MATERIAL ANALYSIS OF WEARABALE HYPERTHERMIA APPLICATOR

by

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ABSTRACT

The purpose of this study was to explore printed antennas as an alternative technique for applying hyperthermia treatment. The antenna consisted of a printed ground plane and a thin copper plate. The ground plane was made of silver conductive ink printed on a flexible substrate. The challenge of the printed ground plane was limited conductivity. Multi-layer printing was one of the ways to increase the conductivity of the printed trace. This study examined whether the multiple-layered printings on the ground plane influence the performance of the antenna. The ground plane printed on a flexible substrate was evaluated for its conductivity and capacity to handle the heat energy for the extended time duration at the elevated temperature.

This research was conducted in two experimental stages. The first stage of the experiment was designed to test conductivity of the ground plane. Ground planes were printed on a 32.5 mm × 17.0 mm substrate. The thickness and resistance of up to five layers of conductive printing were tested to verify how repeated printing improved the resistance and resistivity. Results showed that the multi-layering technique reduced the resistance of the printed trace, but statistically, the ground plane had no significant improvement in resistance beyond the triple layer printing. With an increase of the thickness, resistivity rather increased after the triple layer printing. The second stage of the experiment was used to assess the performance of the entire antenna. Antennas were fabricated using ground planes with triple and quintuple layers based on resistance and resistivity measurements. The antennas showed an acceptable level of performance in terms of antenna return loss and temperature elevation. The statistical analysis of return loss, power handling capability over the time, and temperature elevation was not significant among the antennas with triple and quintuple layered ground planes. Antennas were able to achieve 42 ˚C within 10 minutes at a 2cm deep location with the return loss of -13.76 dB. Most importantly, experimental results showed that antennas were able to handle 15 watt power without degrading the antenna performance. The antenna showed a successful performance in power handling and reaching the tumor temperature.

Keywords: Breast Cancer, Wearable Hyperthermia Applicator, Conductive Printing, Printed Antenna,

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CHAPTER