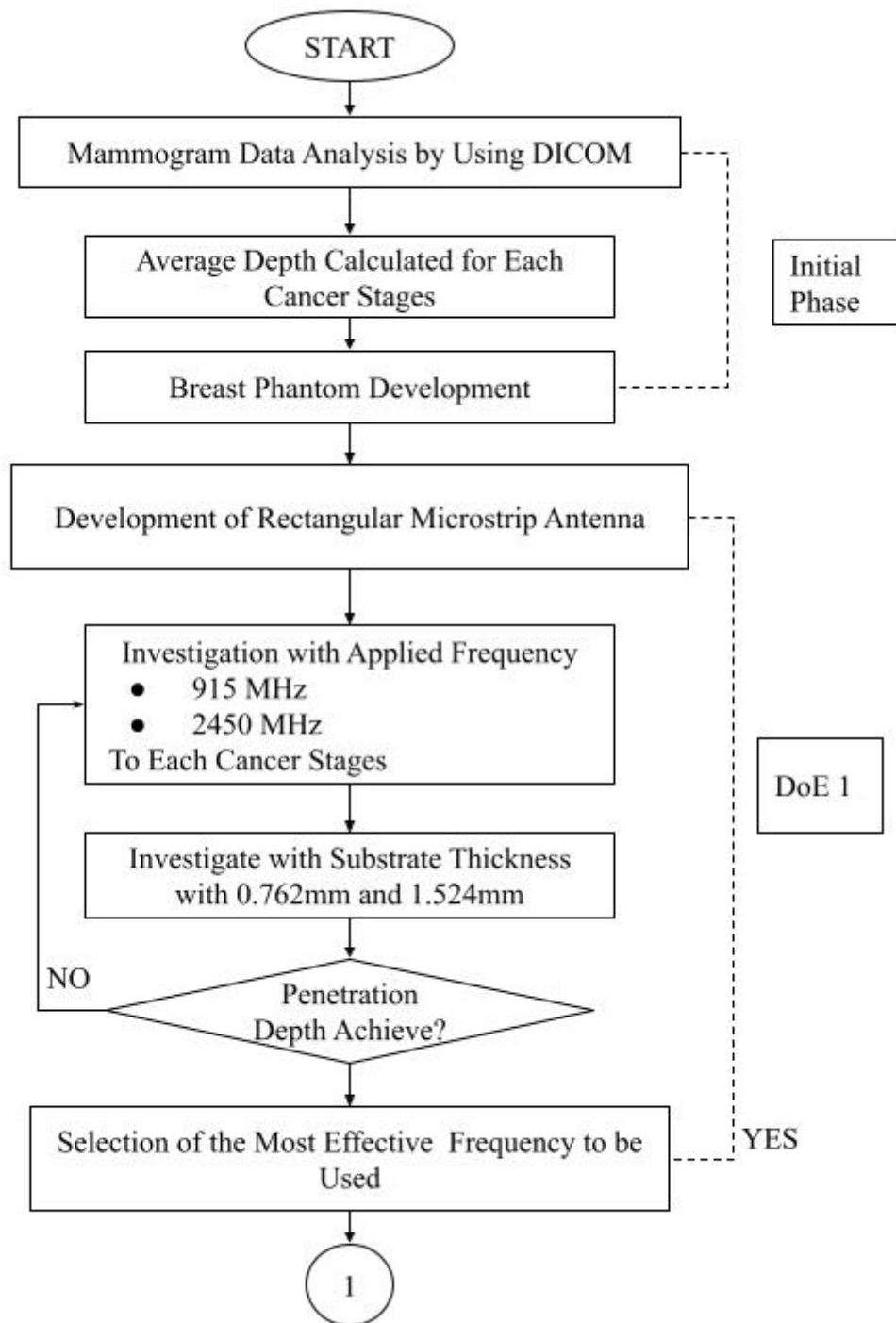


Figure 3.11: Initial Phase and DoE 1 of the Research

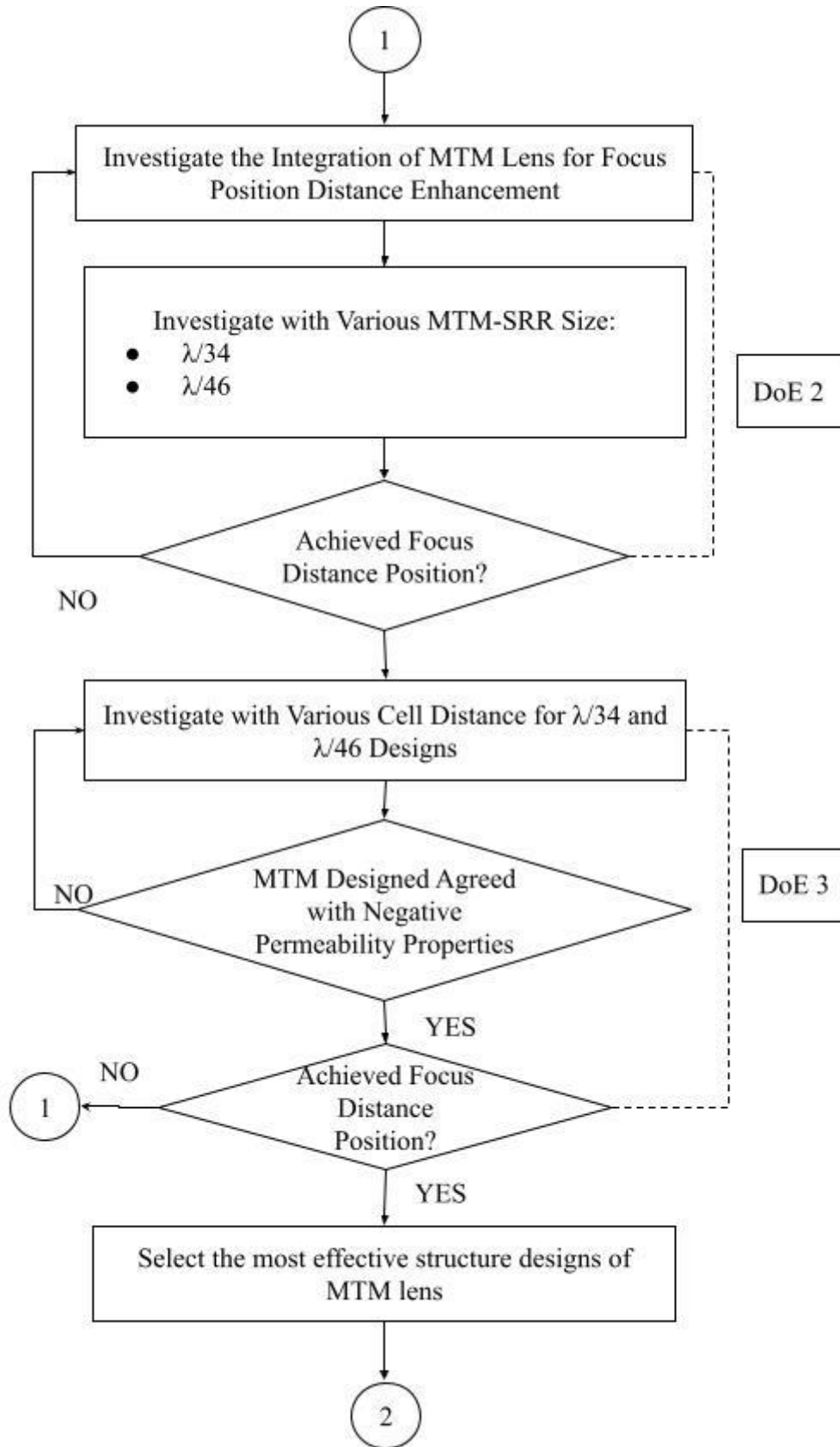


Figure 3.12: DoEs 2 and 3 of the Research

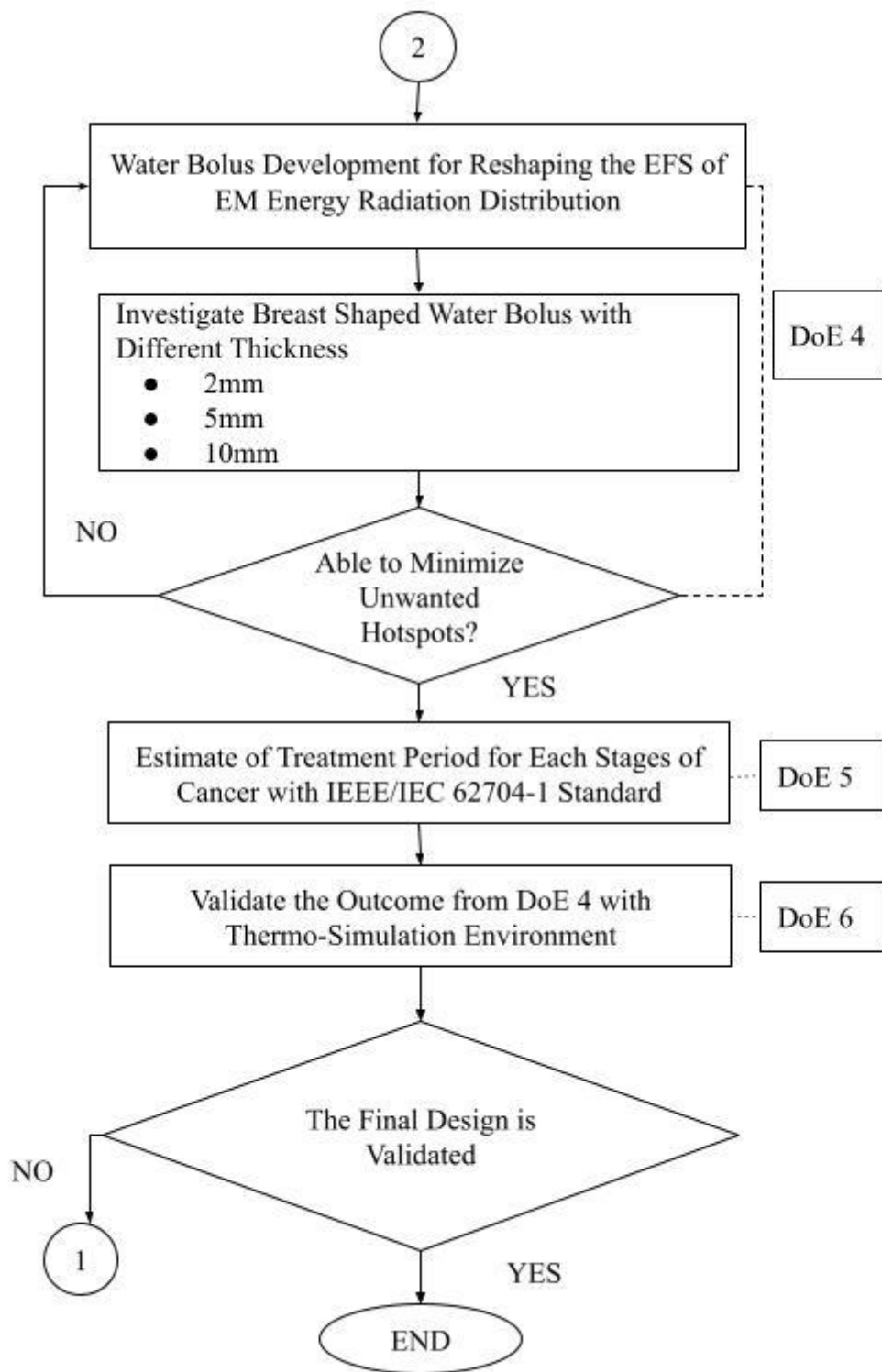


Figure 3.13: DoEs 4, 5 and 6 of the Research

3.8.1 DoE 1: Rectangular Microstrip Antenna Designs under Frequency 915 and 2450MHz with Substrate Thickness 0.762mm and 1.524mm

Table 3.2 presents the rectangular microstrip antenna sized with operating frequencies of 915MHz and 2450MHz which are calculated with **Equation 3.1 until 3.7 (Section 3.6.2)**. Meanwhile, **Figure 3.14** (a) and (b) show the modelling of the antenna with breast phantom under 915MHz and 2450MHz, respectively.

The thermal properties and electrical properties of materials used in antenna design are presented in **Table 3.1, Section 3.6.1.3** previously. The substrate thicknesses used for RO4350 are 0.762mm and 1.524mm, respectively, while the standard copper cladding used is 0.035 μ m, which are referred to RO4000 Series Datasheet by Rogers Corporation released in 2018 as in **Appendix C**.

Table 3.2: Rectangular Microstrip Antenna Designs Under Frequencies 915MHz and 2450MHz

Frequency, MHz	h, mm	W, mm	ϵ_{eff} , mm	L_{eff} , mm	ΔL , mm	L, mm	L_g , mm	W_g , mm
915	1.524	109.46	3.39	89.00	0.73	87.54	96.68	118.60
	0.762	109.46	3.43	88.44	0.37	87.70	92.28	114.03
2450	1.524	37.23	4.09	30.24	0.46	29.32	38.46	46.38
	0.762	37.23	4.22	29.77	0.46	28.84	33.41	41.81

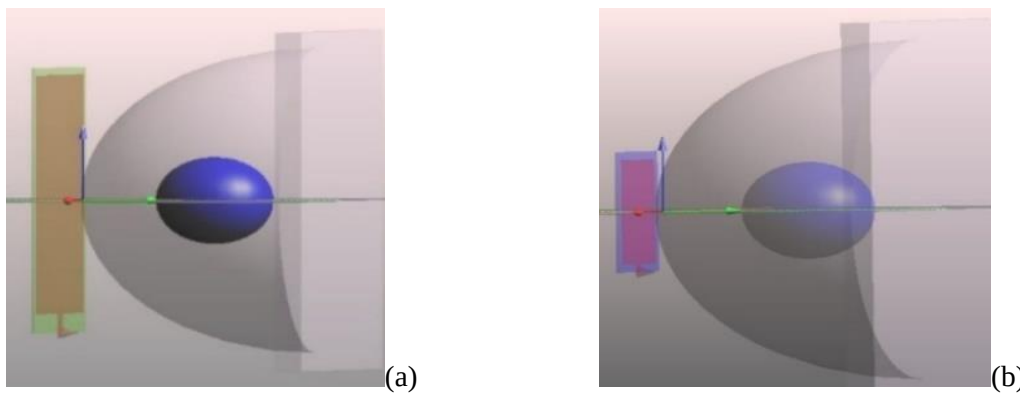


Figure 3.14: Modelling of microstrip antenna with breast phantom under (a) 915MHz and (b) 2450MHz

3.8.2 DoE 2: Implementation of MTM-SRR Cell with Size $\lambda/34$ and $\lambda/46$

As discussed in **Section 3.6.3**, the MTM design used in this research is the MTM-SRR cell. The SRR is investigated into two (2) different measurements, which are $\lambda/34$ and $\lambda/46$. The SRR unit cells design can be referred to as **Figure 3.15**, while detailed parameters are presented in **Table 3.3**.

The metal and substrate chosen for the unit cell are copper and Roger RO4350, respectively, with the same properties as antenna materials in **Table 3.1**. The initial distance, D_0 , between cells is designed as 2.1 times larger than the outermost layer, L_1 . **Table 3.4** shows the MTM-SRR design with each 915MHz and 2450MHz antenna.

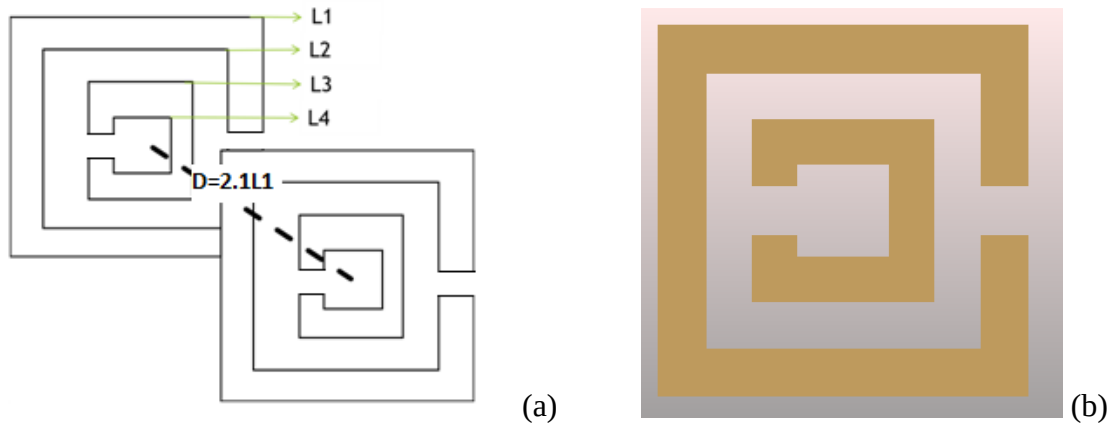
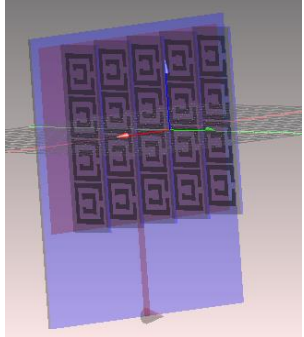
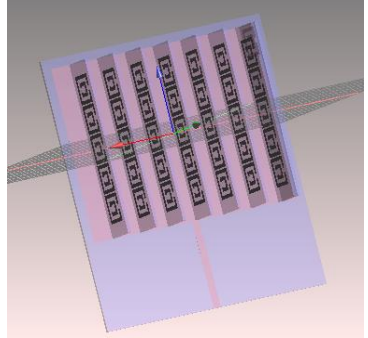
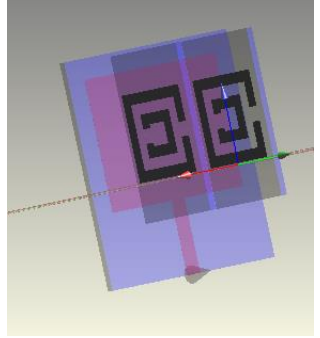
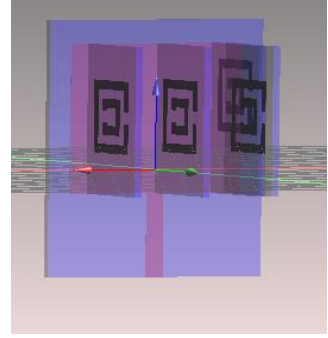


Figure 3.15: (a) Unit Cells Design (b) A SRR Unit Cell used in Simulation.

Table 3.3: Parameters of MTM as Loading Designs

SRR Size	$\lambda/34$	$\lambda/46$
Line 1, mm	9.63653	7.12265
Line 2, mm	7.22740	5.34199
Line 3, mm	4.81827	3.56133
Line 4, mm	2.40913	1.78066
D_0 , mm	20.23671	14.95757

Table 3.4: Visuals of MTM-SRR Cells

Designs Name	Diagrams
915MHz with $\lambda/34$ SRR	
915MHz with $\lambda/46$ SRR	
2450MHz with $\lambda/34$ SRR	
2450MHz with $\lambda/46$ SRR	

3.8.3 DoE 3: Implementation of MTM-SRR Cell with Different Cell Distance

In order to investigate the effect of MTM cell distance in HTP, the distance between cells is noted as D_0 , which is equal to the multiple of L_1 by 2.1 ($D_0 = 2.1L_1$). The MTM designs are further developed to investigate the effect of a number of unit cells toward its performance in HTP by multiplying the D_0 until it reaches the following limitations (i) and (ii), while the parameters of variation in unit cell number are stated in **Table 3.5**, while the visualised MTM-SRR cell designs are presented in **Table 3.6**.

- (i) 1.4 times D_0 ($nD_0, n=1.0, 1.2, 1.4$) or
- (ii) the cell sequence (column $\times$ rows) becomes at least 3×3 for 915MHz and 1×2 for 2450MHz when fitted into the width and length of the antenna patch (referred to **Table 3.2**).

Table 3.5: Variation in Unit Cells Number

Unit Cell Size	Applied Frequency, MHz	Variation	Distance Between Cell, D/mm	Number Of Cells (column $\times$ rows)
$\lambda/34$	915	1.0 D_0	20.2367	4×5
		1.2 D_0	24.2840	3×4
		1.4 D_0	28.3313	3×3
	2450	1.0 D_0	20.2367	1×2
$\lambda/46$	915	1.0 D_0	14.9575	5×7
		1.2 D_0	17.9490	4×6
		1.4 D_0	20.9406	4×5
	2450	1.0 D_0	14.9575	1×3
		1.2 D_0	17.9490	1×2

Table 3.6: Visuals of MTM-SRR Cells

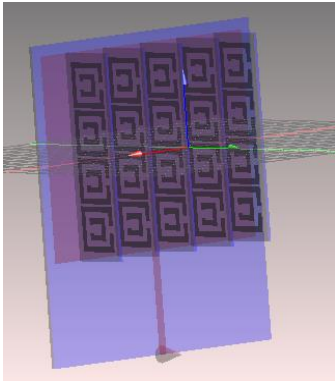
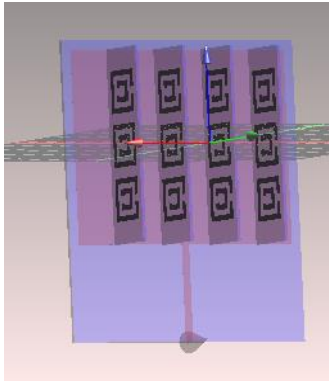
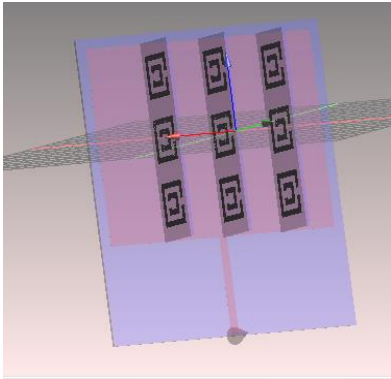
Designs Name	Diagrams
915MHz with $\lambda/34$ SRR and distance 1.0 D_0	
915MHz with $\lambda/34$ SRR and distance 1.2 D_0	
915MHz with $\lambda/34$ SRR and distance 1.4 D_0	

Table 3.6 continued

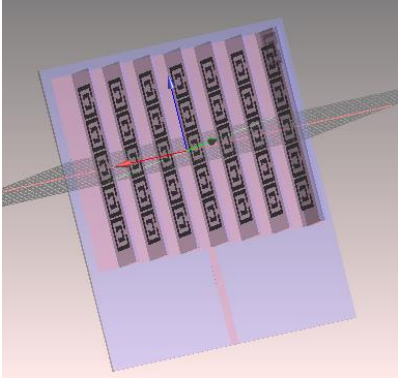
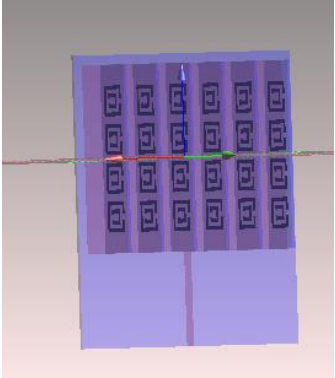
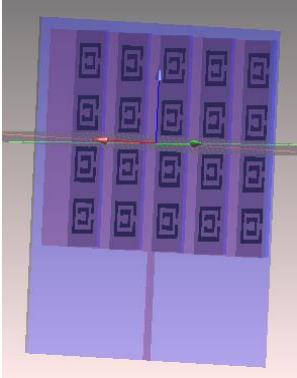
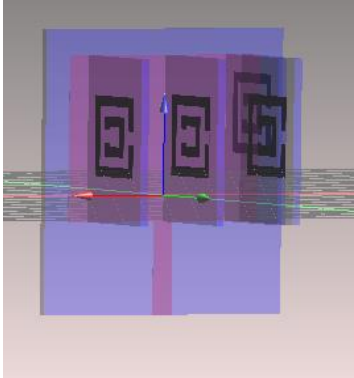
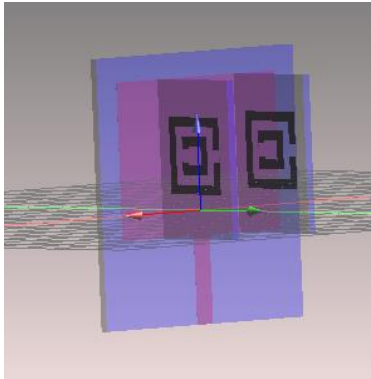
Designs Name	Diagrams
915MHz with $\lambda/46$ SRR and distance 1.0 D_0	 A 3D perspective view of a periodic structure. It consists of a blue rectangular base with a grid of square-shaped SRRs on top. The SRRs are arranged in a 4x4 grid. The structure is tilted slightly to the right. A red line and a green line are visible on the surface, possibly indicating a coordinate system or a specific path.
915MHz with $\lambda/46$ SRR and distance 1.2 D_0	 A 3D perspective view of a periodic structure, similar to the first one but with a different distance. It features a blue rectangular base with a grid of square-shaped SRRs. The structure is tilted slightly to the right. A red line and a green line are visible on the surface.
915MHz with $\lambda/46$ SRR and distance 1.4 D_0	 A 3D perspective view of a periodic structure, similar to the previous ones but with a different distance. It features a blue rectangular base with a grid of square-shaped SRRs. The structure is tilted slightly to the right. A red line and a green line are visible on the surface.

Table 3.6 continued

Designs Name	Diagrams
2450MHz with $\lambda/46$ SRR and distance $1.0 D_0$	
2450MHz with $\lambda/46$ SRR and distance $1.2 D_0$	

3.8.3.1 Proposed MTM Retrieving Negative Electrical Properties

In order to retrieve the value of the current supply in port 1, current supply in port 2, voltage port 1 and voltage port 2 for calculations of **Equation 3.13 until Equation 3.27**, as discussed in **Section 3.6.3.1**, the voltage sensor port 1 and 2 are inserted into the centre of MTM lens as **Figure 3.16** to obtain the V_1 , V_2 , I_1 and I_2 .

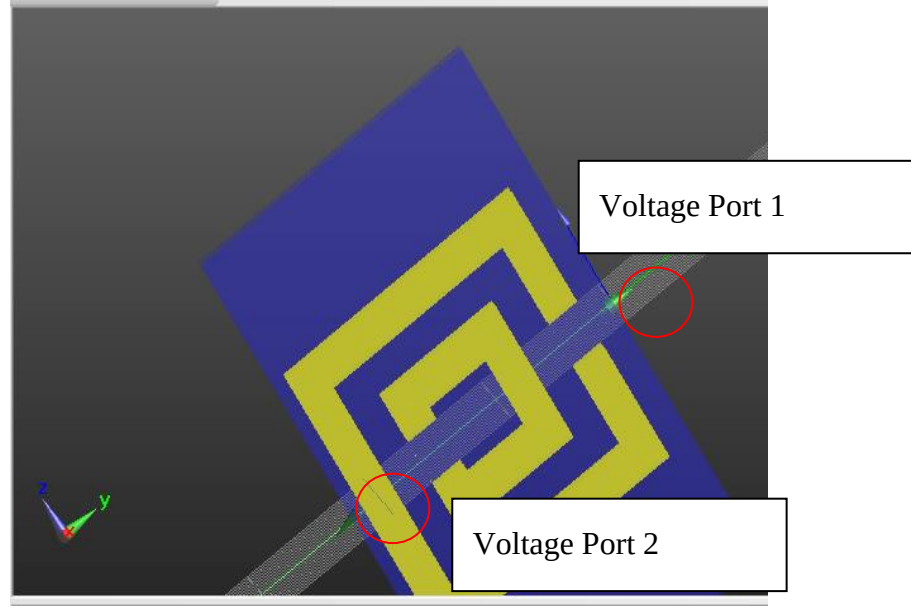


Figure 3.16: Illustration of the Location of the Voltage Port

Then, the values of V_1 , V_2 , I_1 and I_2 are recorded through the simulation of $I(f_0)$ and $U(f_0)$ for each voltage sensor in SEMCAD X.

3.8.4 DoE 4: Development of Water Bolus with Different Thickness

As discussed in **Section 3.6.4**, the water bolus (WB) developments are referred to in the previous publication of our research team in the year 2022, which is the breast-shaped WB. Three variations which are 2mm, 5mm and 10mm WB are developed and investigated its effectiveness in reducing the unwanted hotspot of HTP treatment. **Figures 3.17, 3.18 and 3.19** showed the designs of WB used.

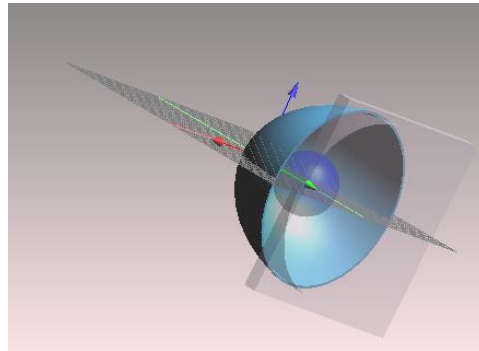


Figure 3.17: WB with 2mm Thickness

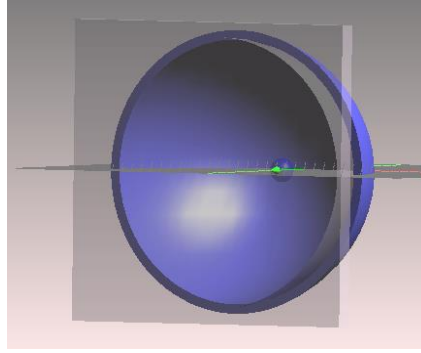


Figure 3.18: WB with 5mm Thickness

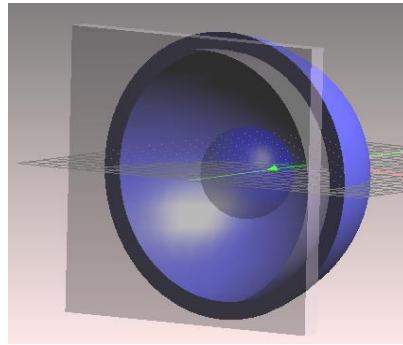


Figure 3.19: WB with 10mm Thickness

3.8.5 DoE 5: Treatment Periods Estimation (TPE)

The TPE was one of the major concerns when researchers investigated the FPD of HTP. To obtain a suitable relationship between FPD, TPE and SAR, SEMCAD X provided a function for the user to observe the heat pattern under the same simulation setting and model design with different target SAR values.

As discussed in **Section 3.7**, SAR is a measurement of the rate of energy absorbed by biological tissues when radiated by radiofrequency (RF) or microwave (MW) EMF. In SEMCAD X, the user can adjust the scale of SAR within the radiated tissue to observe the suitable SAR concentration for the heated region. **Figure 3.20** shows simulated results for 915MHz HTP with 1.524mm antenna thickness for the stage 2 breast cancer model under different SAR value observations.

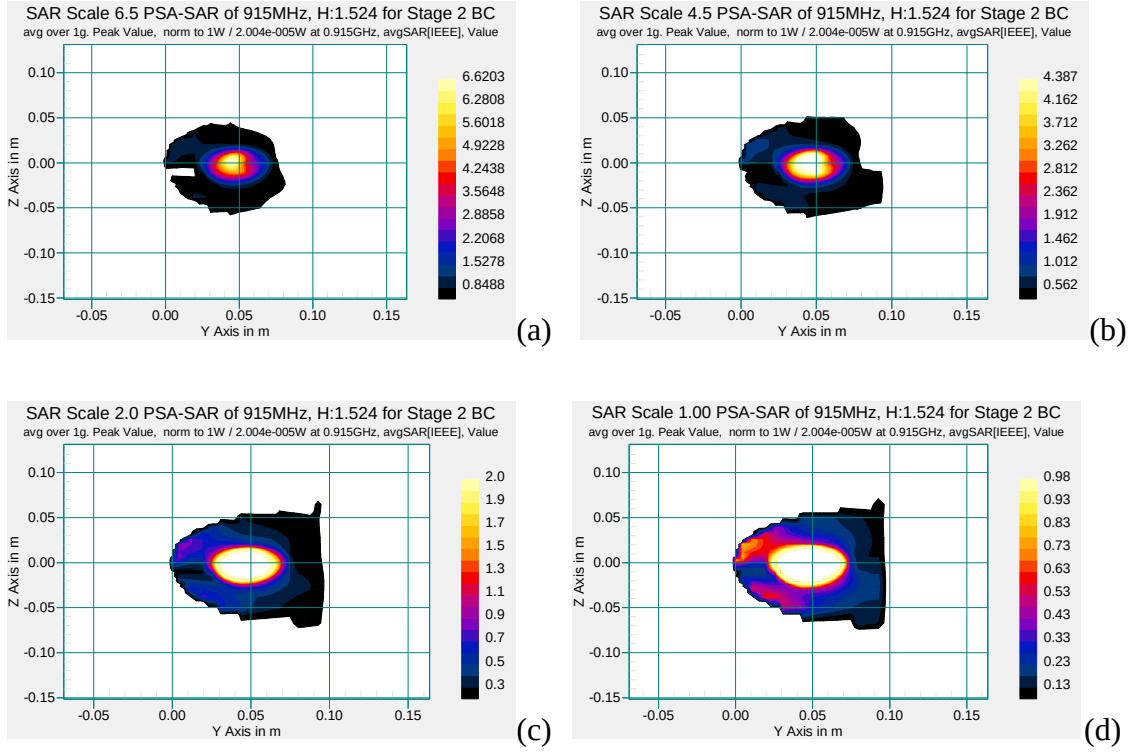


Figure 3.20: The Differences of HTP Results (915MHz, $TH=1.524$ mm) for Stage 2 Breast Cancer Under Different SAR Reading Scale [mW/g]: (a) 6.63, (b) 4.5, (c) 2.0 and (d) 1.0

As shown in **Figure 3.20**, by using a different scale of SAR, the heated regions are significantly different for **Figure 3.20** (a), (b), (c) and (d). Thus, after the simulation, the scale is adjusted until the heated region reaches the targeted PD and FPD. In this case, **Figure 3.20** (c) result is chosen as the heated region covered cancer while no excessively heated area in healthy tissue as shown in **Figure 3.20** (d).

Besides that, the SAR value chosen must follow the common treatment periods used by current research trends, which is mentioned in Behrouzkia (2016), that 60 to 360 minutes are required to reach 41°C until 45°C by using HTP. Therefore, the SAR value will be controlled between 1.3mW/g and 7.8mW/g as calculated with **Equation 3.31** (Section 3.7).

3.8.6 DoE 6: Validation of EM Simulation Results with the Hyperthermia-T-Multi-Simulation Setup

The SAR distributions, which are obtained through the EM-simulation tool with the SEMCAD X 14.8.4, are also validated with the hyperthermia simulation tool of SEMCAD X 14.8.4. The final designed or modified HTPs are simulated under the "Hyperthermia-T-Multi-Simulation Setup", where T-Multi-Simulation stands for Thermo-multi-simulation. The Thermo-Simulation uses the Penne Bio-heat model and bio-heat equation approach. Both EM and Thermo-Simulations are results in SAR distributions and compared for the validation process.

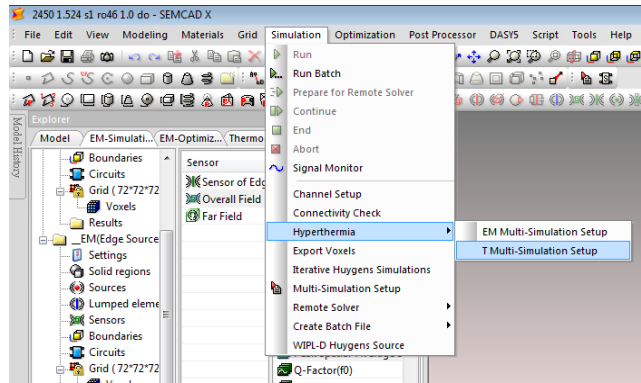


Figure 3.21: T-Multi-Simulation Setup in SEMCAD X

3.9 Summary of Chapter

In conclusion, for this chapter, this quantitative approach research is mainly simulation-based research by using SEMCAD X software to achieve the Research Objectives mentioned in Chapter 1.

There are five phases of research involved, which are the Initial Phase: Design Process of Breast Phantom, Phase 1: Microstrip Antenna Development, Phase 2: Metamaterial Lens Development, Phase 3: Water Bolus Development and Phase 4: Validation with Thermo-Simulation Environment. In addition, six (6) experiments or DoEs are conducted to achieve the stated Research Objectives in **Section 1.5**.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

This chapter presents and discusses the results, which are based on six (6) DoEs in Chapter 3.

4.2 Initial Phase: Average Breast Cancer Size Analysis

Mammogram is an imaging method for screening breast cancer (Salimian et al., 2019). Fifty-seven mammogram breast cancer images are gathered from one of the General Hospitals in Malaysia. As the details of the hospital and raw data are confidential under ethical approval, only the analysed results are presented in this section. The images included breast cancer from the early stage until stage 3. Stage 4 breast cancer mammogram images are not discussed because it directly refers to surgical procedures.

Data analysis proceeds with DICOM software. The depth and size of the cancer tissue are determined and analysed with the mentioned software (**Appendix B**). The surface depth (SD) and inner depth (ID) of breast cancer in each stage are measured, as illustrated in **Figure 4.1**.

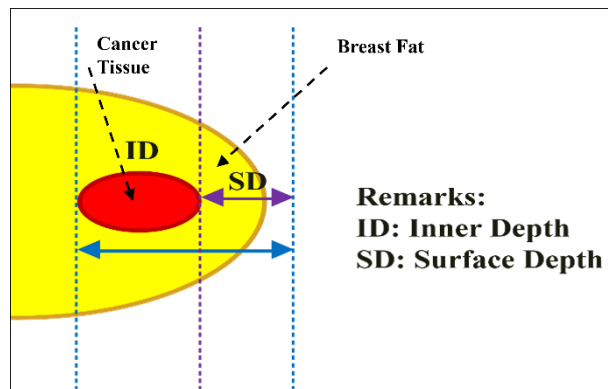
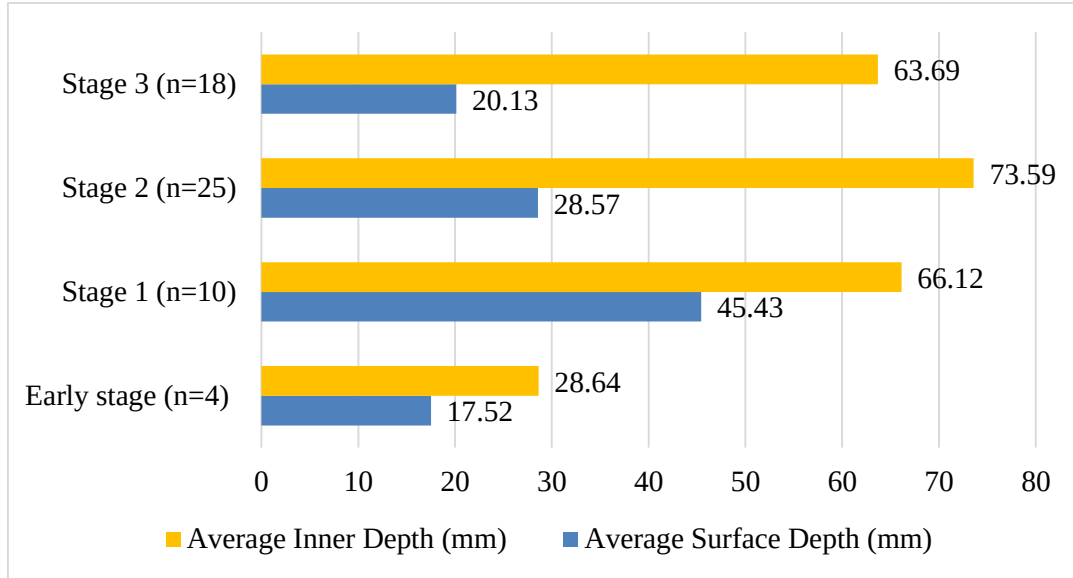


Figure 4.1: Surface Depth and Inner Depth Illustrations



n = number of samples

Figure 4.2: SD and ID for Each Cancer Stage

Figure 4.2 shows the average SD and ID calculated according to the number of samples for each cancer stage obtained. The depths are basically to identify the required focus position distance and penetration depth of each cancer that necessitates being heated for hyperthermia execution. Breast phantoms consisting of breast fat with 4 inches (10.16cm) as this breast size is investigated as average South East Asia women breast size by Lim et al. at 2018 and breast cancer with the analysed size from mammograms images analysis for each stage are modelled.

The data shown in **Figure 4.2** are agreed with the result by Wang et al. with almost similar cancer depth and sizes (Z. Wang et al., 2014).

4.3 DoE 1: Focus Position Distance with Different Applied Frequency and Substrate Thickness

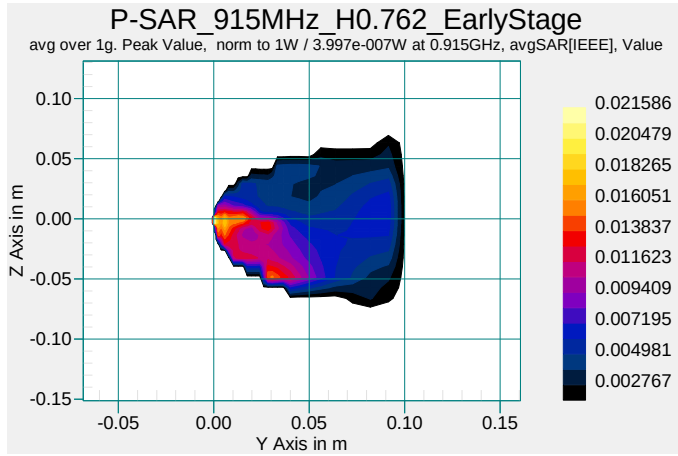
As mentioned in **Section 3.8**, the first DoE is to investigate the effects of different applied frequencies and two (2) common substrate thicknesses of Roger RO4350 into the HTP focus position distance (FPD).

The simulation results are presented in **Table 4.1**, which are included the focusing position distance (FPD) of the heating region and Peak Spatial-Average SAR reading for each cancer stage. Meanwhile, the images of the simulation results for each cancer stages are shown in **Figures 4.3** until **4.6**. Meanwhile, **Figure 4.7** showed percentage of FPD coverage of each design which is calculated by Equation 4.1. The abbreviation *FQ* and *TH* represented applied frequency and substrate thickness, respectively.

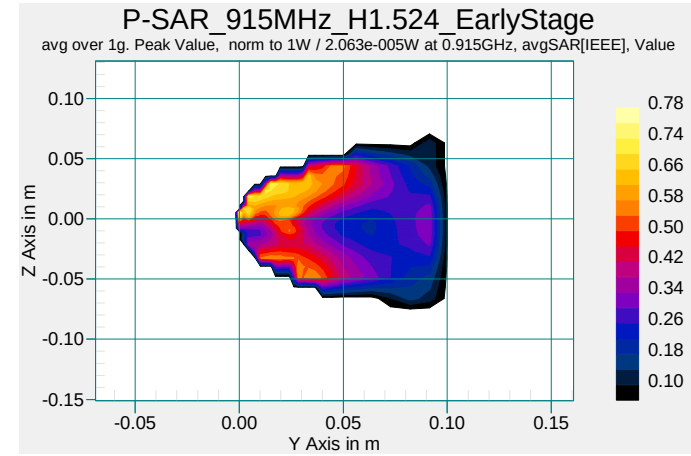
Table 4.1: Focus Position Distance (FPD) and Peak-Spatial-Average SAR Results for Different Applied Frequency and Substrate Thickness

Frequency , <i>FQ</i>	Substrate Thickness, <i>TH</i> (mm)	Early Stage		Stage 1		Stage 2		Stage 3	
		FPD (mm)	SAR (mW/g)	FPD (mm)	SAR (mW/g)	FPD (mm)	SAR (mW/g)	FPD (mm)	SAR (mW/g)
915MHz	0.762	Not covered in cancer region	N/A	47.3-62.7	0.0311	45.3-57.6	0.111	32.7-48.3	0.127
	1.524	0-34.9	0.9	45.9-63.8	0.0573	26.9-63.3	2	17.9-54.8	2
2450MHz	0.762	13.9 - 27.6	14	0- 19.8	5	0 - 38.7	5	0- 34.3	5
	1.524	15.4-27.2	14	0- 15.3 and 41.9 - 62.4	5	0- 42.1	5	0- 44.8	5

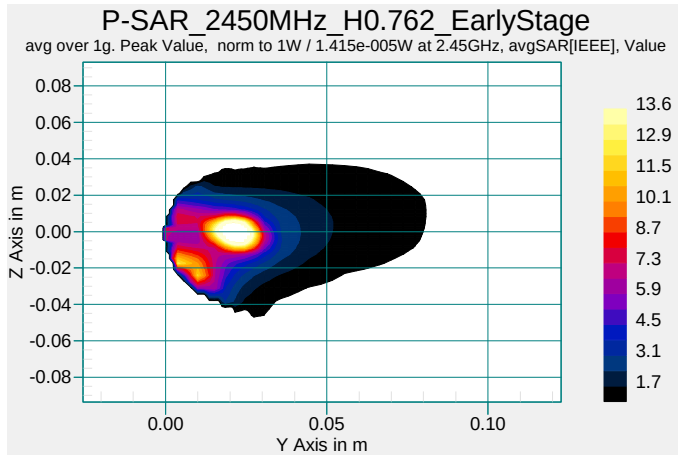
*The Yellow Coloured box indicates the selected model for the next phase of the experiment.



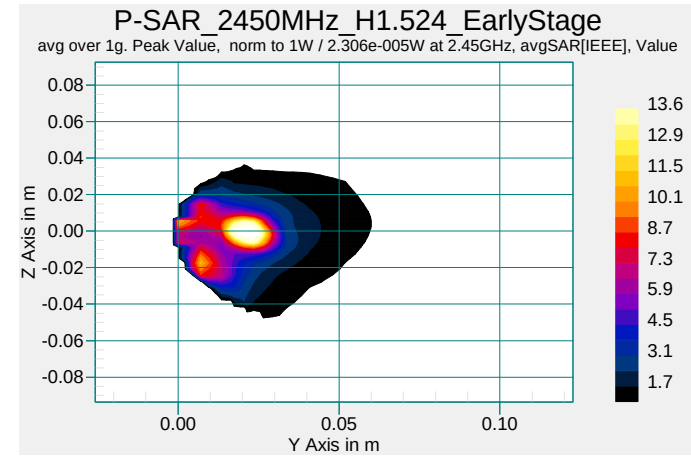
(a)



(b)

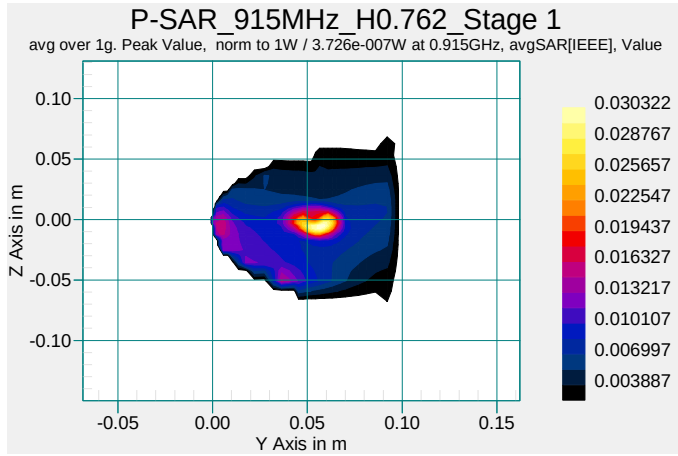


(c)

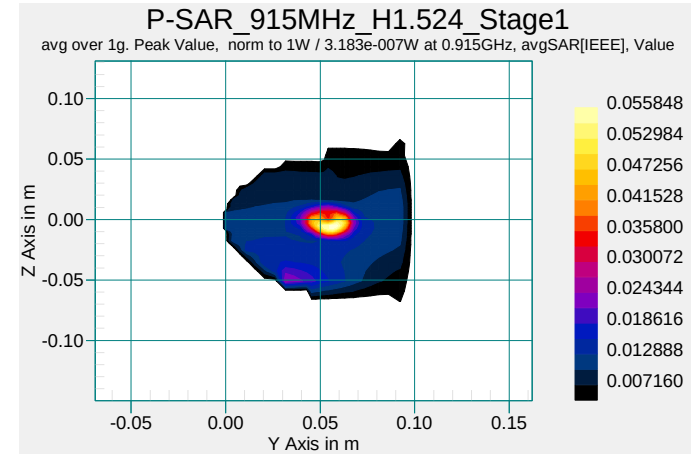


(d)

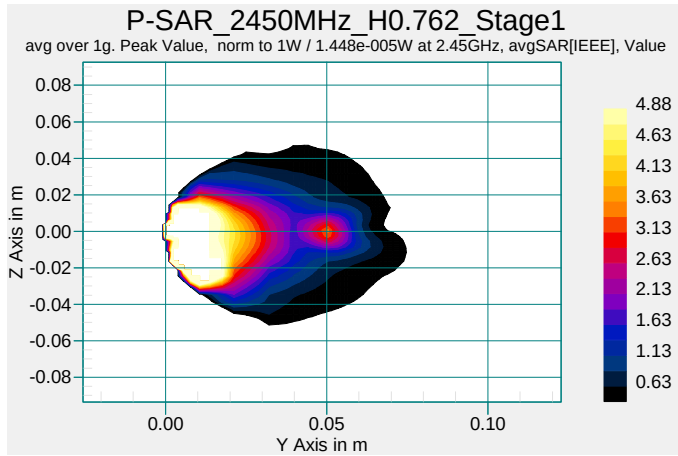
Figure 4.3: Early Stage Cancer SAR Distribution Results in (a) $FQ=915\text{MHz}$; $TH=0.762\text{mm}$, (b) $FQ=915\text{MHz}$; $TH=1.562\text{mm}$, (c) $FQ=2450\text{MHz}$; $TH=0.762\text{mm}$ and (d) $FQ=2450\text{MHz}$; $TH=1.524\text{mm}$



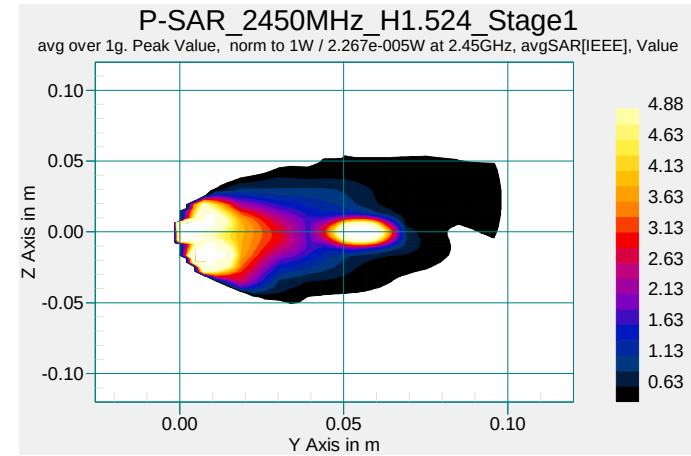
(a)



(b)

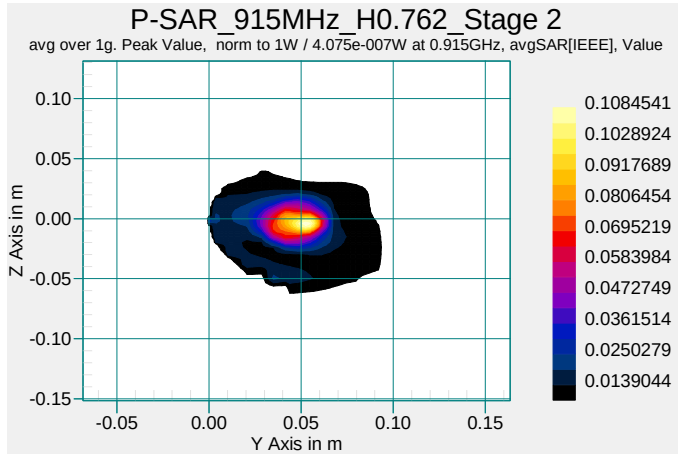


(c)

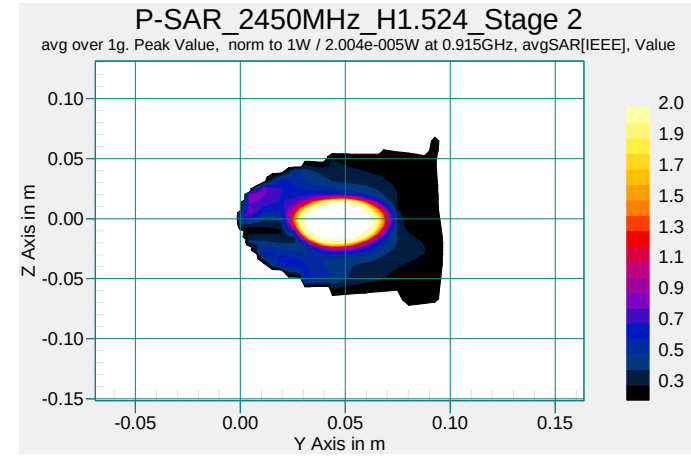


(d)

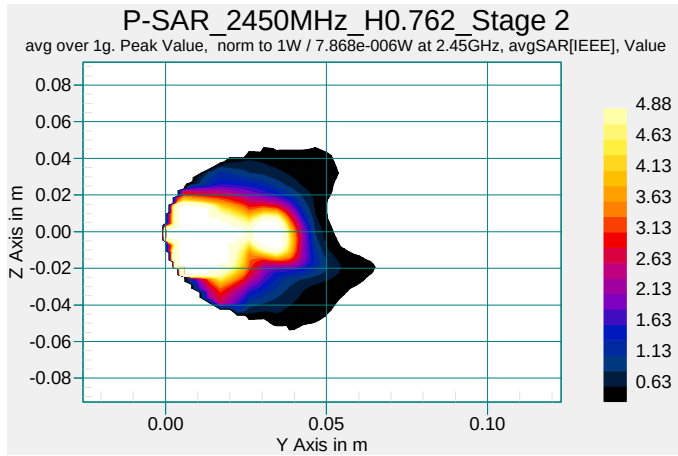
Figure 4.4: Stage 1 Cancer SAR Distribution Results in (a) $FQ=915\text{MHz}$; $TH=0.762\text{mm}$, (b) $FQ=915\text{MHz}$; $TH= 1.562\text{mm}$, (c) $FQ=2450\text{MHz}$; $TH= 0.762\text{mm}$ and (d) $FQ=2450\text{MHz}$; $TH=1.524\text{mm}$



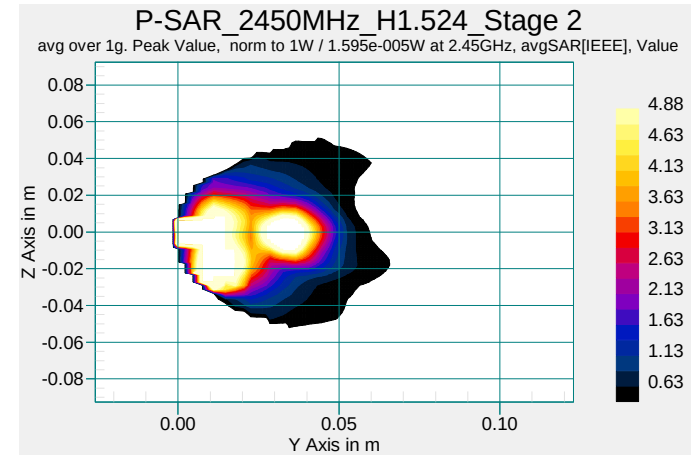
(a)



(b)

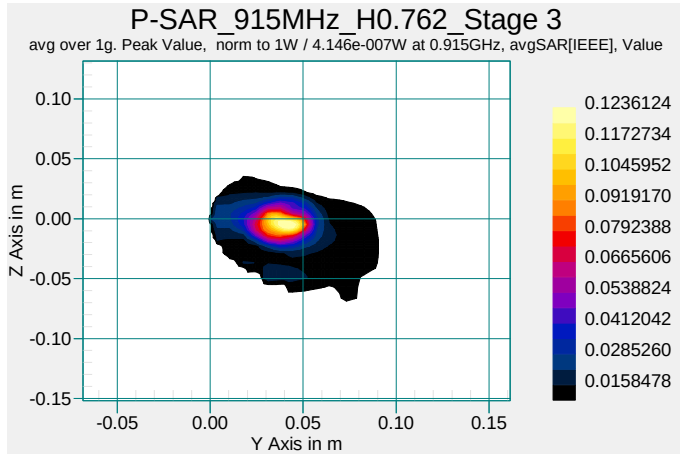


(c)

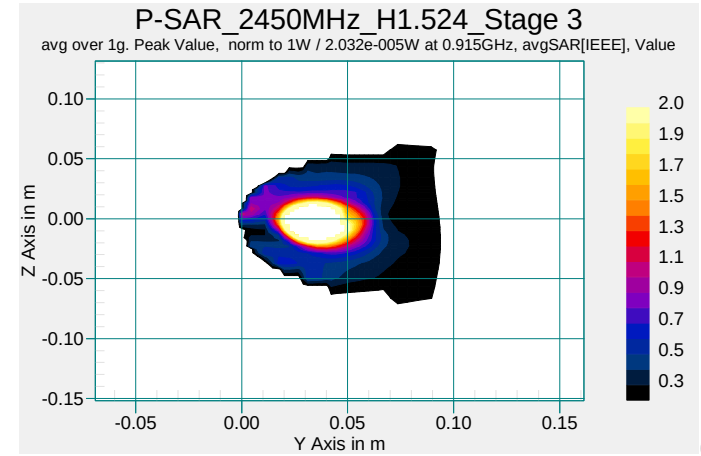


(d)

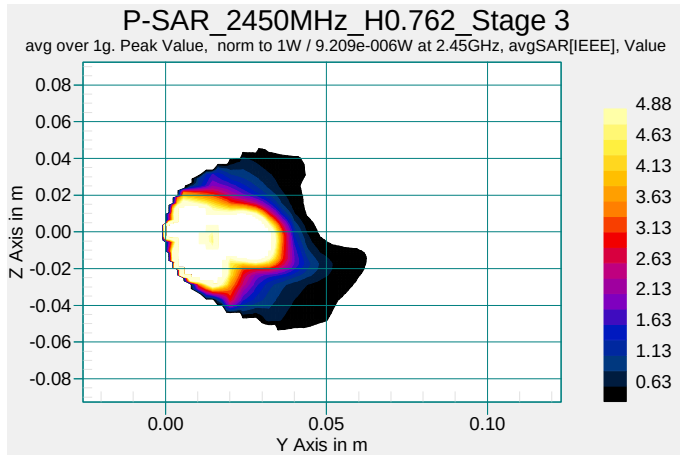
Figure 4.5: Stage 2 Cancer SAR Distribution Results in (a) $FQ=915\text{MHz}$; $TH=0.762\text{mm}$, (b) $FQ=915\text{MHz}$; $TH= 1.562\text{mm}$, (c) $FQ=2450\text{MHz}$; $TH= 0.762\text{mm}$ and (d) $FQ=2450\text{MHz}$; $TH=1.524\text{mm}$



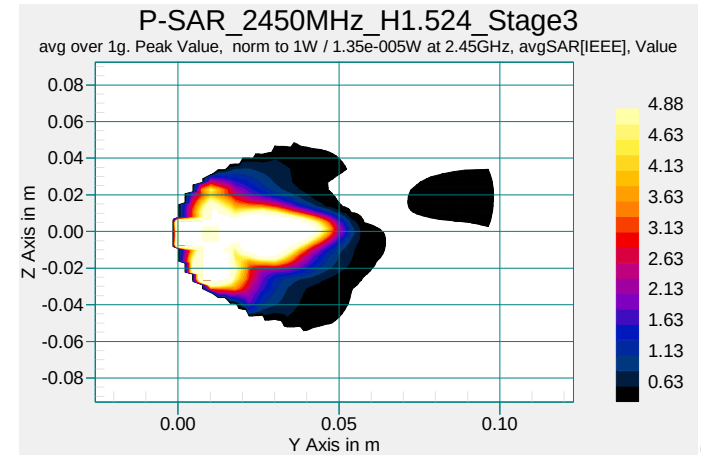
(a)



(b)



(c)



(d)

Figure 4.6: Stage 3 Cancer SAR Distribution Results in (a) $FQ=915\text{MHz}$; $TH=0.762\text{mm}$, (b) $FQ=915\text{MHz}$; $TH=1.562\text{mm}$, (c) $FQ=2450\text{MHz}$; $TH=0.762\text{mm}$ and (d) $FQ=2450\text{MHz}$; $TH=1.524\text{mm}$

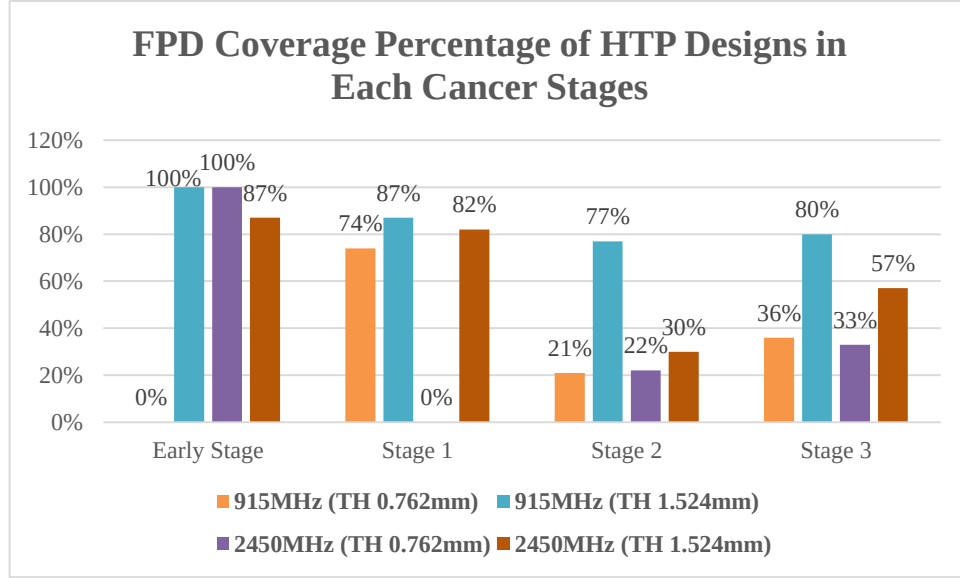


Figure 4.7: FPD Coverage Percentage of HTP Designs in Each Cancer Stages

$$FPD \text{ Coverage} = \frac{\text{Acquired FPD from SAR Distribution Result}}{\text{Required FPD for Each Cancr Stage}} \times 100\% \quad \text{Equation 4.1}$$

As shown in **Figure 4.3**, **Figure 4.4**, **Figure 4.5**, **Figure 4.6**, **Figure 4.7** and **Table 4.1**, different applied frequencies and substrate thickness have shown significant effects on the FPD of HTP. Antenna with $FQ=2450\text{MHz}$; $TH=1.524\text{mm}$ is the most suitable design for early-stage cancer, where the heat from the microstrip antenna has heated cancer with good focus position distance and penetration depth.

Although $FQ=2450\text{MHz}$; $TH=0.762\text{mm}$ and $FQ=915\text{MHz}$; $TH=0.762\text{mm}$ designs showed 100% FPD coverage, but because of the large overheated region in normal tissue, thus this two designs are not selected.

According to the Universal Wave Equation, $c = \frac{f}{\lambda}$, where the wavelength is directly proportional to the penetration depth of the wave. Thus, a 2450MHz antenna with higher gain but low penetration depth is suitable for early-stage cancer as the location of cancer for the early stage is near the skin.

Meanwhile, an $FQ=915\text{MHz}$; $TH=1.524\text{mm}$ antenna with a longer wavelength and penetration depth performed better than the 2450MHz antenna for Stage -2 and -3 breast cancers, in which the cancer locations are in the deeper region. For Stage-1 cancer with moderate cancer depth, both antenna $FQ=915\text{MHz}$; $TH=1.524\text{mm}$ and $FQ=2450\text{MHz}$; $TH=1.524\text{mm}$ is selected as both showed suitable FPD and acceptable SAR.

An overview study made by Kok et al. also stated that 2450MHz is suitable for cancer with a diameter of less than 20mm , while 915MHz performs better for cancer tissue up to 40mm . If the cancer tissue is larger (i.e. neck cancer or lung cancer), Kok mentioned that a 434 MHz antenna would be better than a 2450MHz and 915MHz antenna (Kok et al., 2020).

These research results can be validated with findings by Gas (2012), whereas temperature or SAR distribution with a 2450MHz antenna decreased rapidly when propagation distance increased. Therefore, the antenna selected for the phase 3 experiment for each cancer stage is listed as follows:

Early Stage : $FQ=2450\text{MHz}$; $TH=1.524\text{mm}$

Stage 1 : $FQ= 915\text{MHz}$; $TH=1.524\text{mm}$ and $FQ= 2450\text{MHz}$; $TH=1.524\text{mm}$

Stage 2 : $FQ=915\text{MHz}$; $TH=1.524\text{mm}$

Stage 3 : $FQ=915\text{MHz}$; $TH=1.524\text{mm}$

4.4 Implementation of MTM

As mentioned in **Section 3.8.2**, MTM as Loading in SRR form are designed into size $\lambda/34$ and $\lambda/46$. Furthermore, both sizes are designed with different cell distances to

investigate the effect of total number of unit cells toward its performance in HTP by multiplying the D_0 , as discussed in **Section 3.8.3**.

To ease the explanation of the FPD and SAR attainments, the results and discussion for DoE 2 and DoE 3 are combined and discussed in **Sections 4.4.1** (MTM-SRR $\lambda/34$ sized) and **4.4.2** (MTM-SRR $\lambda/46$ sized).

4.4.1 DoE 2 and DoE 3: Split-Ring Resonator (SRR) with size $\lambda/34$

Table 4.2 and **Figures 4.9** until **Figure 4.12** show the simulation results with $\lambda/34$ sized MTM.

Table 4.2: Focus Position Distance (FPD) and Peak-Spatial-Average SAR Results for a Different Distance, D_0 of $\lambda/34$ SRR.

Frequency	1.0 D_0		1.2 D_0		1.4 D_0		Results in Table 4.1	
	FPD (mm)	SAR (mW/g)	FPD (mm)	SAR (mW/g)	FPD (mm)	SAR (mW/g)	FPD (mm)	SAR (mW/g)
Early Stage (FQ=2450MHz, TH=1.524mm)	15.1-27.6	5	N/A	N/A	N/A	N/A	15.4-27.2	14
Stage 1 (FQ=915MHz, TH=1.524mm)	44.3-62.6	0.0294	45.1-64.5	0.0377	46.1-64.1	0.0329	45.9-63.8	0.0573
Stage 1 (FQ=2450MHz, TH=1.524mm)	43.5-63.0	3.5	N/A	N/A	N/A	N/A	0- 15.3 and 41.9 -62.4	5
Stage 2 (FQ=915MHz, TH=1.524mm)	29.1-61.3	2	29.5-62.3	2	29.4-60.9	2	26.9-67.3	2
Stage 3 (FQ=915MHz, TH=1.524mm)	21.9-54.5	2	21.3-55.3	2	21.1-55.4	2	17.9-54.8	2

**Yellow coloured box indicates the design(s) selected for the next DoE (after comparing with Table 4.3)*

Figure 4.8 presents the percentage of FPD coverage of each $\lambda/34$ MTM-SRR designs in respective stage of cancer. For a clearer comparison between the results of implementation of $\lambda/34$ and $\lambda/46$ sized MTM-SRR, the discussion of this section is discussed together with the results of the implementation of $\lambda/46$ sized MTM-SRR in the next section, **Section 4.4.2**.

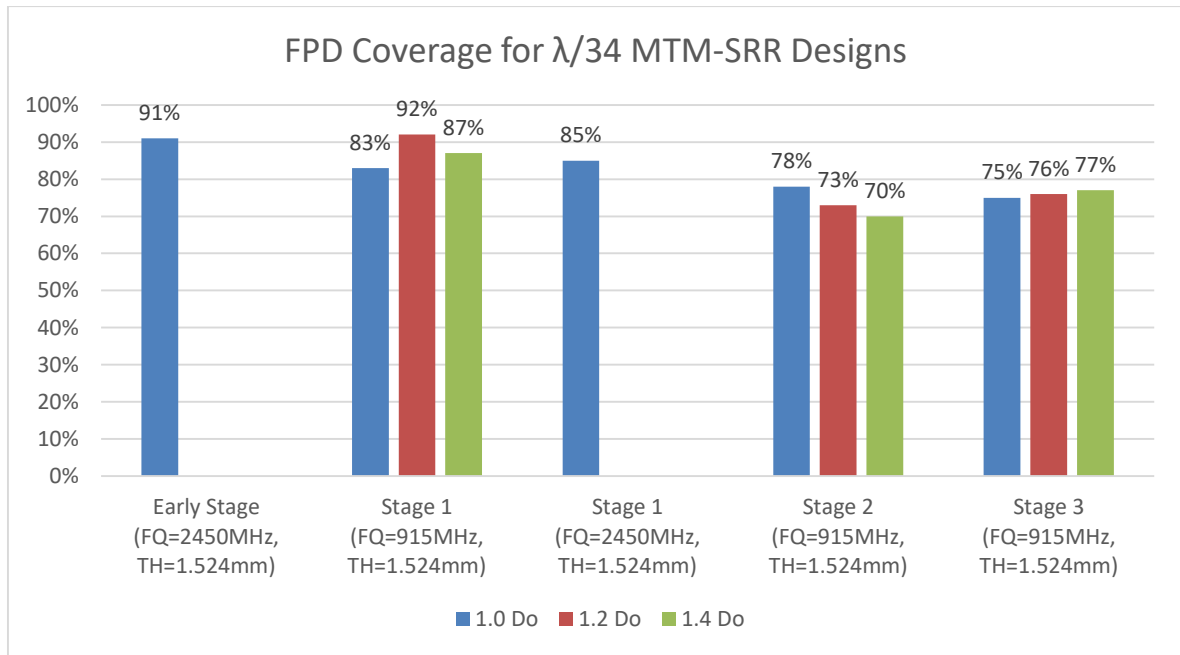


Figure 4.8: The Percentage of FPD Coverage of Each $\lambda/34$ Sized MTM-SRR Designs in Respective Stage of Cancer

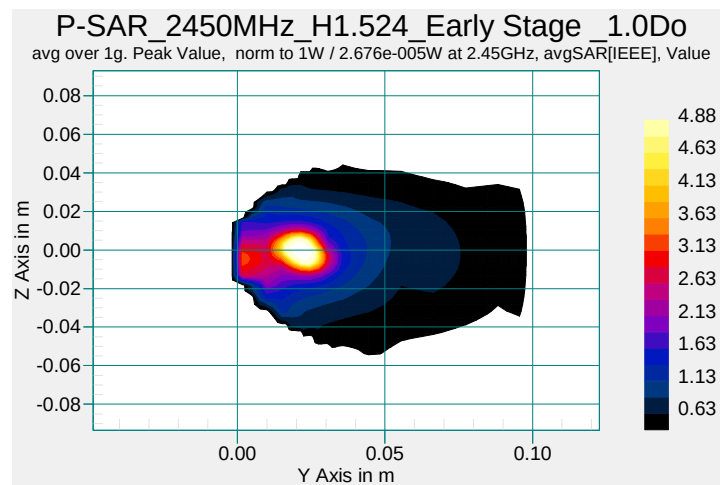
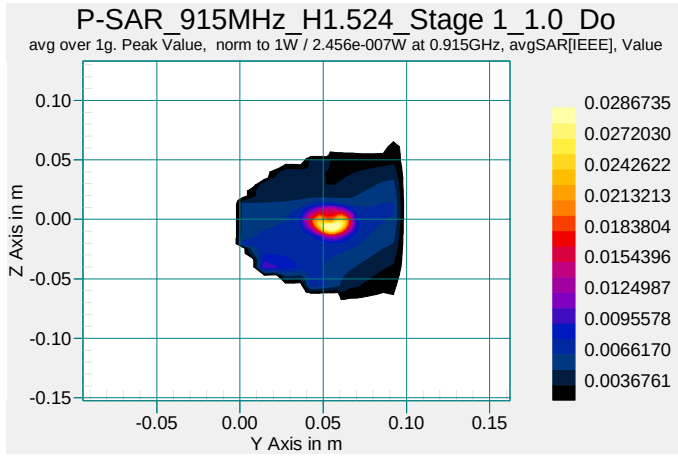
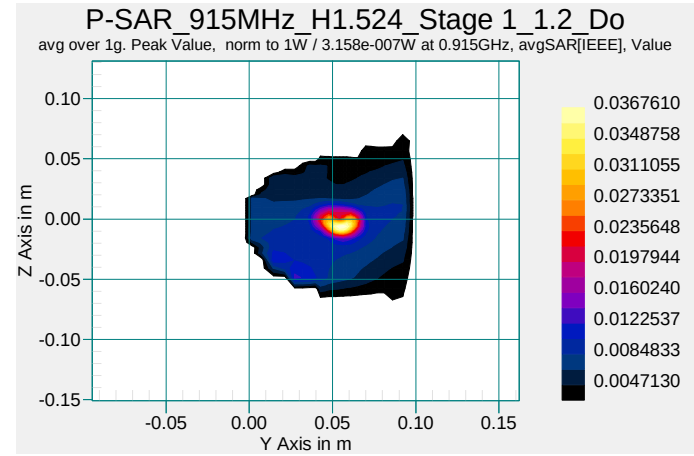


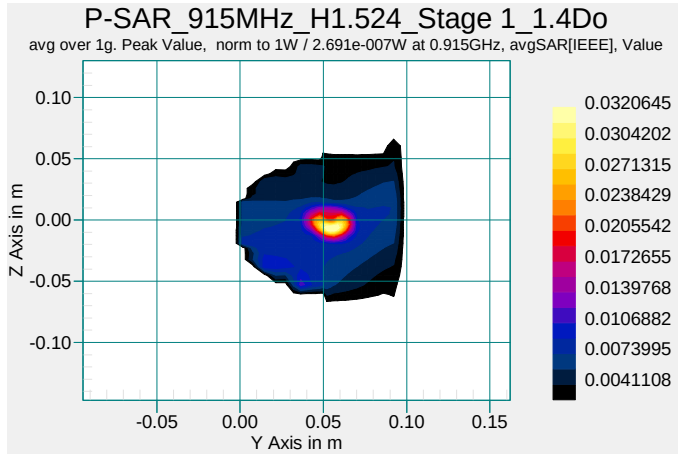
Figure 4.9: Early-Stage SAR Distribution Results in $FQ=2450\text{MHz}$; $TH=1.524\text{mm}$ for MTM $\lambda/34$



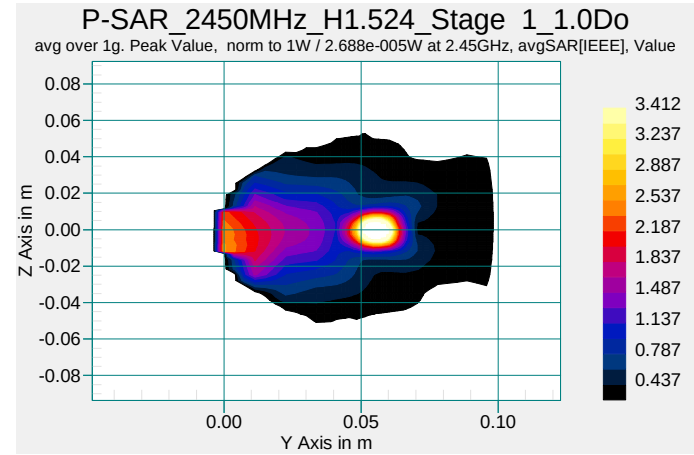
(a)



(b)

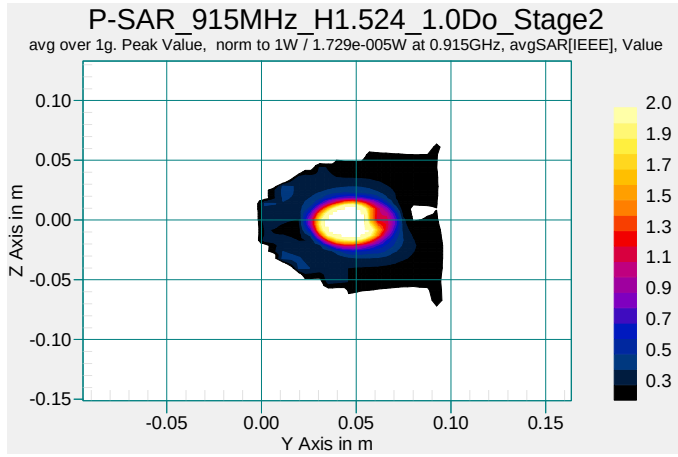


(c)

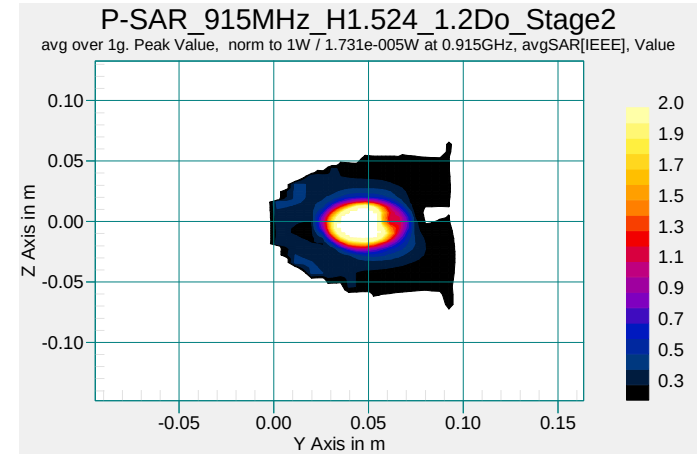


(d)

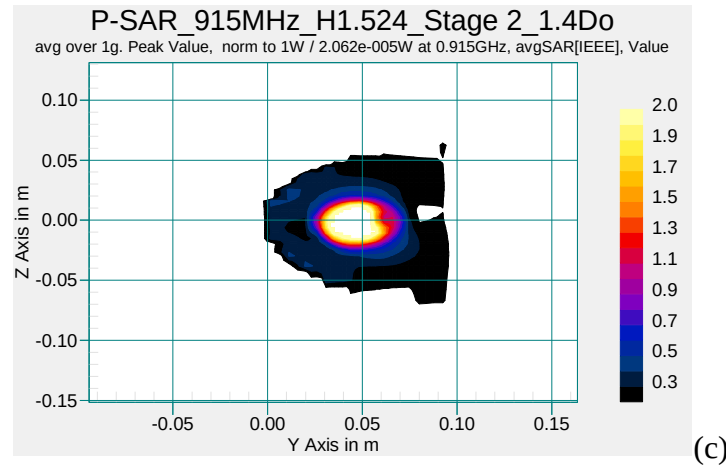
Figure 4.10: Stage 1 Cancer SAR Distribution Results in (a) $FQ=915\text{MHz}$; $TH= 1.562\text{mm}$; $1.0 D_0$, (b) $FQ=915\text{MHz}$; $TH= 1.562\text{mm}$; $1.2 D_0$ (c) $FQ=915\text{MHz}$; $TH= 1.562\text{mm}$; $1.4 D_0$ and (d) $FQ=2450\text{MHz}$; $TH=1.524\text{mm}$; $1.0 D_0$ for MTM $\lambda/34$



(a)

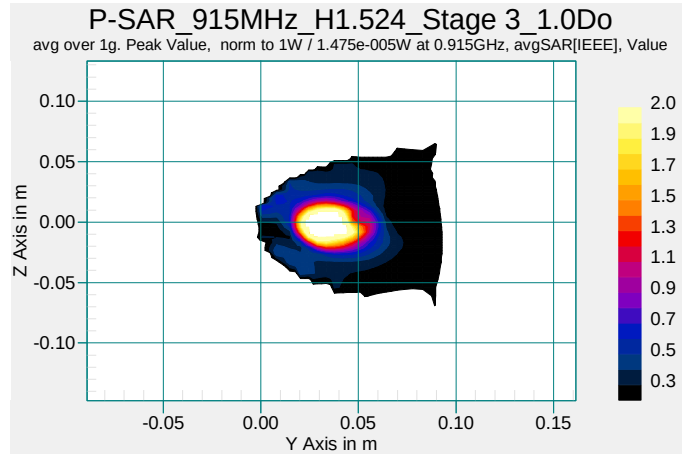


(b)

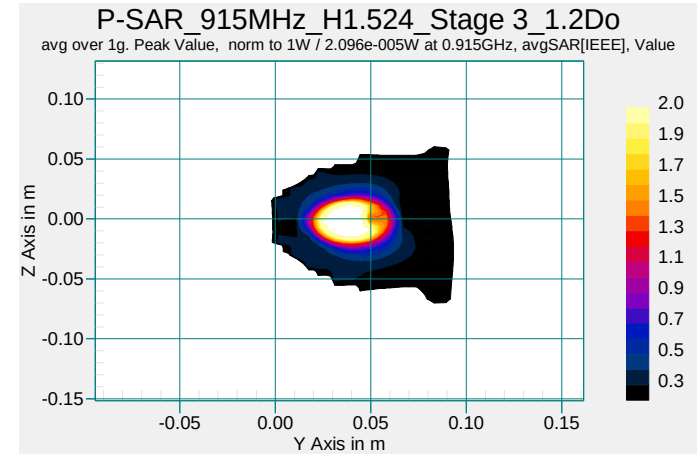


(c)

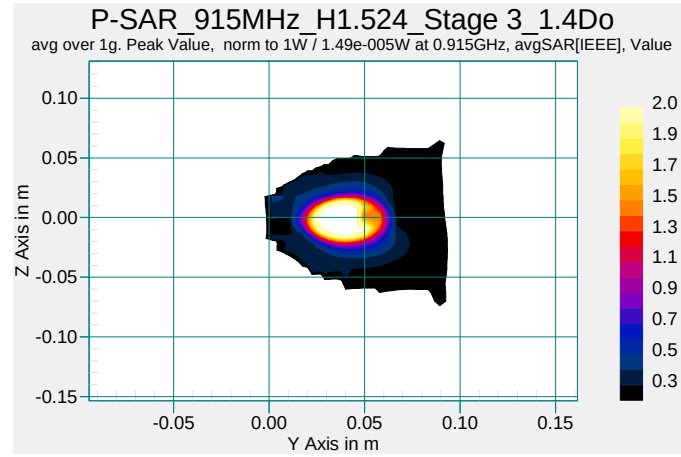
Figure 4.11: Stage 2 Cancer SAR Distribution Results in (a) $FQ=915\text{MHz}$; $TH= 1.562\text{mm}$; $1.0 D_0$, (b) $FQ=915\text{MHz}$; $TH= 1.562\text{mm}$; $1.2 D_0$ and (c) $FQ=915\text{MHz}$; $TH= 1.562\text{mm}$; $1.4 D_0$



(a)



(b)



(c)

Figure 4.12: Stage 3 Cancer SAR Distribution Results in (a) $FQ=915\text{MHz}$; $TH= 1.562\text{mm}$; 1.0 Do,(b) $FQ=915\text{MHz}$; $TH= 1.562\text{mm}$; 1.2 Do and (c) $FQ=915\text{MHz}$; $TH= 1.562\text{mm}$; 1.4 Do

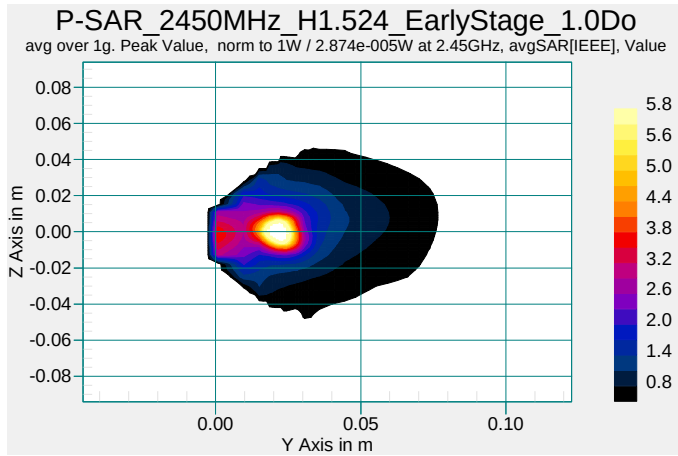
4.4.2 DoE 2 and DoE 3: Split-Ring Resonator (SRR) with size $\lambda/46$

Table 4.3 and Figure 4.13, 4.14, 4.15 and 4.16 show the simulation results with $\lambda/46$ sized MTM. Figure 4.17 presents the percentage of FPD coverage of each $\lambda/46$ MTM-SRR designs in respective stage of cancer. The results discussions for Sections 4.4.1 and 4.4.2 are also presented in this section.

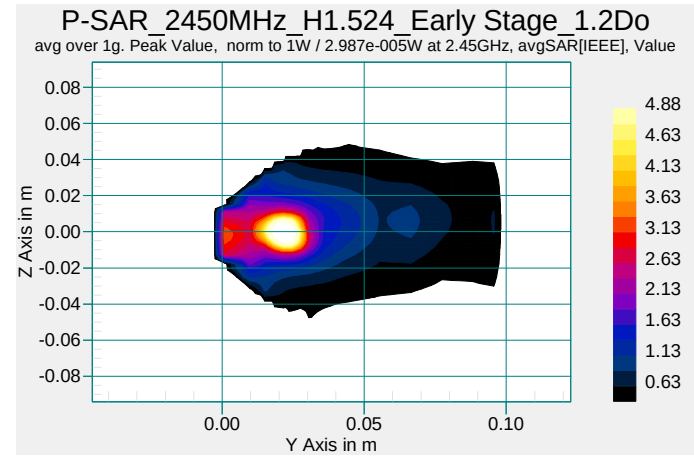
Table 4.3: Focus Position Distance (FPD) and Peak-Spatial-Average SAR Results for a Different Distance, D_0 of $\lambda/46$ SRR.

Frequency	1.0 D_0		1.2 D_0		1.4 D_0		Results in Table 4.1	
	FPD (mm)	SAR (mW/g)	FPD (mm)	SAR (mW/g)	FPD (mm)	SAR (mW/g)	FPD (mm)	SAR (mW/g)
Early Stage (FQ=2450MHz, TH=1.524mm)	14.8-27.5	6.0	14.8-28.1	5.0	N/A	N/A	15.4-27.2	14
Stage 1 (FQ=915MHz, TH=1.524mm)	45.6-63.4	0.0294	44.5-64.2	0.0377	46.2-63.4	0.0343	45.9-63.8	0.0573
Stage 1 (FQ=2450MHz, TH=1.524mm)	0-15.8 and 49.2-57.3	3.5	Not heated cancer region	N/A	N/A	N/A	0- 15.3 and 41.9-62.4	5
Stage 2 (FQ=915MHz, TH=1.524mm)	29.2-64.7	2	29.1-65.7	2	29.2-64.4	2	26.9-63.3	2
Stage 3 (FQ=915MHz, TH=1.524mm)	19.6-50.0	2	20.5-57.1	2	21.6-54.6	2	17.9-54.8	2

*Yellow coloured box indicates the design(s) selected for the next DoE (after comparing with Table 4.2)



(a)



(b)

Figure 4.13: Early Stage SAR Distribution Results in (a) $FQ=2450\text{MHz}$; $TH=1.524\text{mm}$; 1.0 D_o and (b) $=2450\text{MHz}$; $TH=1.524\text{mm}$; 1.2 D_o for MTM $\lambda/46$

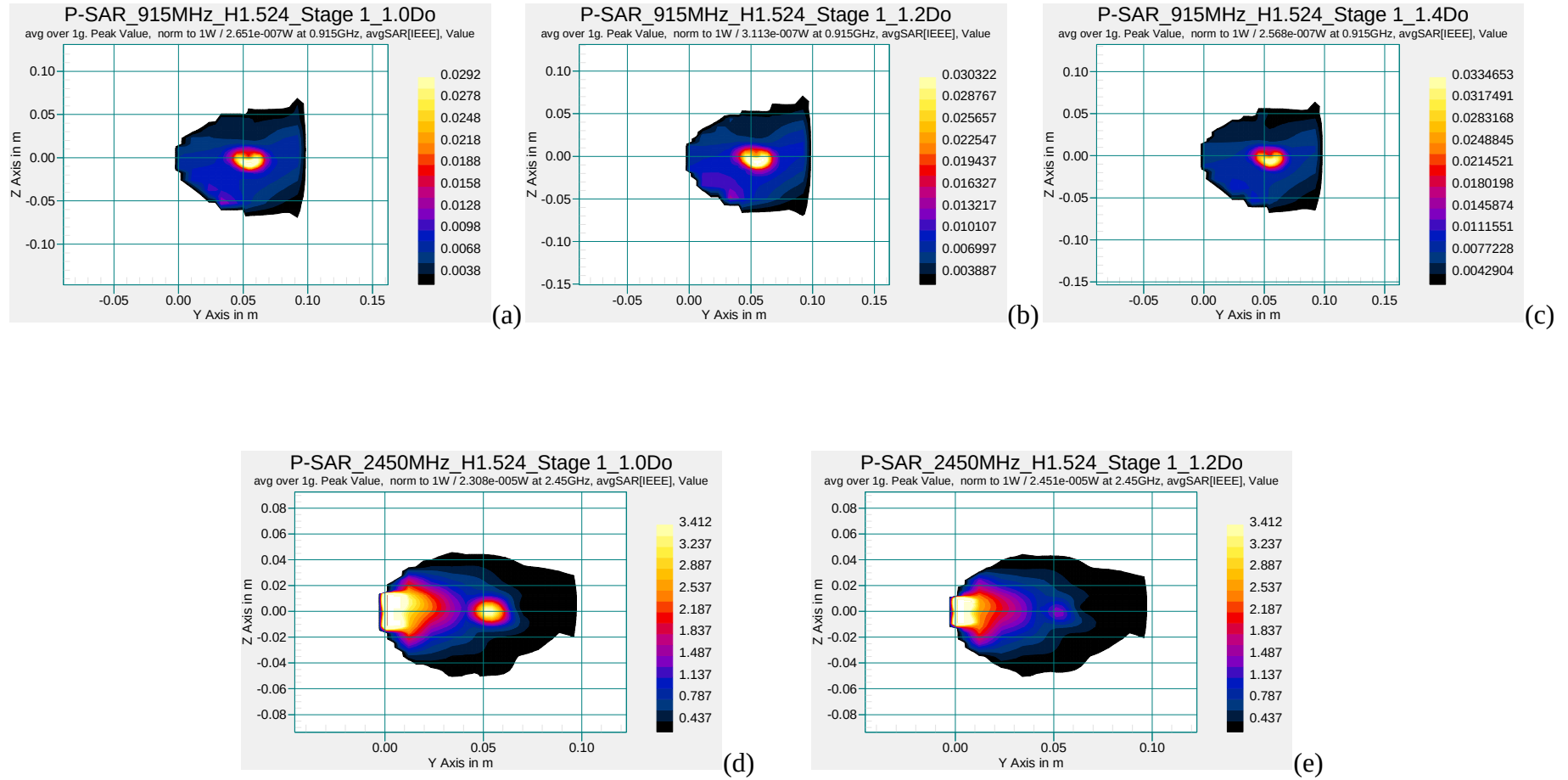
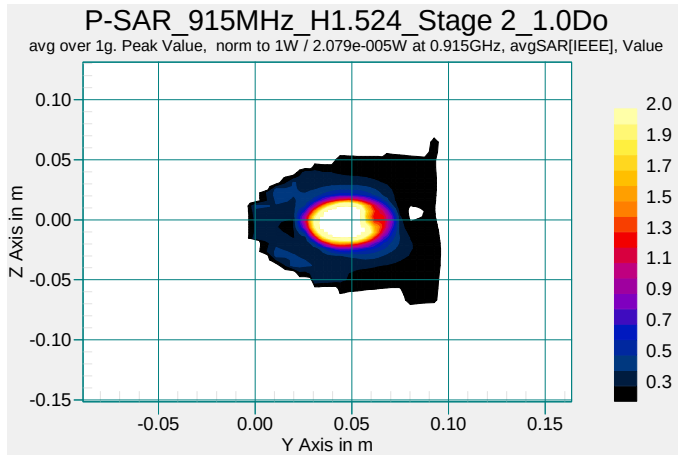
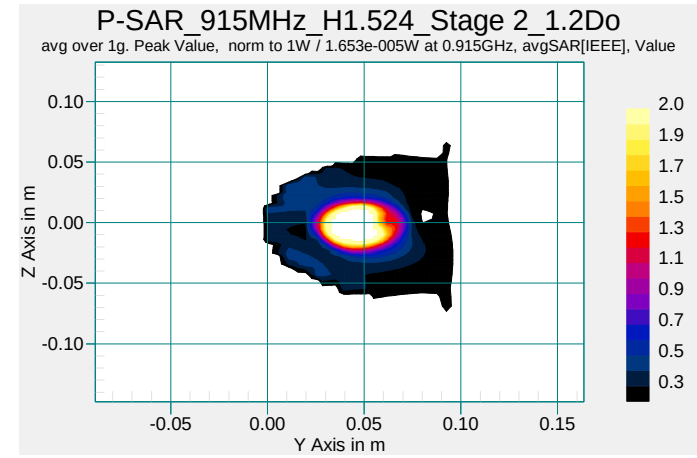


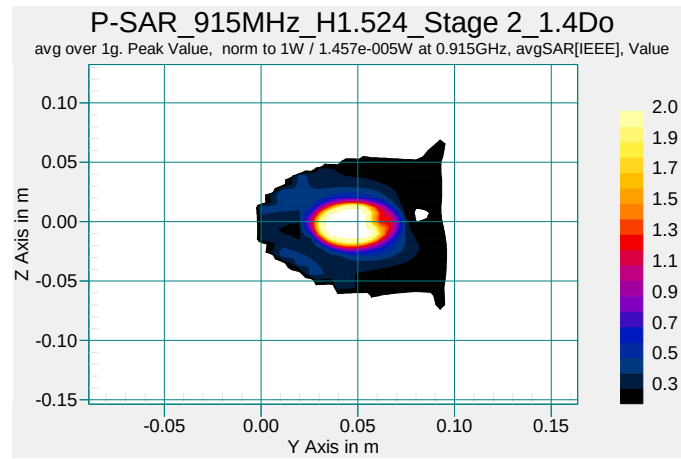
Figure 4.14: Stage 1 Cancer SAR Distribution Results in (a) $FQ=915\text{MHz}$; $TH= 1.562\text{mm}$; $1.0 D_0$, (b) $FQ=915\text{MHz}$; $TH= 1.562\text{mm}$; $1.2 D_0$ (c) $FQ=915\text{MHz}$; $TH= 1.562\text{mm}$; $1.4 D_0$, (d) $FQ=2450\text{MHz}$; $TH=1.524\text{mm}$; $1.0 D_0$ and (e) $FQ=2450\text{MHz}$; $TH=1.524\text{mm}$; $1.2 D_0$ for MTM $\lambda/46$



(a)

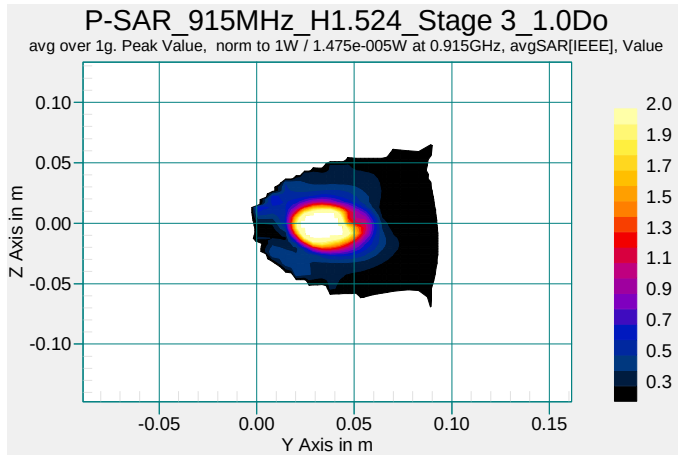


(b)

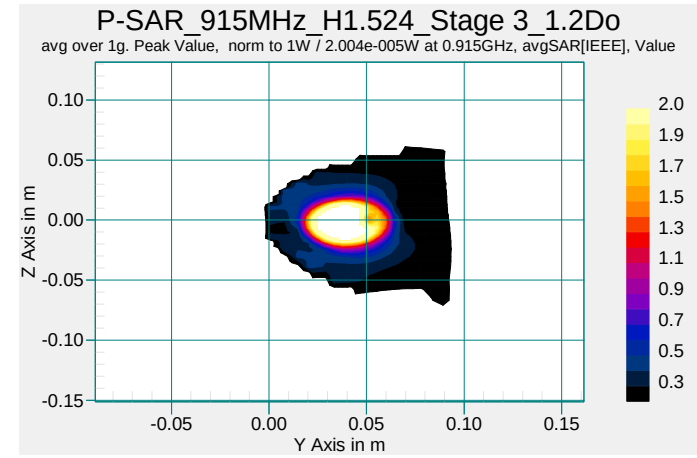


(c)

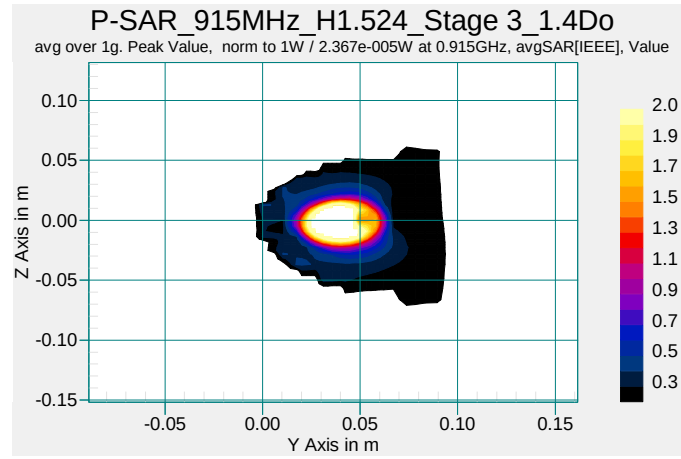
Figure 4.15: Stage 2 Cancer SAR Distribution Results in (a) $FQ=915\text{MHz}$; $TH= 1.562\text{mm}$; 1.0 D_0 , (b) $FQ=915\text{MHz}$; $TH= 1.562\text{mm}$; 1.2 D_0 and (c) $FQ=915\text{MHz}$; $TH= 1.562\text{mm}$; 1.4 D_0 , for MTM $\lambda/46$



(a)



(b)



(c)

Figure 4.16: Stage 3 Cancer SAR Distribution Results in (a) $FQ=915\text{MHz}$; $TH= 1.562\text{mm}$; 1.0 D_o , (b) $FQ=915\text{MHz}$; $TH= 1.562\text{mm}$; 1.2 D_o and (c) $FQ=915\text{MHz}$; $TH= 1.562\text{mm}$; 1.4 D_o , for MTM $\lambda/46$

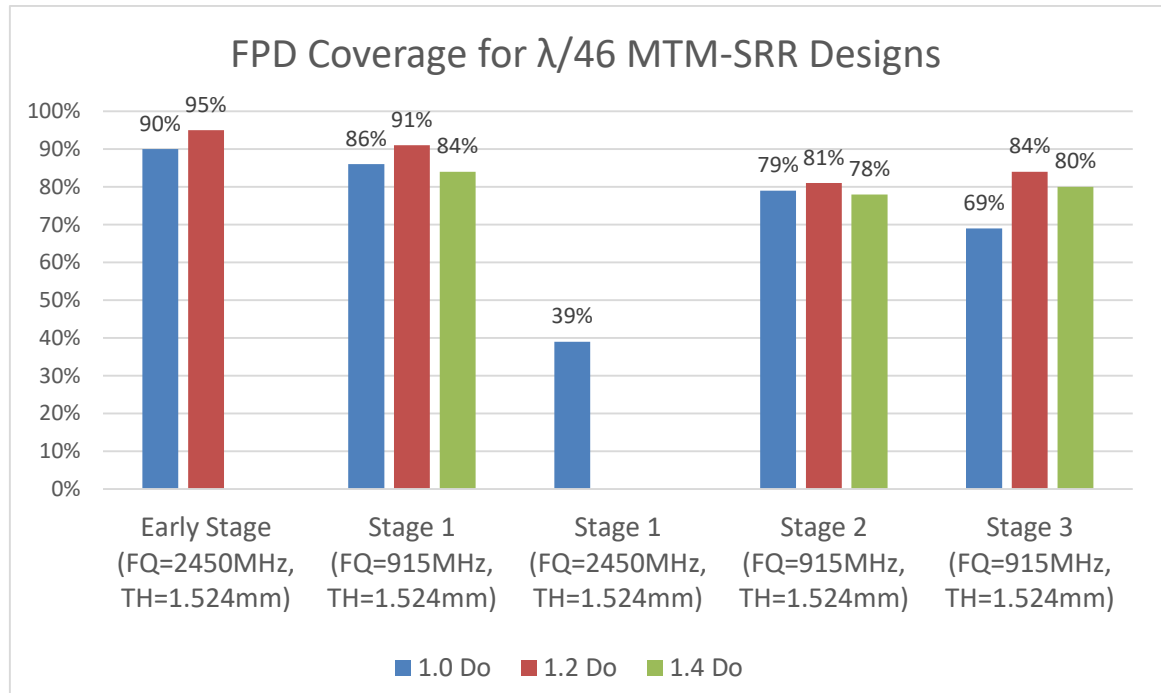


Figure 4.17: The Percentage of FPD Coverage of Each $\lambda/46$ Sized MTM-SRR Designs in Respective Stage of Cancer

As presented in **Table 4.2 (Page 75)**, **Table 4.3 (Page 80)**, **Figure 4.8 (Page 76)** and **Figure 4.17**, the integration of MTM resulted in a significant effect in terms of FPD and SAR value. Almost all results with MTM-SRR integration showed a more concentrated heating region compared with HTP without MTM.

The designs which show the most suitable SAR and larger heated cancer region are selected. Thus, despite FPD coverage of $FQ=915\text{MHz}$ with $\lambda/46$ showed better result than design of $FQ=2450\text{MHz}$, $TH=1.524\text{mm}$, $\lambda/34$ in stage 1 cancer, but because of its poor SAR attainment, the $FQ=2450\text{MHz}$, $TH=1.524\text{mm}$, $\lambda/34$ design is selected.

As the results for DoE 2 and DoE 3, the best designs for each stage are stated as following:

Early Stage : $FQ=2450\text{MHz}$, $TH=1.524\text{mm}$, $\lambda/46$, 1.2Do

Stage 1 : $FQ=2450\text{MHz}$, $TH=1.524\text{mm}$, $\lambda/34$, $1.0D_0$

Stage 2 : $FQ=915\text{MHz}$, $TH=1.524\text{mm}$, $\lambda/46$, $1.2D_0$

Stage 3 : $FQ=915\text{MHz}$, $TH=1.524\text{mm}$, $\lambda/46$, $1.2D_0$

The results agreed with the findings of Slimi et al. (2022), Yusri and Muldarisnur (2021), where the addition of MTM-SRR is able to increase the antenna efficiency. These results also proved the statement by Velazquez-Ahumada et al. (2011) and Vrba et al. (2016) that MTM is able to generate deeper penetration depth towards biological tissue.

Besides, the results also showed that compared with $\lambda/34$ sized MTM-SRR, $\lambda/46$ sized performed better in all cancer stages except stage 1. This can also be seen from the research of Huang et al. (2011), Suthar et al. (2015), Pereira and Kallos (2015) and Yusri and Muldarisnur (2021). A smaller-sized cell that resulted in a larger total cell number or with a higher cell loop could show better results.

In addition, to prove the negative electrical properties or whether the MTM designed is left-handed properties material, as discussed in **Section 2.3**. The MTM lens designed is simulated with two (2) isolated voltage sensor ports, as mentioned in **Sections 3.6.3.1 and 3.8.3.1 (Equation 3.13 to Equation 3.27)**.

As the result, the measured values of V_1 , V_2 , I_1 and I_2 from voltage sensor ports and calculated permittivity and permeability of MTM designed for each cancer stage are shown in **Table 4.4**.

Table 4.4: The Permittivity and Permeability of MTM Designed for Each Stage of Cancer.

Cancer Stages and Final Design	V₁ (V); I₁ (A)	V₂ (V); I₂ (A)	Permittivity	Permeability
Early Stage (FQ=2450MHz, TH=1.524mm, $\lambda/46$, 1.2D ₀)	V₁: $-(0.2757 - 0.1783i) \times 10^{-2}$ I₁: $(-0.2333 + 0.2845i) \times 10^{-9}$	V₂: $(0.1054 + 0.0613i) \times 10^{-2}$ I₂: $(5.8471 - 0.1083i) \times 10^{-9}$	0.5114+3.3681i	-0.1703-1.1230i
Stage 1 (FQ=2450MHz, TH=1.524mm, $\lambda/34$, 1.0D ₀)	V₁: $(-0.5066 - 0.1697i) \times 10^{-2}$ I₁: $(6.8675 - 0.1957i) \times 10^{-8}$	V₂: $0.02195 + 0.02759i$ I₂: $(1.5369 - 1.1855i) \times 10^{-6}$	0.0211-2.3910i	-0.0069+0.7961i
Stage 2 and Stage 3 (FQ=915MHz, TH=1.524mm, $\lambda/46$, 1.2D ₀)	V₁: $(-0.4397 - 0.4304i) \times 10^{-3}$ I₁: $(-4.3238 + 4.4380i) \times 10^{-7}$	V₂: $(0.3027 + 0.2924i) \times 10^{-3}$ I₂: $(-2.2543 + 2.3563i) \times 10^{-7}$	0.5241+2.3870i	-0.1232-0.8072i

Based on **Table 4.4**, the calculated values proved that the MTM lens designed are negative in permeability and considered as MNG MTM, which was based on the works presented by Wojciech and Thanh in the year 2019.

4.5 DoE 4: Development of Water Bolus with Different Thickness

As mentioned in **Section 3.8.4**, the four (4) selected MTM-SRR designs with respective breast cancer stages are integrated with breast-shaped WB in 2mm, 5mm and 10mm thickness. **Table 4.5**, **Figure 4.18** and **4.19** present the simulation results while **Figure 4.20** represents the FPD coverage percentage with WB implementation.

Table 4.5: FPD and Peak-Spatial-Average SAR Results After Implementation of WB

Frequency	2mm WB		5mm WB		10mm WB		Selected MTM-SRR Results in Table 4.2 or 4.3	
	FPD (mm)	SAR (mW/g)	FPD (mm)	SAR (mW/g)	FPD (mm)	SAR (mW/g)	FPD (mm)	SAR (mW/g)
Early Stage ($FQ=2450\text{MHz}$, $TH=1.524\text{mm}$, $\lambda/46$, 1.2Do)	16.8- 27.5	4.8	N/A	N/A	N/A	N/A	15.4- 28.1	5.0
Stage 1 ($FQ=2450\text{MHz}$, $TH=1.524\text{mm}$, $\lambda/34$, 1.0Do)	47.4- 65.5	3.0	44.5- 64.2	1.5	N/A	N/A	43.5- 63.0	3.5
Stage 2 ($FQ=915\text{MHz}$, $TH=1.524\text{mm}$, $\lambda/46$, 1.2Do)	28.9- 65.4	1.5	29.1- 63.5	1.5	29.2- 63.4	1.5	26.9- 65.7	2
Stage 3 ($FQ=915\text{MHz}$, $TH=1.524\text{mm}$, $\lambda/46$, 1.2Do)	23.5- 62.5	1.5	20.5- 57.1	1.5	21.6- 54.6	1.5	17.9- 54.8	2

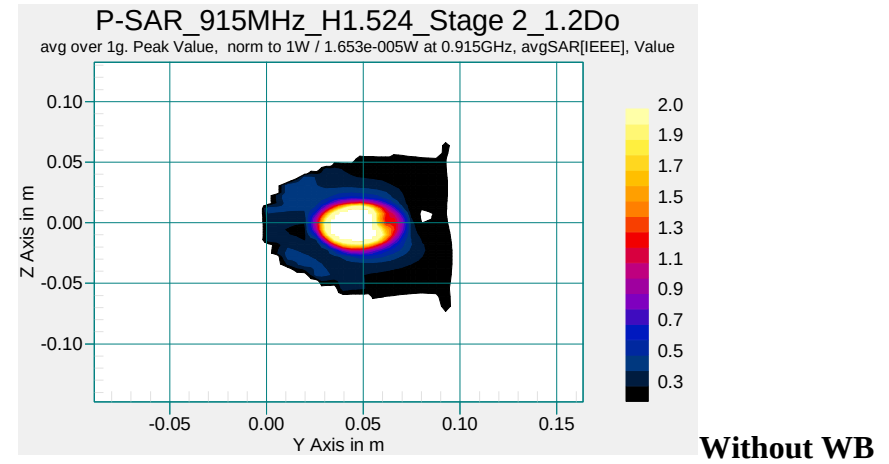
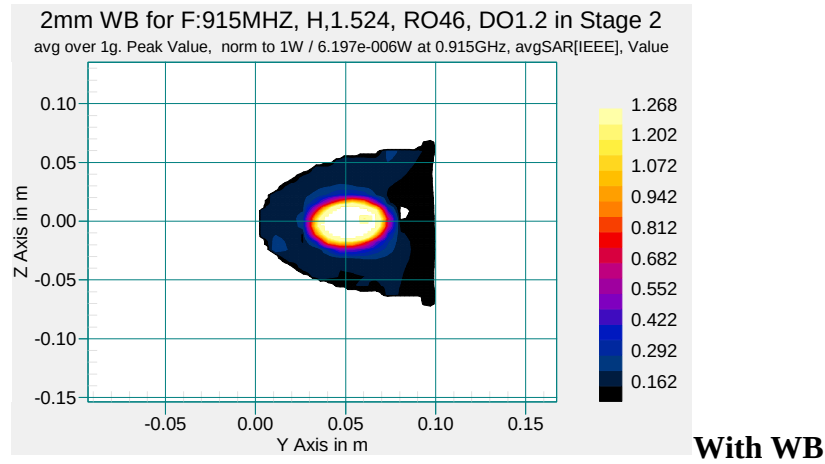


Figure 4.18: Comparing the SAR Simulation between HTP with the Implementation of 2mm WB and HTP without WB for Stage 2

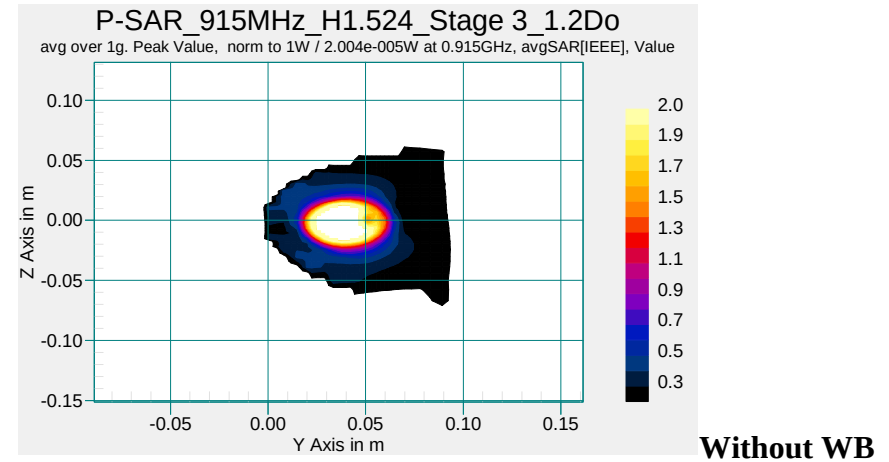
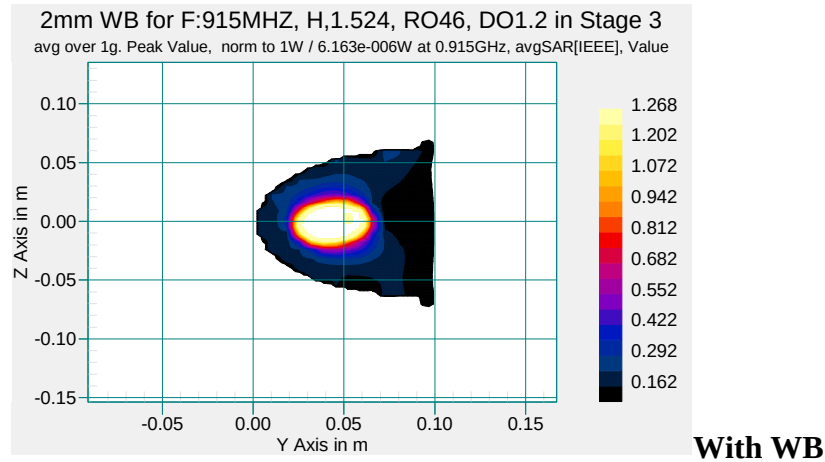


Figure 4.19: Comparing the SAR Simulation between HTP with Implementation of 2mm WB and HTP without WB for Stage 3

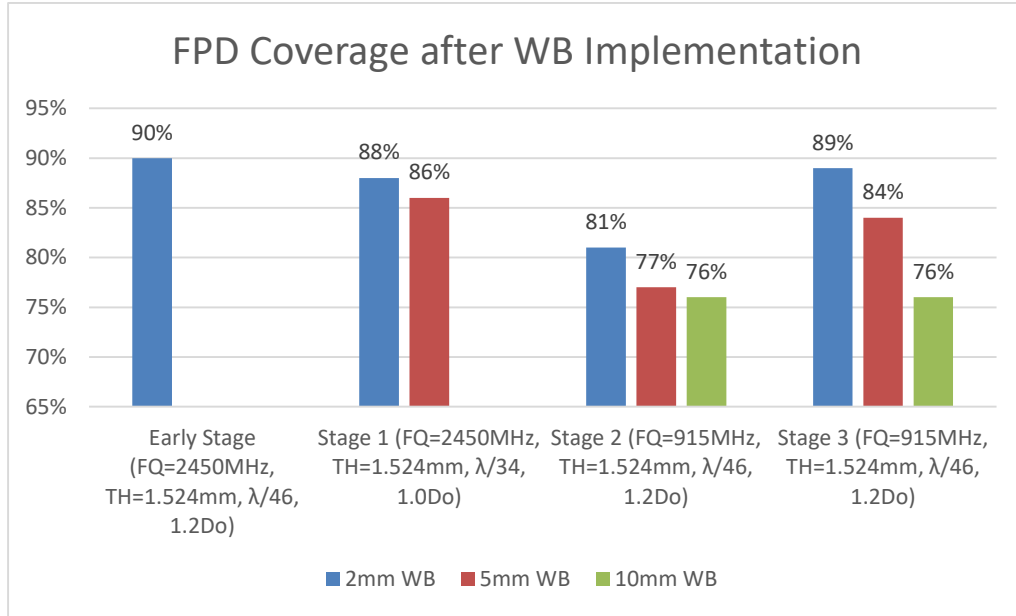


Figure 4.20: The FPD Coverage Percentage After WB Implementations

As presented in **Table 4.5**, **Figure 4.18** and **Figure 4.19**, the water bolus implementations showed some significant effect on HTP executions. The reshaping effect of EFS can be seen clearly, especially for stage 2 and stage 3 ($FQ=915\text{MHz}$, $TH=1.524\text{mm}$, $\lambda/46$, 1.2Do) in 2mm water bolus implementation in HTP. The heating pattern shifted to the left and spread more evenly compared with the result without water bolus. These results proved by observations from S.Singh et al.(2017) and Stauffer et al. (2017)

However, the effective SAR value decreased from 2.0mW/g to 1.3mW/g. This would affect the total treatment periods and make it become longer. Besides that, due to the low wavelength in 2450MHz HTP, the thick water bolus (5mm and 10mm) has sharply decreased the efficiency for both designs in early stage and stage 1 cancer simulation. The SAR distribution is unable to focus on the cancer tissue and is mostly concentrated on the skin area, as shown in **Figure 4.17**.

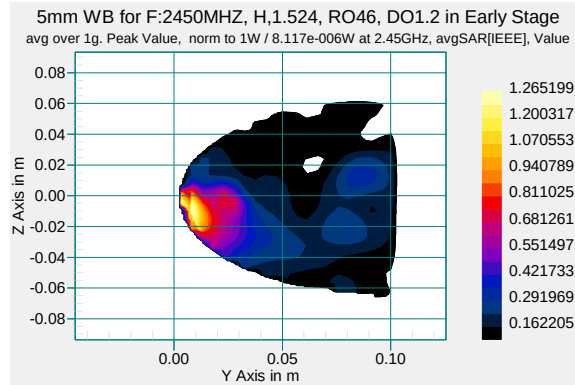


Figure 4.21: SAR Result for 5mm WB Implementation in Early Stage HTP ($FQ=2450\text{MHz}$, $TH=1.524\text{mm}$, $\lambda/46$, $1.2D_o$)

This finding is agreed by Lias et al. (2022), where water bolus can reshape the heating pattern in HTP while the thinnest water bolus showed the best effect in the purpose of reducing the unwanted hotspot and reshaping the heating pattern, especially in concentrating the heat toward cancer tissue.

4.6 DoE 5: Treatment Periods Required for Each Final Design

Based on **Equation 3.31 (Section 3.7)**, the treatment period of each final design in the respective stage are calculated and tabulated in **Table 4.6**.

Table 4.6: Treatment Period for Each Stage.

Cancer Stages and Final Design	Treatment Period Required
Early Stage ($FQ=2450\text{MHz}$, $TH=1.524\text{mm}$, $\lambda/46$, $1.2D_o$, 2mm WB) SAR=4.8mW/g	48.75 to 97.5mins
Stage 1 ($FQ=2450\text{MHz}$, $TH=1.524\text{mm}$, $\lambda/34$, $1.0D_o$, 2mm WB) SAR= 3.0mW/g	78.00 to 156.00mins
Stage 2 ($FQ=915\text{MHz}$, $TH=1.524\text{mm}$, $\lambda/46$, $1.2D_o$, 2mm WB) SAR=1.3mW/g	180.00 to 360.00mins
Stage 3 ($FQ=915\text{MHz}$, $TH=1.524\text{mm}$, $\lambda/46$, $1.2D_o$, 2mm WB) SAR=1.3mW/g	180.00 to 360.00mins

The treatment period estimation is important, especially for hyperthermia treatment planning. Hence, this estimation period helps in planning for the treatment and ensuring minimal side effects.

The animal studies mentioned by Behrouzkia at 2016 stated that 60 to 360 minutes are required to reach 42°C by using HTP, which agrees with the results above (Behrouzkia et al., 2016). While findings by Gas also proved that the increase in temperature and treatment periods could be affected by applied frequency, electrical properties of tissue and required penetration depth (Gas, 2012).

4.7 DoE 6: Validation with Thermo-simulation

For the DoE 6 results, all the most suitable designs shown in **Table 4.6** are conducted under the Hyperthermia-T-Multi-Simulation Setup, as discussed in **Section 3.8.6**. The simulation results are compared in **Table 4.7**

Table 4.7: Comparison Between EM Simulation Results and Thermo-Simulation

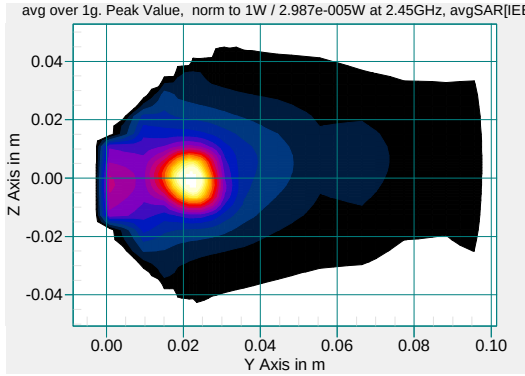
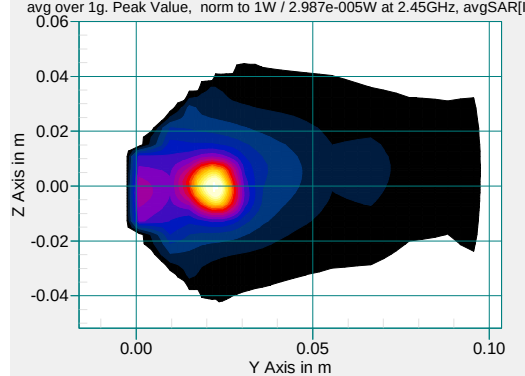
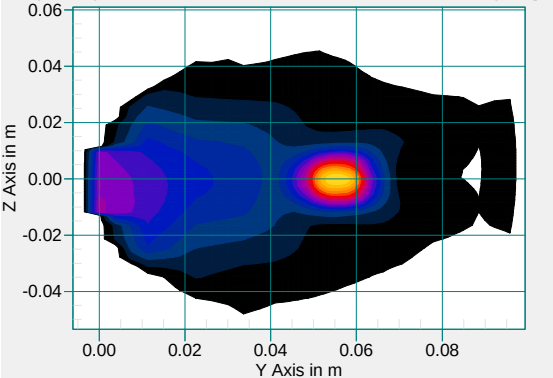
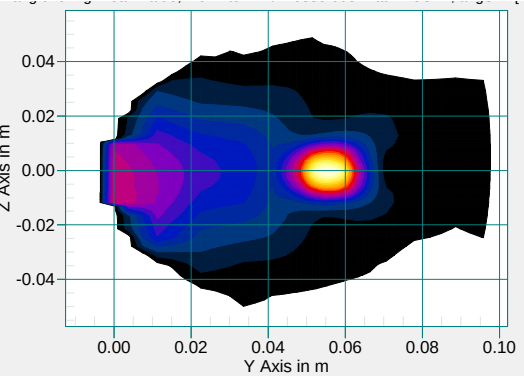
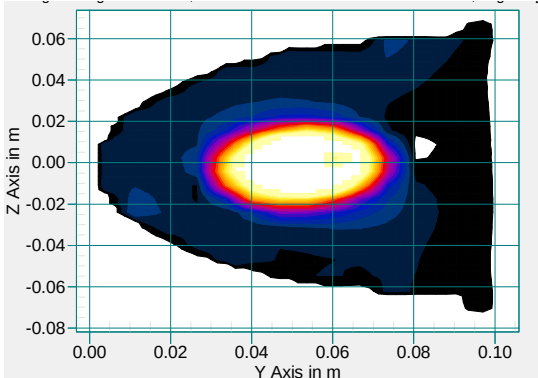
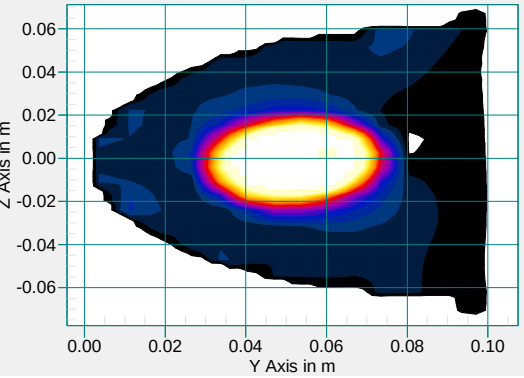
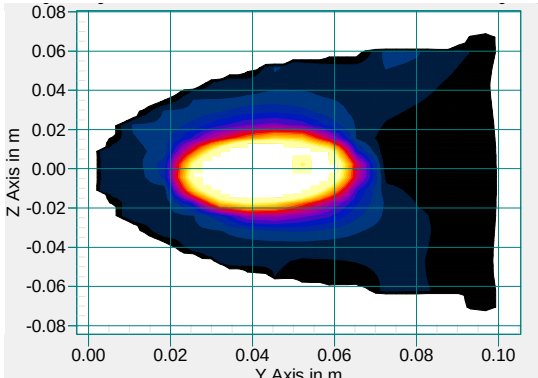
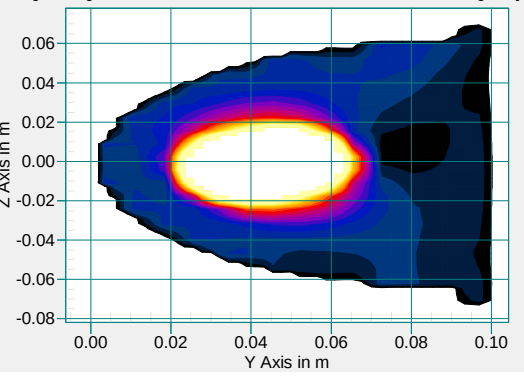
EM Simulation Results	Thermo-Simulation Results
Early Stage ($FQ=2450\text{MHz}$, $TH=1.524\text{mm}$, $\lambda/46$, $1.2D_0$, 2mm WB) 	Early Stage ($FQ=2450\text{MHz}$, $TH=1.524\text{mm}$, $\lambda/46$, $1.2D_0$, 2mm WB) 

Table 4.7 continued

EM Simulation Results	Thermo-Simulation Results
Stage 1(FQ=2450MHz, TH=1.524mm, $\lambda/34$, 1.0D_o, 2mm WB) 	Stage 1(FQ=2450MHz, TH=1.524mm, $\lambda/34$, 1.0D_o, 2mm WB) 
Stage 2 (FQ=915MHz, TH=1.524mm, $\lambda/46$, 1.2D_o, 2mm WB) 	Stage 2 (FQ=915MHz, TH=1.524mm, $\lambda/46$, 1.2D_o, 2mm WB) 
Stage 3 (FQ=915MHz, TH=1.524mm, $\lambda/46$, 1.2D_o, 2mm WB) 	Stage 3 (FQ=915MHz, TH=1.524mm, $\lambda/46$, 1.2D_o, 2mm WB) 

The Thermo-Simulation results showed that the SAR distribution under the bio-heat equation approach method, showed almost similar findings as EM simulation, where the heating regions in Thermo-Simulation are slightly larger than EM simulation results. Hence, these results are validated.

4.8 Summarisation of FPD Coverage and Size of Unwanted Hotspot

To summarize the improvement of HTP efficiency with each component integrated from DoE 1 (microstrip antenna) until DoE 4 (WB), **Figure 4.22** presents the summary of selection of designs for each cancer stage through each DoE, while **Table 4.8** showed the improvement in the aspect of FPD coverage (**Equation 4.1**) and the size of unwanted hotspot region.

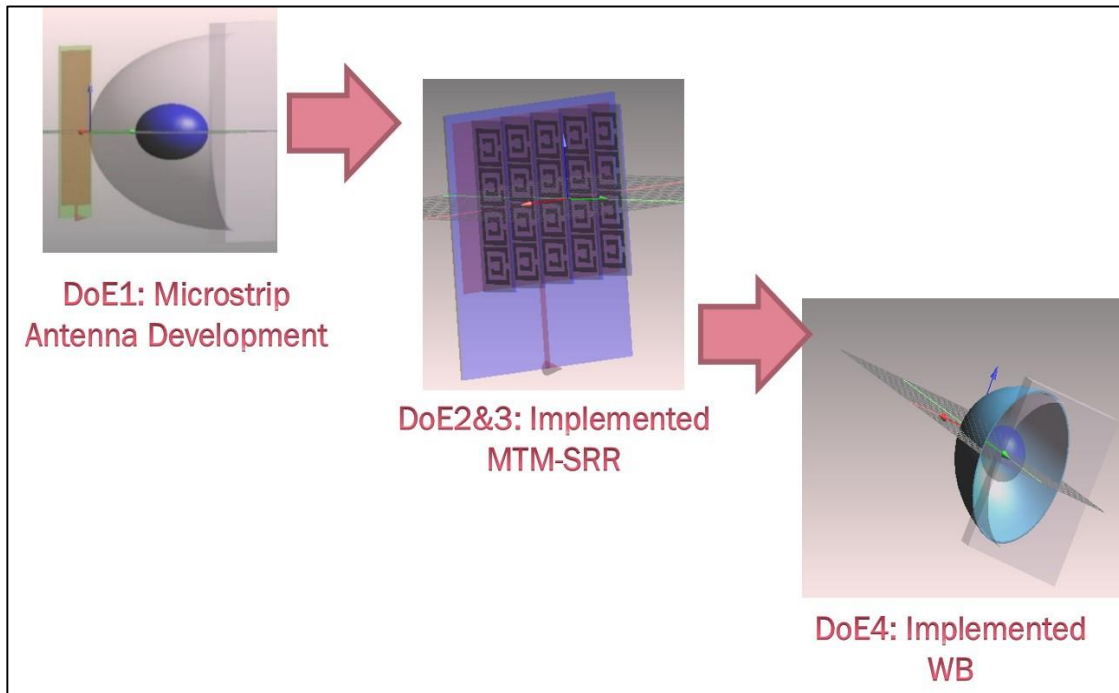


Figure 4.22: Summary of Selection of Design for Each Cancer Stage Under Respective DoEs

Table 4.8: FPD Coverage and Size of Unwanted Hotspot for Selected Design in Each Cancer Stages

Selected Design Based on Each DoE	FPD (mm)	FPD Coverage (%)	Size of Unwanted Hotspot (mm)	Refer to
Required FPD for Early-Stage breast cancer is 17.5 to 28.6mm				Figure 4.2
DoE 1: Microstrip antenna of $FQ=2450\text{MHz}$; $TH=1.524\text{mm}$	15.4-27.2	87.05	13.4	Table 4.1
DoEs 2 and 3: MTM-SRR with $\lambda/46$, $1.2D_0$	14.8-28.1	95.32	7.3	Table 4.2
DoE4: 2mm WB	16.8-27.5	89.92	2.7	Table 4.5
Required FPD for Stage 1 breast cancer is 45.4 to 66.1mm				Figure 4.2
DoE 1: Microstrip antenna of $FQ= 2450\text{MHz}$; $TH=1.524\text{mm}$	0 -15.3 and 41.9- 62.4	82.02	19.6	Table 4.1
DoEs 2 and 3: MTM-SRR with $\lambda/34$, $1.0 D_0$	43.5-63.0	84.58	9.2	Table 4.3
DoE4: 2mm WB	47.4-65.5	87.48	2.2	Table 4.5

Table 4.8 continued

Selected Design Based on Each DoE	FPD (mm)	FPD Coverage (%)	Size of Unwanted Hotspot (mm)	Refer to
Required FPD for Stage 2 breast cancer is 28.6 to 73.6 mm				Figure 4.2
DoE 1: Microstrip antenna of $FQ=915\text{MHz}$; $TH=1.524\text{mm}$	26.9-63.3	77.11	4.2	Table 4.1
DoEs 2 and 3: MTM-SRR with $\lambda/46$, $1.2D_0$	29.1-65.7	81.30	0	Table 4.3
DoE4: 2mm WB	28.9-65.4	81.08	0	Table 4.5
Required FPD for Stage 3 breast cancer is 20.1 to 63.7 mm				Figure 4.2
DoE 1: Microstrip antenna of $FQ=915\text{MHz}$; $TH=1.524\text{mm}$	17.9-54.8	79.59	2.2	Table 4.1
DoEs 2 and 3: MTM-SRR with $\lambda/46$, $1.2D_0$	20.5-57.1	83.94	0	Table 4.3
DoE4: 2mm WB	23.5-62.5	89.45	0	Table 4.5

4.9 Validation with Previous MTM Research

Based on **Table 4.8**, in this research, the MTM-SRR can reach the FPD coverage from 81.30% until 95.32%. The increment of FPD coverage with MTM integration also can be seen in research by Vrba et al. in year 2016. In their research, the 2×3 MTM-ZOR arrays, obtained the FPD that reaching of 3.5 cm deep plane with 86% of region that can heated more 41°C (Vrba et al., 2016).

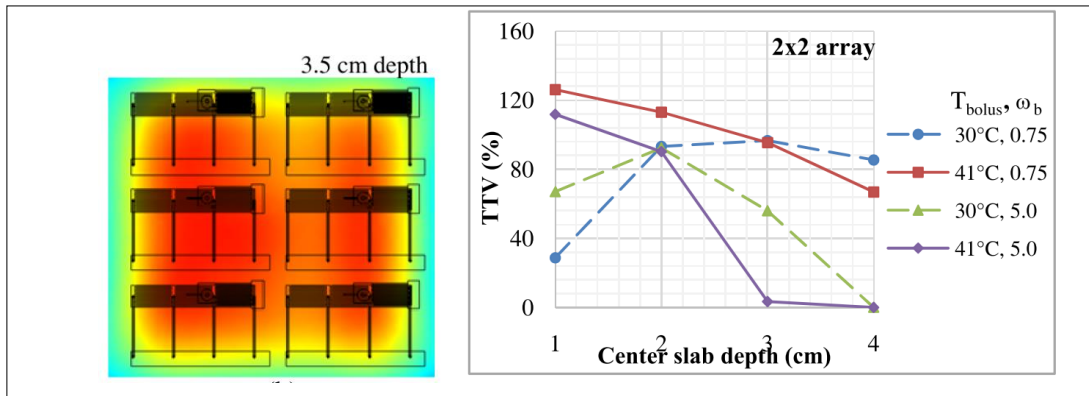


Figure 4.23: Simulation Results by Vrba et al. in 2016

Therefore, the stage 2 and stage 3 breast cancer (cancer tissue located deeper than 3.5cm) results in this research can be validated with Vrba et al. findings, where the FPD coverage for these two stages can reach above 81.30 %.

While the effect of MTM-SRR cell and distance between MTM-SRR cell investigated are agreed with results of Yusri and Muldarisnur in year 2021.

Yusri and Muldarisnur found that, due to resonance effect produce by gaps will shift the antenna directivity, the simulations results did not show that always the MTM-SRR with higher number of cells performed better results (Yusri & Muldarisnur, 2021). This agreed with DoEs 2 and 3 results, whereas MTM-SRR $\lambda/34$ has higher efficacy in

stage 1 cancer HTP simulation. While distance between cell that can lead smaller cell number also showed that 1.2 D_0 performed better in early, stage 2 and stage 3 cancer.

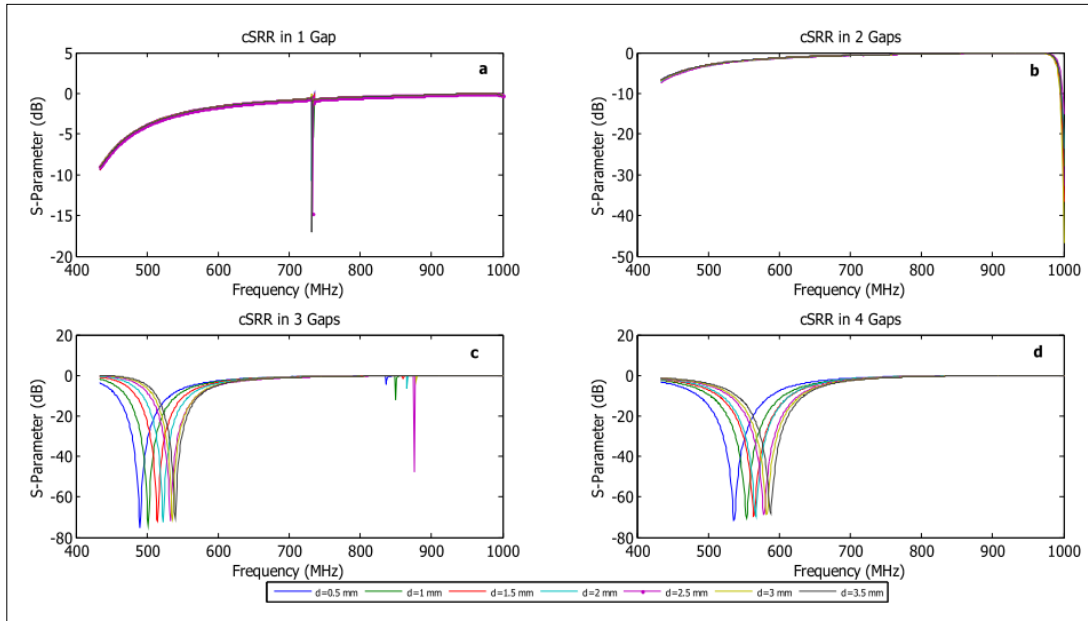


Figure 4.24: Return Loss Shifted Due to Various SRR Gaps Applied (Yusri & Muldarisnur, 2021)

4.10 Summary of Chapter

This chapter presented the results and discussion. For the initial phase, the average breast size for each cancer stage has been calculated and presented in **Figure 4.2**.

The results in **DoE 1** have shown that applied frequency and thickness contributed to significant differences in terms of PD and FPD of HTP. The selected designs for the next step of the experiment are: **Early Stage:** $FQ=2450\text{MHz}$; $TH=1.524\text{mm}$, **Stage 1:** $FQ=915\text{MHz}$; $TH=1.524\text{mm}$ and $FQ=2450\text{MHz}$; $TH=1.524\text{mm}$, **Stage 2:** $FQ=915\text{MHz}$; $TH=1.524\text{mm}$ and **Stage 3:** $FQ=915\text{MHz}$; $TH=1.524\text{mm}$.

Meanwhile, **DoE 2 and DoE 3** have investigated the integration of MTM, and resulted in a significant effect, especially in terms of FPD and SAR values. Almost all results with MTM-SRR integration showed a more concentrated heating region compared

with HTP without MTM. The best results for each stage are, **Early Stage:** $FQ=2450\text{MHz}$, $TH=1.524\text{mm}$, $\lambda/46$, $1.2D_0$, **Stage 1:** $FQ=2450\text{MHz}$, $TH=1.524\text{mm}$, $\lambda/34$, $1.0D_0$, **Stage 2:** $FQ=915\text{MHz}$, $TH=1.524\text{mm}$, $\lambda/46$, $1.2D_0$ and **Stage 3:** $FQ=915\text{MHz}$, $TH=1.524\text{mm}$, $\lambda/46$, $1.2D_{0+}$.

DoE 4 proved that implementation of WB can reshape the heating pattern of HTP, and the best design of WB is a 2mm thickness breast-shaped WB for all cancer stages.

DoE 5 indicated that all selected HTP designs are under suitable TPE, where the estimated time is between 60 minutes to 360 minutes. While Thermo-Simulations involved in **DoE 6** validated the outcomes in **DoE 4**.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Introduction

This chapter discusses the research finding based on the targeted research objectives, research limitations and future recommendations to improve the HTP.

5.2 Research Findings

The research findings are summarized in **Table 5.1**.

Table 5.1: Summarization of Research Findings

Research Objective (R.O)	Phase	DoE Involved	Results	Status
R.O. 1	Initial Phase	None	Cancer location of each stage Early Stage: 17.5 to 28.6mm Stage 1: 45.4 to 66.1mm Stage 2: 28.5 to 73.6 mm Stage 3: 20.1 to 63.7mm	R.O. 1 is achieved
	Phase 1	DoE 1	The most suitable antenna designs for each stage: Early Stage: $FQ=2450\text{MHz}$, $TH=1.524\text{mm}$, $FPD=15.4$ to 27.2 mm, $SAR=14$ mW/g Stage 1: $FQ=915\text{MHz}$, $TH=1.524\text{mm}$, $FPD=45.9$ to 63.8mm , $SAR=0.0573\text{mW/g}$ and $FQ=2450\text{MHz}$, $TH=1.524\text{mm}$, $FPD=0$ to 15.3mm and 41.9 to 62.4mm , $SAR=5\text{mW/g}$ Stage 2: $FQ=915\text{MHz}$, $TH=1.524\text{mm}$, $FPD=26.9$ to 67.3mm , $SAR=2\text{mW/g}$ Stage 3: $FQ=915\text{MHz}$, $TH=1.524\text{mm}$, $FPD=17.9$ to 54.8mm , $SAR=2\text{mW/g}$	

Table 5.1 continued

R. O.2	Phase 2	DoE 2	The most suitable SRR MTM designs for each stage: Early Stage: $FQ=2450\text{MHz}$, $TH=1.524\text{mm}$, $\lambda/46$, 1.2Do, FPD= 14.8 to 28.1mm, SAR=5mW/g Stage 1 : $FQ=2450\text{MHz}$, $TH=1.524\text{mm}$, $\lambda/34$, 1.0Do, FPD= 43.5 to 63.0mm, SAR=3.5mW/g Stage 2 : $FQ=915\text{MHz}$, $TH=1.524\text{mm}$, $\lambda/46$, 1.2Do, FPD= 29.1 to 61.5mm, SAR=2mW/g Stage 3 : $FQ=915\text{MHz}$, $TH=1.524\text{mm}$, $\lambda/46$, 1.2Do, FPD= 20.5 to 57.1mm, SAR=2mW/g	R.O. 2 is achieved
		DoE 3		
		DoE 4	2mm thick WB is the most suitable WB thickness for all cancer stages. The FPD and SAR for each stage become more focused, and unwanted hotspots become lesser.	
	Phase 3			
R.O. 3	Phase 4	DoE 5	The treatment periods required for each final design are calculated. The modified HTP designed for stage 2 and stage 3 took the longest time (180.00 to 360.00mins), while the modified HTP for the early stage used the least time, it cost only 48.75 to 97.5mins.	R.O. 3 is achieved
		DoE 6	The EM simulation results validated by the Thermo Simulation results	

Based on **Table 5.1**, all the research objectives are completed. Nevertheless, further enhancement on the HTP applicators is significantly required to ensure the heating regions will completely cover the targeted cancer tissues.

5.3 Research Limitations and Future Recommendations

The major challenge in this research is to attain the mu-negative properties of SRR for MTM lens structure. Most of the MTM research works previously significantly used manual input for MTM properties. The negative properties retrieving theorem based on

(Orfanidis, 2016; Pendry, 2000; Pozar, 2012; Smith et al., 2005; Wojciech & Thanh, 2019) were mainly measured by MATLAB software. With regard, a series of investigations have been conducted to identify the permeability and permittivity of the SRR for the MTM lens in SEMCAD X. Finally, the retrieving of mu-negative has been achieved.

However, in this research, there are some limitations that have the opportunity for improvement. The first limitation is only one type of MTM pattern or type is investigated in this research. The MTM pattern used in this research is rectangular SRR, meanwhile the circle SRR, MTM-ZOR, broadside-coupled SRR, multi-direction-array MTM, DNG MTM and such could be the good perspective way to improve the MTM efficiency for HTP improvement.

Besides, hardware fabrication is required to further observe the effects of heat distribution on the treated tissue, which can be developed with mimicked cancer gel tissue or animal experiment, with helps from medical experts. Through these experiments, the performance of HTP designs can be validated under the real environment and identifying other variable that could effect the HTP performance.

Moreover, for the HTP future development, various research approach such as variety of water bolus solvents, antenna substrates, antenna patterns, different organs and cancer tissues research are also recommended.

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APPENDICES

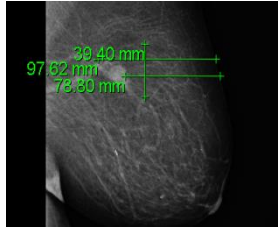
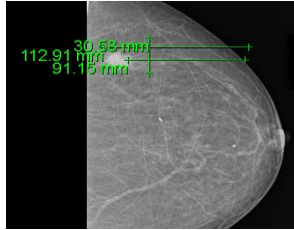
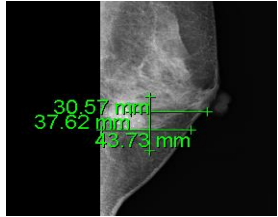
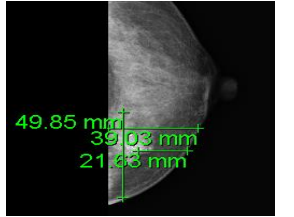
APPENDIX A: PUBLICATIONS

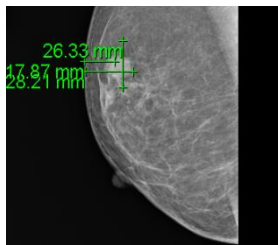
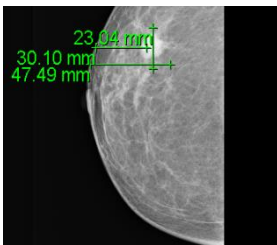
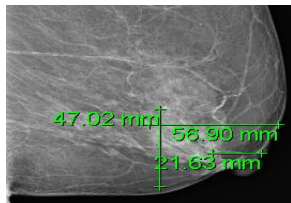
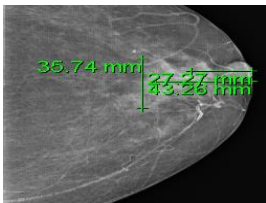
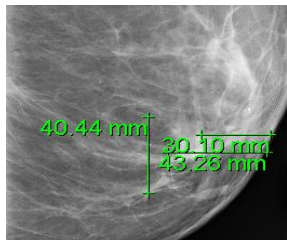
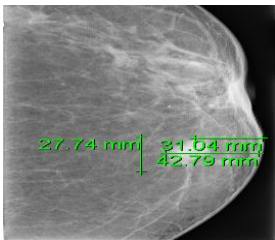
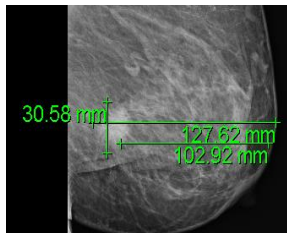
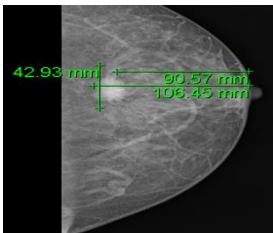
1. Wong, V. L., Lias, K., Buniyamin, N., Basri, H. M., & Ahmad Narihan, M. Z. (2021). SAR distribution of non-invasive hyperthermia with microstrip applicators on different breast cancer stages. *Indonesian Journal of Electrical Engineering and Computer Science*, 22(1), 232–240. <https://doi.org/10.11591/ijeecs.v22.i1.pp232-240>
2. Lias, K., Basri, H. M., Wong, V. L., & Kipli, K. (2022). Integrated lens microstrip-slot applicator for breast hyperthermia procedure. *Applied Engineering*, 6(1), 1–6. <https://doi.org/10.11648/j.ae.20220601.11>
3. Wong, V. L., & Lias, K. (2021). Metamaterial applicator for hyperthermia cancer treatment procedure: overview study. In *3rd International Conference for Innovation in Biomedical Engineering and Life Sciences* (pp. 86–92). Springer International Publishing.

APPENDIX B: REAL PATIENT MAMMOGRAM DATA AND DICOM ANALYSIS

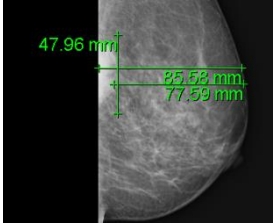
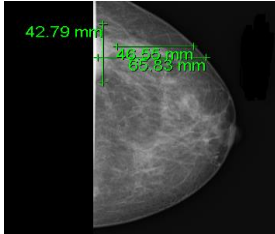
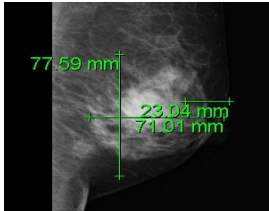
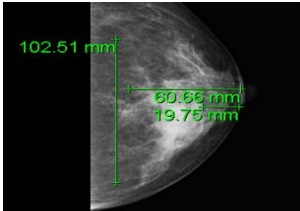
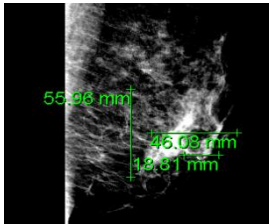
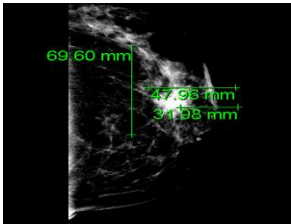
DEPTH ANALYSIS OF BREAST MAMMOGRAM IMAGES BY USING DICOM.

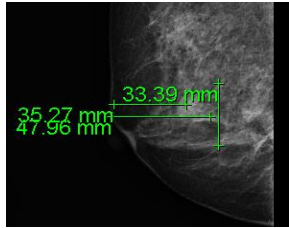
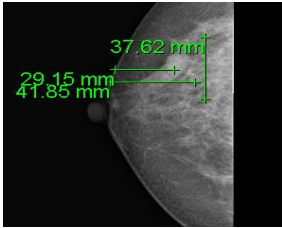
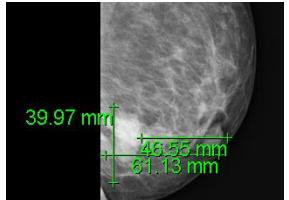
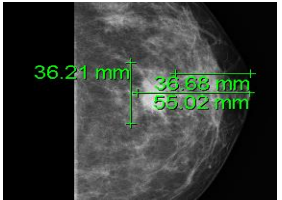
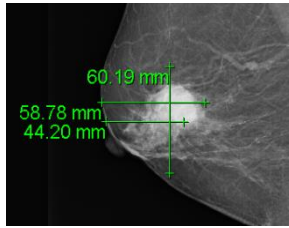
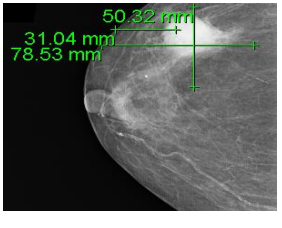
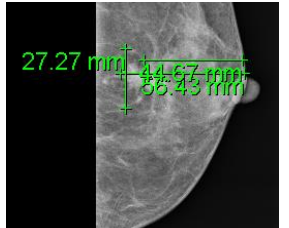
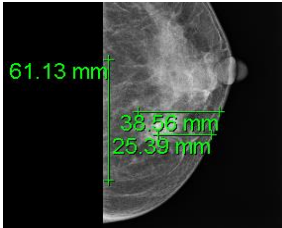
Early Stage (Stage In situ): Growth of cancerous is focused to the starting site, while the tumour does not spread to surrounding body tissues or other organs. According to ground through with co-supervisor (medical doctor), breast cancer images in early stage are difficult to detect because of equipment limitations

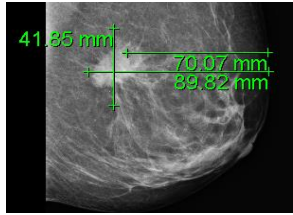
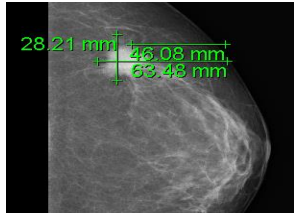
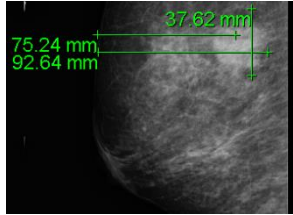
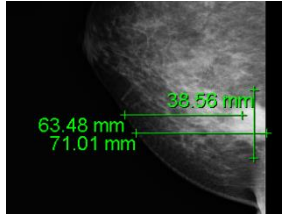
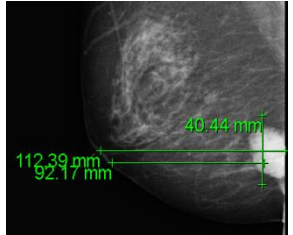
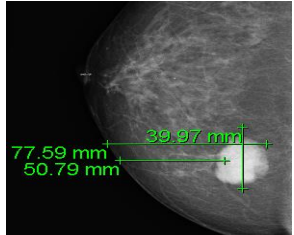
No.	Image of Cancer		Breast Cancer Location
	Medio-Lateral Oblique (MLO)	Cranio-Caudal (CC)	
1.			Average SD $[(MLO+CC)/2] = (78.80\text{mm} + 91.15\text{mm})/2 = 84.98\text{mm}$ Average ID $[(MLO+CC)/2] = (97.62\text{mm} + 112.91\text{mm})/2 = 105.27\text{mm}$
2.			Average SD $[(MLO+CC)/2] = (30.57\text{mm} + 21.63\text{mm})/2 = 26.10\text{mm}$ Average ID $[(MLO+CC)/2] = (43.73\text{mm} + 39.03\text{mm})/2 = 41.38\text{mm}$

3.			Average SD [(MLO+CC)/2] = (17.87mm + 30.10mm)/2 = 23.99mm Average ID [(MLO+CC)/2] = (28.21mm + 47.49mm)/2 = 37.85mm
4.			Average SD [(MLO+CC)/2] = (21.63mm + 27.27mm)/2 = 24.45mm Average ID [(MLO+CC)/2] = (56.90mm + 43.26mm)/2 = 50.08mm
5.			Average SD [(MLO+CC)/2] = (30.10mm + 31.04mm)/2 = 30.57mm Average ID [(MLO+CC)/2] = (43.26mm + 42.79mm)/2 = 43.03mm
6.			Average SD [(MLO+CC)/2] = (102.92mm + 90.57mm)/2 = 96.75mm Average ID [(MLO+CC)/2] = (127.62mm + 106.45mm)/2 = 117.04mm

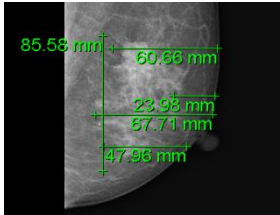
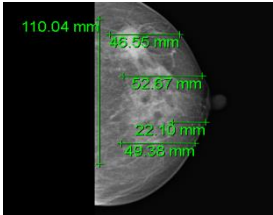
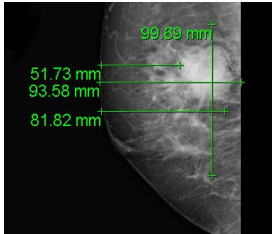
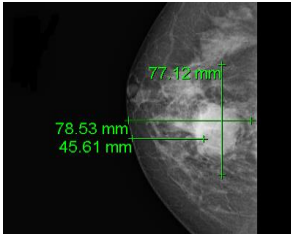
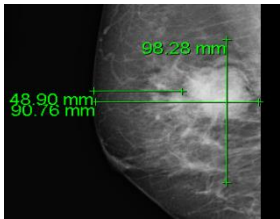
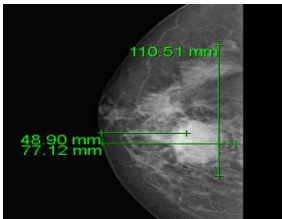
Stage 1 :Stage 1 cancer is relatively small and focused within the organ where it started.

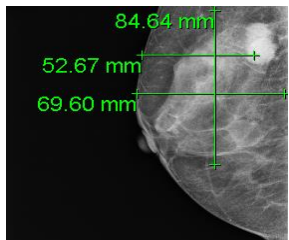
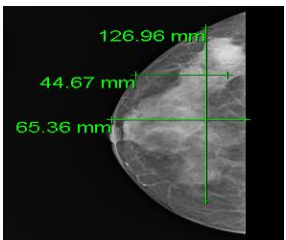
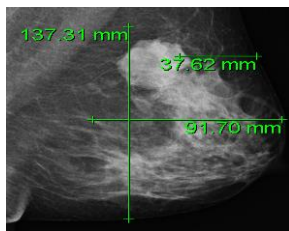
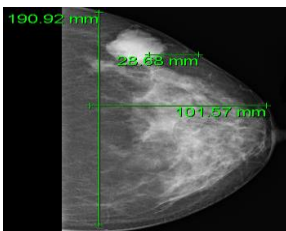
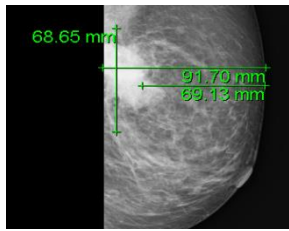
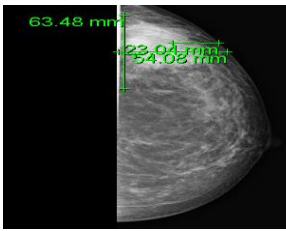
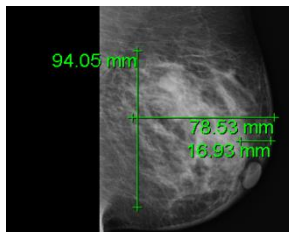
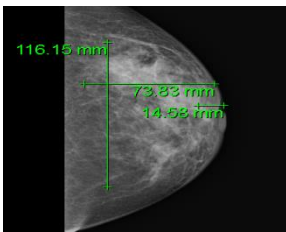
No.	Image of Cancer		Breast Cancer Location
	Medio-Lateral Oblique (MLO)	Cranio-Caudal (CC)	
1.			Average SD [(MLO+CC)/2] = (77.59mm + 46.55mm)/2 = 62.07mm Average ID [(MLO+CC)/2] = (85.58mm + 65.83mm)/2 = 75.71mm
2.			Average SD [(MLO+CC)/2] = (23.04mm + 19.75mm)/2 = 21.40mm Average ID [(MLO+CC)/2] = (71.01mm + 60.66mm)/2 = 65.84mm
3.			Average SD [(MLO+CC)/2] = (18.81mm + 31.98mm)/2 = 25.40mm Average ID [(MLO+CC)/2] = (46.08mm + 47.96mm)/2 = 47.02mm

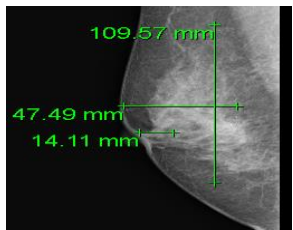
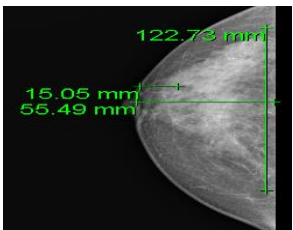
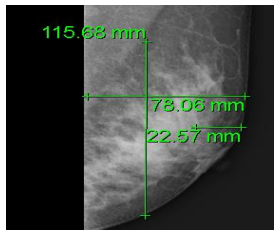
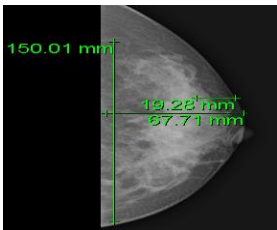
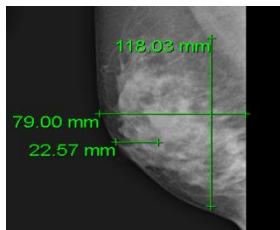
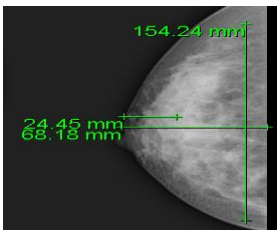
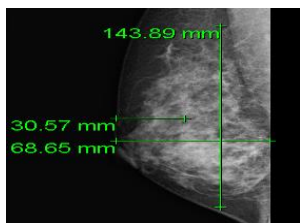
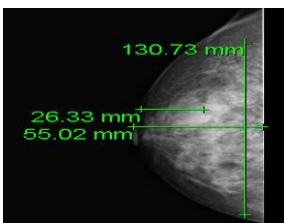
4.			Average SD [(MLO+CC)/2] = (35.27mm + 29.15mm)/2 = 32.21mm Average ID [(MLO+CC)/2] = (47.96mm + 41.85mm)/2 = 44.91mm
5.			Average SD [(MLO+CC)/2] = (46.55mm + 36.68mm)/2 = 41.62mm Average ID [(MLO+CC)/2] = (61.13mm + 55.02mm)/2 = 58.08mm
6.			Average SD [(MLO+CC)/2] = (44.20mm + 31.04mm)/2 = 37.62mm Average ID [(MLO+CC)/2] = (58.78mm + 78.53mm)/2 = 68.66mm
7.			Average SD [(MLO+CC)/2] = (44.67mm + 25.39mm)/2 = 35.03mm Average ID [(MLO+CC)/2] = (56.43mm + 38.56mm)/2 = 47.50mm

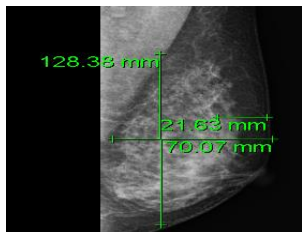
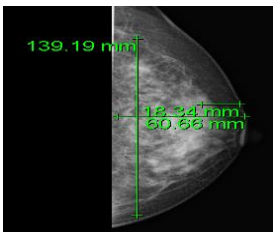
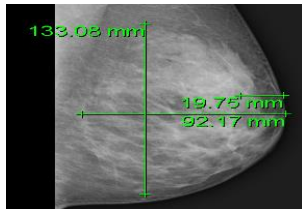
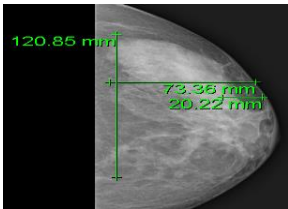
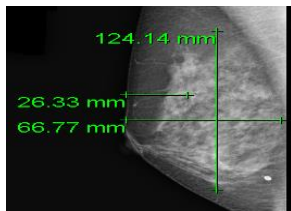
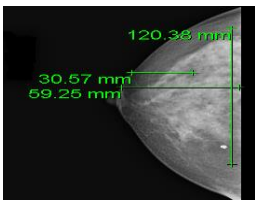
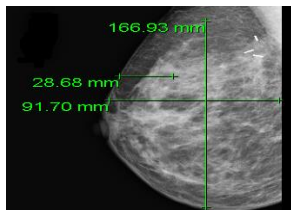
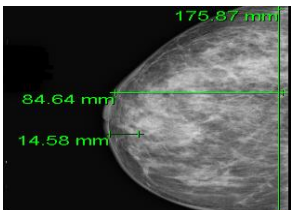
8.			Average SD [(MLO+CC)/2] = (70.07mm + 46.08mm)/2 = 58.08mm Average ID [(MLO+CC)/2] = (89.82mm + 63.48mm)/2 = 76.65mm
9.			Average SD [(MLO+CC)/2] = (75.24mm + 63.48mm)/2 = 69.36mm Average ID [(MLO+CC)/2] = (92.64mm + 71.01mm)/2 = 81.83mm
10.			Average SD [(MLO+CC)/2] = (92.17mm + 50.79mm)/2 = 71.48mm Average ID [(MLO+CC)/2] = (112.39mm + 77.59mm)/2 = 84.88mm

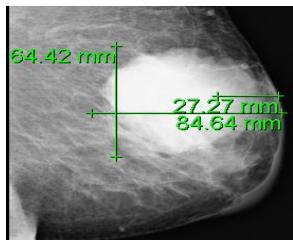
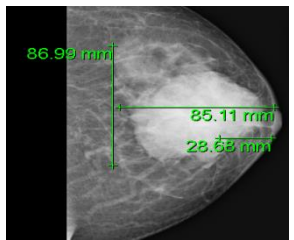
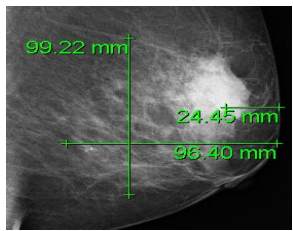
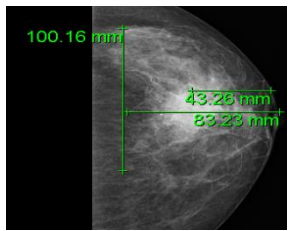
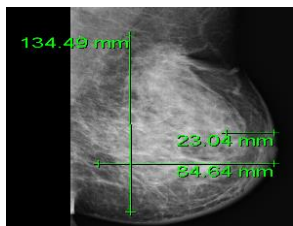
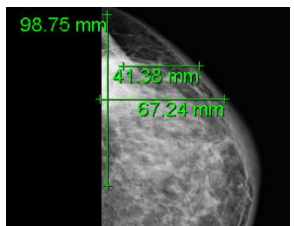
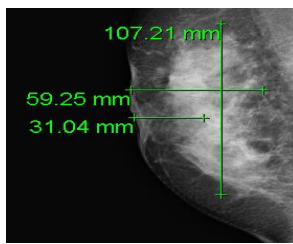
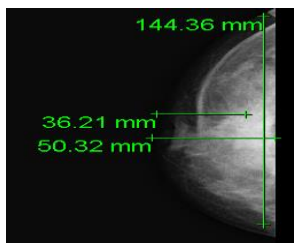
Stage 2 :Stage 2 cancer do not started to spread into surrounding tissues however tumour become larger than that in stage 1. Generally, stage 2 means that cancer cells have spread into lymph nodes near to the tumor, based on the type of cancer.

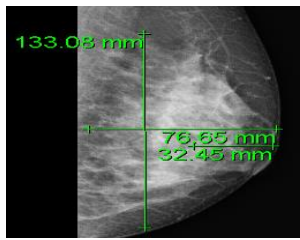
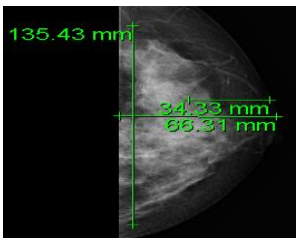
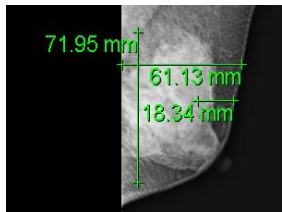
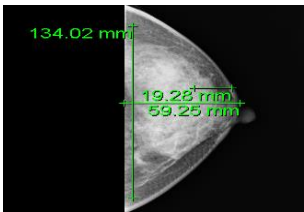
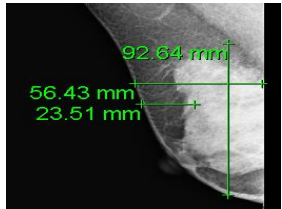
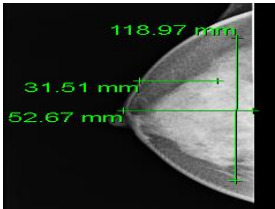
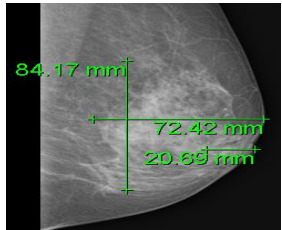
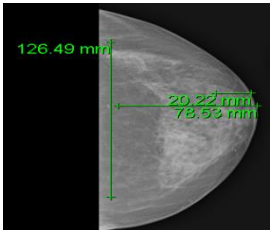
No.	Image of Cancer		Breast Cancer Location
	Medio-Lateral Oblique (MLO)	Cranio-Caudal (CC)	
1.			Average SD $[(MLO+CC)/2] = (23.98\text{mm} + 22.10\text{mm})/2 = 23.04\text{mm}$ Average ID $[(MLO+CC)/2] = (67.71\text{ mm} + 49.38\text{mm})/2 = 58.55\text{ mm}$
2.			Average SD $[(MLO+CC)/2] = (51.73\text{mm} + 45.61\text{mm})/2 = 48.67\text{mm}$ Average ID $[(MLO+CC)/2] = (93.58\text{mm} + 78.53\text{mm})/2 = 86.06\text{mm}$
3.			Average SD $[(MLO+CC)/2] = (48.90\text{mm} + 48.90\text{mm})/2 = 48.90\text{mm}$ Average ID $[(MLO+CC)/2] = (90.76\text{mm} + 77.12\text{mm})/2 = 83.94\text{mm}$

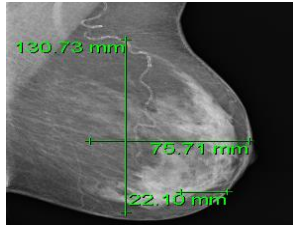
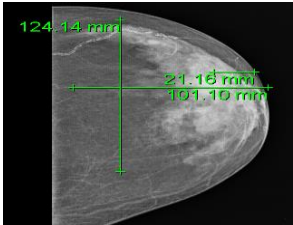
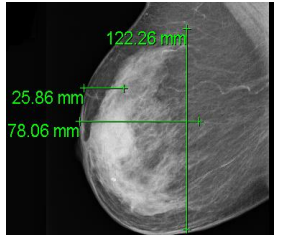
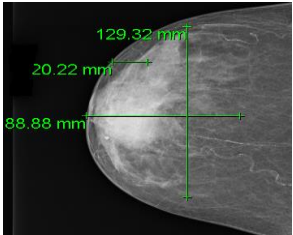
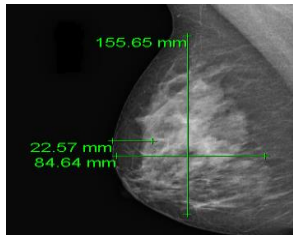
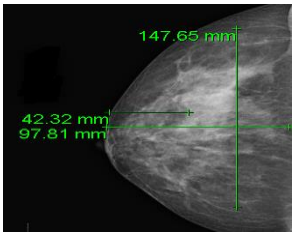
4.			Average SD [(MLO+CC)/2] = (52.67mm + 44.67mm)/2 = 48.67mm Average ID [(MLO+CC)/2] = (69.60mm + 65.36mm)/2 = 67.48mm
5.			Average SD [(MLO+CC)/2] = (37.62mm + 28.68mm)/2 = 33.15mm Average ID [(MLO+CC)/2] = (91.70 mm + 101.57mm)/2 =96.64mm
6.			Average SD [(MLO+CC)/2] = (69.13mm + 23.04mm)/2 = 46.09mm Average ID [(MLO+CC)/2] = (91.70mm + 54.08mm)/2 =72.89mm
7.			Average SD [(MLO+CC)/2] = (16.93mm + 14.58mm)/2 = 15.76mm Average ID [(MLO+CC)/2] = (78.53mm + 73.83mm)/2 =76.18mm

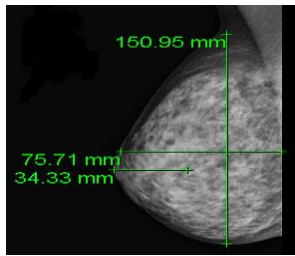
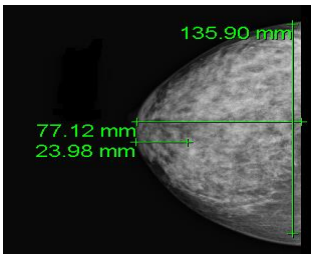
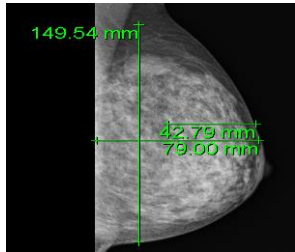
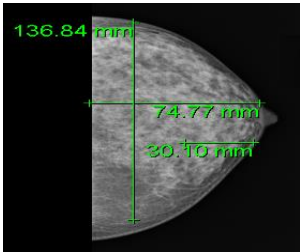
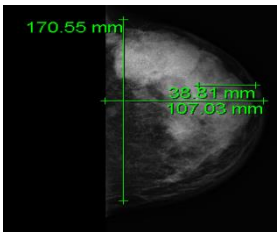
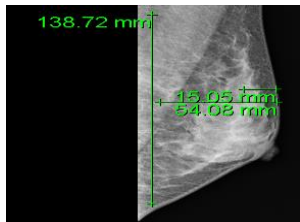
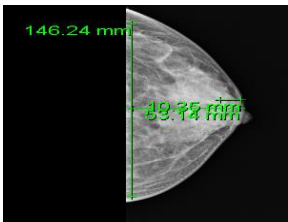
8.			Average SD [(MLO+CC)/2] = (14.11mm + 15.05mm)/2 = 14.58mm Average ID [(MLO+CC)/2] = (47.49mm + 55.49mm)/2 = 51.49mm
9.			Average SD [(MLO+CC)/2] = (22.57mm + 19.28mm)/2 = 20.93mm Average ID [(MLO+CC)/2] = (73.06mm + 67.71mm)/2 = 72.89mm
10.			Average SD [(MLO+CC)/2] = (22.57mm + 24.45mm)/2 = 23.51mm Average ID [(MLO+CC)/2] = (79.00mm + 68.18mm)/2 = 73.59mm
11.			Average SD [(MLO+CC)/2] = (30.57mm + 26.33mm)/2 = 28.45mm Average ID [(MLO+CC)/2] = (68.65mm + 55.02mm)/2 = 61.84mm

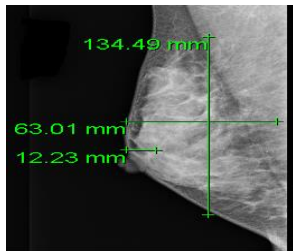
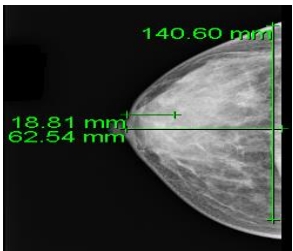
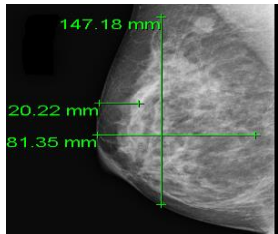
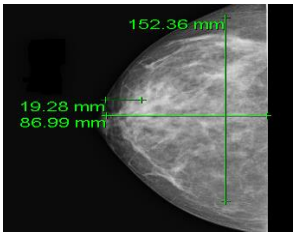
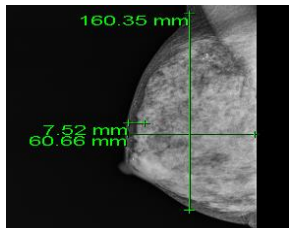
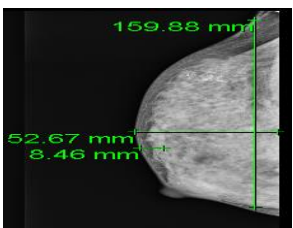
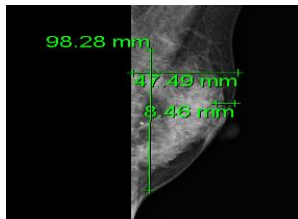
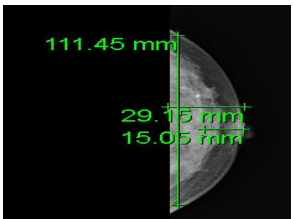
12.			Average SD [(MLO+CC)/2] = (21.63mm + 18.34mm)/2 = 19.99mm Average ID [(MLO+CC)/2] = (70.07mm + 60.66mm)/2 = 65.37mm
13.			Average SD [(MLO+CC)/2] = (19.75mm + 20.22mm)/2 = 19.99mm Average ID [(MLO+CC)/2] = (92.17mm + 73.36mm)/2 = 82.77mm
14.			Average SD [(MLO+CC)/2] = (26.33mm + 30.57mm)/2 = 28.45mm Average ID [(MLO+CC)/2] = (66.77mm + 59.25mm)/2 = 63.01mm
15.			Average SD [(MLO+CC)/2] = (28.68mm + 14.58mm)/2 = 21.63mm Average ID [(MLO+CC)/2] = (91.70mm + 84.64mm)/2 = 88.17mm

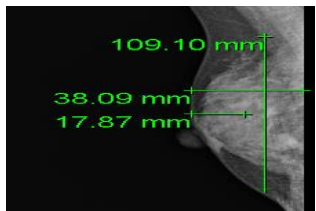
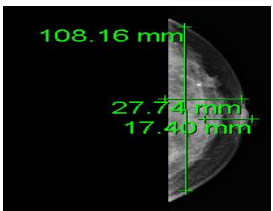
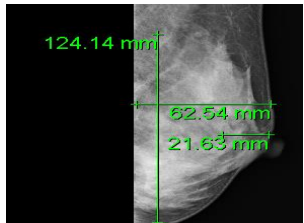
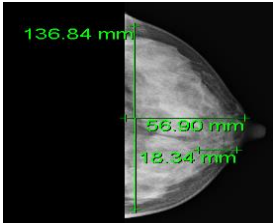
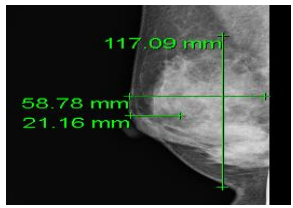
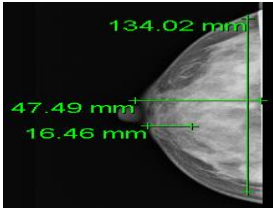
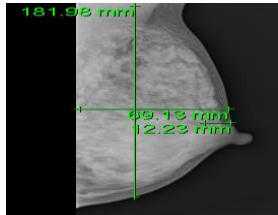
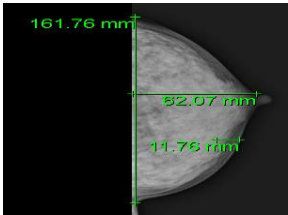
16.			Average SD [(MLO+CC)/2] = (27.27mm + 28.68mm)/2 = 27.98mm Average ID [(MLO+CC)/2] = (84.64mm + 85.11mm)/2 =84.88mm
17.			Average SD [(MLO+CC)/2] = (24.45mm + 43.26mm)/2 = 33.86mm Average ID [(MLO+CC)/2] = (96.40mm + 83.23mm)/2 =89.82mm
18.			Average SD [(MLO+CC)/2] = (23.04mm + 41.38mm)/2 = 32.21mm Average ID [(MLO+CC)/2] = (84.64mm + 67.24mm)/2 =75.94mm
19.			Average SD [(MLO+CC)/2] = (31.04mm + 36.21mm)/2 = 33.63mm Average ID [(MLO+CC)/2] = (59.25mm + 50.32mm)/2 =54.79mm

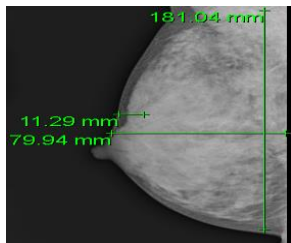
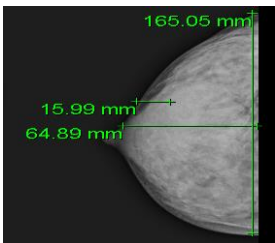
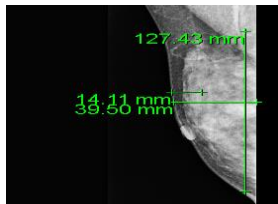
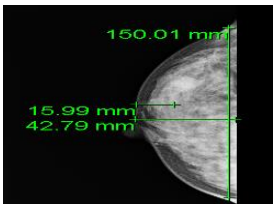
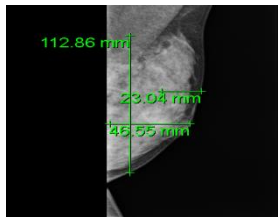
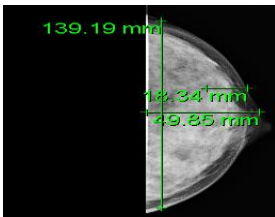
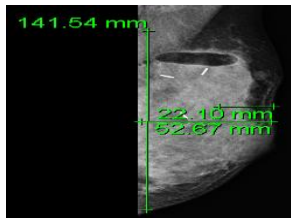
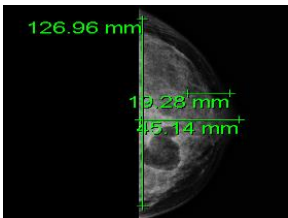
20.			Average SD [(MLO+CC)/2] = (32.45mm + 34.33mm)/2 = 33.39mm Average ID [(MLO+CC)/2] = (76.65mm + 66.31mm)/2 = 71.48mm
21.			Average SD [(MLO+CC)/2] = (18.34mm + 19.28mm)/2 = 18.81mm Average ID [(MLO+CC)/2] = (61.13mm + 59.25mm)/2 = 60.19mm
22.			Average SD [(MLO+CC)/2] = (23.51mm + 31.51mm)/2 = 27.51mm Average ID [(MLO+CC)/2] = (56.43mm + 52.67mm)/2 = 54.55mm
23.			Average SD [(MLO+CC)/2] = (20.69mm + 20.22mm)/2 = 20.46mm Average ID [(MLO+CC)/2] = (72.42mm + 78.53mm)/2 = 75.48mm

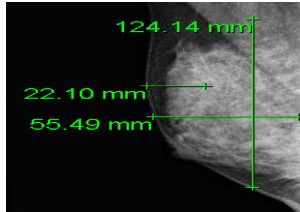
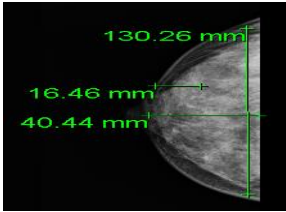
24.			Average SD [(MLO+CC)/2] = (22.10mm + 21.16mm)/2 = 21.63mm Average ID [(MLO+CC)/2] = (75.71mm + 101.10mm)/2 = 88.41mm
25.			Average SD [(MLO+CC)/2] = (25.86mm + 20.22mm)/2 = 23.04mm Average ID [(MLO+CC)/2] = (78.06mm + 88.88mm)/2 = 83.47mm
Stage 3 :Stage 3 cancer is larger and it started to spread into nearby tissues. The cancerous cells are found in the lymph nodes.			
No. Cancer Image		Location of the Breast Cancer	
1.			Average SD [(MLO+CC)/2] = (22.57mm + 42.32mm)/2 = 32.45mm Average ID [(MLO+CC)/2] = (84.64mm + 97.81mm)/2 = 91.23mm

2.			Average SD [(MLO+CC)/2] = (34.33mm + 23.98mm)/2 = 29.16mm Average ID [(MLO+CC)/2] = (75.71mm + 77.12mm)/2 = 76.42mm
3.			Average SD [(MLO+CC)/2] = (42.79mm + 30.10mm)/2 = 36.45mm Average ID [(MLO+CC)/2] = (79.00mm + 74.77mm)/2 = 76.89mm
4.	Not Provided		SD = 38.81mm ID = 107.03mm
5.			Average SD [(MLO+CC)/2] = (15.05mm + 10.35mm)/2 = 12.70mm Average ID [(MLO+CC)/2] = (54.08mm + 53.14mm)/2 = 53.61mm

6.			Average SD [(MLO+CC)/2] = (12.23mm + 18.81mm)/2 = 15.52mm Average ID [(MLO+CC)/2] = (63.01mm + 62.54mm)/2 = 62.78mm
7.			Average SD [(MLO+CC)/2] = (20.22mm + 19.28mm)/2 = 19.75mm Average ID [(MLO+CC)/2] = (81.35mm + 86.99mm)/2 = 84.17mm
8.			Average SD [(MLO+CC)/2] = (7.52mm + 8.46mm)/2 = 7.99mm Average ID [(MLO+CC)/2] = (60.66mm + 52.67mm)/2 = 56.67mm
9.			Average SD [(MLO+CC)/2] = (8.46mm + 15.05mm)/2 = 11.76mm Average ID [(MLO+CC)/2] = (47.49mm + 29.15mm)/2 = 38.32mm

10.			Average SD [(MLO+CC)/2] = (17.87mm + 17.40mm)/2 = 17.64mm Average ID [(MLO+CC)/2] = (38.09mm + 27.74mm)/2 = 32.92mm
11.			Average SD [(MLO+CC)/2] = (21.63mm + 18.34mm)/2 = 19.99mm Average ID [(MLO+CC)/2] = (62.54mm + 56.90mm)/2 = 59.72mm
12.			Average SD [(MLO+CC)/2] = (21.16mm + 16.46mm)/2 = 18.81mm Average ID [(MLO+CC)/2] = (58.78mm + 47.49mm)/2 = 53.14mm
13.			Average SD [(MLO+CC)/2] = (12.23mm + 11.76mm)/2 = 12mm Average ID [(MLO+CC)/2] = (69.13mm + 62.07mm)/2 = 65.6mm

14.			Average SD [(MLO+CC)/2] = (11.29mm + 15.99mm)/2 = 13.64mm Average ID [(MLO+CC)/2] = (79.94mm + 64.89mm)/2 = 72.42mm
15.			Average SD [(MLO+CC)/2] = (14.11mm + 15.99mm)/2 = 15.05mm Average ID [(MLO+CC)/2] = (39.50mm + 42.79mm)/2 = 41.15mm
16.			Average SD [(MLO+CC)/2] = (23.04mm + 18.34mm)/2 = 20.69mm Average ID [(MLO+CC)/2] = (46.55mm + 49.85mm)/2 = 48.20mm
17.			Average SD [(MLO+CC)/2] = (22.10mm + 19.28mm)/2 = 20.69mm Average ID [(MLO+CC)/2] = (52.67mm + 45.14mm)/2 = 48.91mm

18.			Average SD $[(MLO+CC)/2] = (22.10\text{mm} + 16.46\text{mm})/2 = 19.28\text{mm}$ Average ID $[(MLO+CC)/2] = (55.49\text{mm} + 40.44\text{mm})/2 = 47.97\text{mm}$
Stage 4: Stage 4 cancer has spread from where the starting region to other body organ. This stage is also called metastatic or secondary cancer. Stage 4 cancer will not be investigated because the images are not provided considering that surgery is implemented for stage 4 cancer			

APPENDIX C: DATASHEET OF RO4000 SERIES



RO4000® Series High Frequency Circuit Materials

RO4000® hydrocarbon ceramic laminates are designed to offer superior high frequency performance and low cost circuit fabrication. The result is a low loss material which can be fabricated using standard epoxy/glass (FR-4) processes offered at competitive prices.

The selection of laminates typically available to designers is significantly reduced once operational frequencies increase to 500 MHz and above. RO4000 material possesses the properties needed by designers of RF microwave circuits and matching networks and controlled impedance transmission lines. Low dielectric loss allows RO4000 series material to be used in many applications where higher operating frequencies limit the use of conventional circuit board laminates. The temperature coefficient of dielectric constant is among the lowest of any circuit board material (Chart 1), and the dielectric constant is stable over a broad frequency range (Chart 2). For reduced insertion loss, LoPro® foil is available (Chart 3). This makes it an ideal substrate for broadband applications.

RO4000 material's thermal coefficient of expansion (CTE) provides several key benefits to the circuit designer. The expansion coefficient of RO4000 material is similar to that of copper which allows the material to exhibit excellent dimensional stability, a property needed for mixed dielectric multi-layer boards constructions. The low Z-axis CTE of RO4000 laminates provides reliable plated through-hole quality, even in severe thermal shock applications. RO4000 series material has a Tg of >280°C (536°F) so its expansion characteristics remain stable over the entire range of circuit processing temperatures.

RO4000 series laminates can easily be fabricated into printed circuit boards using standard FR-4 circuit board processing techniques. Unlike PTFE based high performance materials, RO4000 series laminates do not require specialized via preparation processes such as sodium etch. This material is a rigid, thermoset laminate that is capable of being processed by automated handling systems and scrubbing equipment used for copper surface preparation.

RO4003C™ laminates are currently offered in various configurations utilizing both 1080 and 1674 glass fabric styles, with all configurations meeting the same laminate electrical performance specification. Specifically designed as a drop-in replacement for the RO4003C™ material, RO4350B™ laminates utilize RoHS compliant flame-retardant technology for applications requiring UL 94V-0 certification. These materials conform to the requirements of IPC-4103, slash sheet /10 for RO4003C, see note #1 for RO4350B slash sheet determination.



Data Sheet

FEATURES AND BENEFITS:

RO4000 materials are reinforced hydrocarbon/ceramic laminates – not PTFE

- Designed for performance sensitive, high volume applications

Low dielectric tolerance and low loss

- Excellent electrical performance
- Allows applications with higher operating frequencies
- Ideal for broadband applications

Stable electrical properties vs. frequency

- Controlled impedance transmission lines

- Repeatable design of filters

Low thermal coefficient of dielectric constant

- Excellent dimensional stability

Low Z-axis expansion

- Reliable plated through holes

Low in-plane expansion coefficient

- Remains stable over an entire range of circuit processing temperatures

Volume manufacturing process

- RO4000 laminates can be fabricated using standard glass epoxy processes

- Competitively priced

CAF resistant

SOME TYPICAL APPLICATIONS:

- Cellular Base Station Antennas and Power Amplifiers
- RF Identification Tags
- Automotive Radar and Sensors
- LNB's for Direct Broadcast Satellites



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Chart 1: RO4000 Series Materials Dielectric Constant vs. Temperature

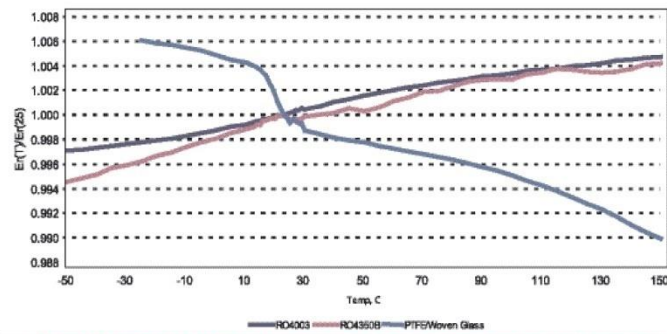


Chart 2: RO4000 Series Materials Dielectric Constant vs. Frequency

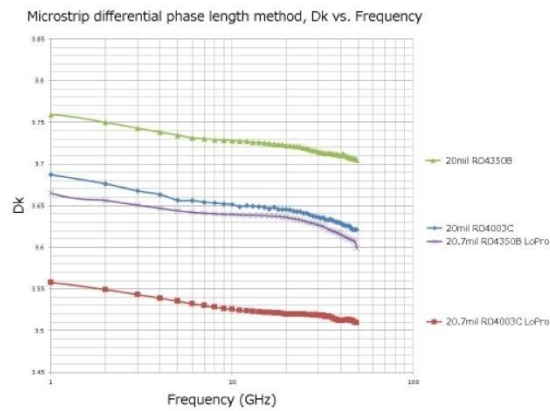
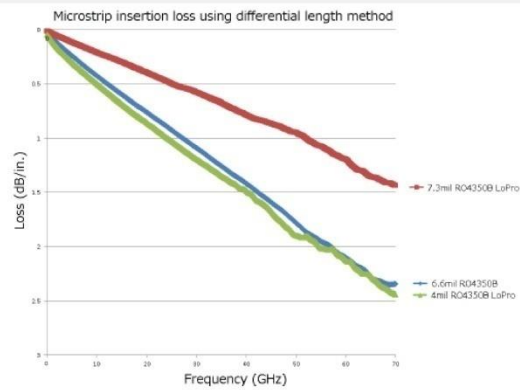


Chart 3: Microstrip Insertion Loss



Property	Typical Value		Direction	Units	Condition	Test Method
	RO4003C	RO4350B				
Dielectric Constant, ϵ_r , Process	3.38 $\pm$ 0.05	⁽¹⁾ 3.48 $\pm$ 0.05	Z	--	10 GHz/23°C	IPC-TM-650 2.5.5.5 Clamped Stripline
⁽²⁾ Dielectric Constant, ϵ_r , Design	3.55	3.66	Z	--	8 to 40 GHz	Differential Phase Length Method
Dissipation Factor tan, δ	0.0027 0.0021	0.0037 0.0031	Z	--	10 GHz/23°C 2.5 GHz/23°C	IPC-TM-650 2.5.5.5
Thermal Coefficient of ϵ_r	+40	+50	Z	ppm/°C	-50°C to 150°C	IPC-TM-650 2.5.5.5
Volume Resistivity	1.7 X 10 ¹⁰	1.2 X 10 ¹⁰		MΩ•cm	COND A	IPC-TM-650 2.5.17.1
Surface Resistivity	4.2 X 10 ⁹	5.7 X 10 ⁹		MΩ	COND A	IPC-TM-650 2.5.17.1
Electrical Strength	31.2 (780)	31.2 (780)	Z	KV/mm (V/mil)	0.51mm (0.020")	IPC-TM-650 2.5.6.2
Tensile Modulus	19,650 (2,850) 19,450 (2,821)	16,767 (2,432) 14,153, (2,053)	X Y	MPa (ksi)	RT	ASTM D638
Tensile Strength	139 (20.2) 100 (14.5)	203 (29.5) 130 (18.9)	X Y	MPa (ksi)	RT	ASTM D638
Flexural Strength	276 (40)	255 (37)		MPa (kpsi)		IPC-TM-650 2.4.4
Dimensional Stability	<0.3	<0.5	X,Y	mm/m (mils/inch)	after etch +E2/150°C	IPC-TM-650 2.4.39A
Coefficient of Thermal Expansion	11 14 46	10 12 32	X Y Z	ppm/°C	-55 to 288°C	IPC-TM-650 2.4.41
Tg	>280	>280		°C TMA	A	IPC-TM-650 2.4.24.3
Td	425	390		°C TGA		ASTM D3850
Thermal Conductivity	0.71	0.69		W/m/°K	80°C	ASTM C518
Moisture Absorption	0.06	0.06		%	48 hrs immersion 0.060" sample Temperature 50°C	ASTM D570
Density	1.79	1.86		gm/cm ³	23°C	ASTM D792
Copper Peel Strength	1.05 (6.0)	0.88 (5.0)		N/mm (pli)	after solder float 1 oz. EDC Foil	IPC-TM-650 2.4.8
Flammability	N/A	⁽³⁾ V-0				UL 94
Lead-Free Process Compatible	Yes	Yes				

NOTES:

- (1) RO4350B 4 mil laminates have a process Dk of 3.33 $\pm$ 0.05 and are in conformance with IPC-4103A/240. All other RO4350B laminate thicknesses are /11 and /240 compliant.
- (2) The design Dk is an average number from several different tested lots of material and on the most common thickness/s. If more detailed information is required, please contact Rogers Corporation or refer to Rogers' technical papers in the Rogers Technology Support Hub available at <http://www.rogerscorp.com>.
- (3) RO4350B LoPro® laminates do not share the same UL designation as standard RO4350B laminates. A separate UL qualification may be necessary.

Typical values are a representation of an average value for the population of the property. For specification values contact Rogers Corporation.

RO4000 LoPro laminate uses a modified version of the RO4000 resin system to bond reverse treated foil. Values shown above are RO4000 laminates without the addition of the LoPro resin. For double-sided boards, the LoPro foil results in a thickness increase of approximately 0.0007" (1.8µm) and the Dk is approximately 2.4. The Dk decreases by about 0.1 as the core thickness decreases from 0.020" to 0.004.

Prolonged exposure in an oxidative environment may cause changes to the dielectric properties of hydrocarbon based materials. The rate of change increases at higher temperatures and is highly dependent on the circuit design. Although Rogers' high frequency materials have been used successfully in innumerable applications and reports of oxidation resulting in performance problems are extremely rare, Rogers recommends that the customer evaluate each material and design combination to determine fitness for use over the entire life of the end product.

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Standard Thickness	Standard Panel Size	Standard Copper Cladding
RO4003C: 0.008" (0.203mm), 0.012 (0.305mm), 0.016"(0.406mm), 0.020" (0.508mm) 0.032" (0.813mm), 0.060" (1.524mm)	12" X 18" (305 X 457 mm)	½ oz. (17µm) electrodeposited copper foil (.5ED/.5ED)
	24" X 18" (610 X 457 mm)	1 oz. (35µm) electrodeposited copper foil (1ED/1ED)
	24" X 36" (610 X 915 mm)	2 oz. (70µm) electrodeposited copper foil (2ED/2ED)
	48" X 36" (1.224 m X 915 mm)	
	*0.004" (0.101mm) material is not available in panel sizes larger than 24"x18" (610 X 457mm)	
RO4350B: *0.004" (0.101mm), 0.0066" (0.168mm), 0.010" (0.254mm), 0.0133" (0.338mm), 0.0166" (0.422mm), 0.020"(0.508mm), 0.030" (0.762mm), 0.060"(1.524mm)		PIM Sensitive Applications:
		½ oz (17µm) LoPro Reverse Treated EDC (.5TC/.5TC)
		1 oz (35µm) LoPro Reverse Treated EDC (1TC/1TC)
Note: Material clad with LoPro foil add 0.0007" (0.018mm) to dielectric thickness		

The information in this data sheet is intended to assist you in designing with Rogers' circuit materials. It is not intended to and does not create any warranties express or implied, including any warranty of merchantability or fitness for a particular purpose or that the results shown on this data sheet will be achieved by a user for a particular purpose. The user should determine the suitability of Rogers' circuit materials for each application.

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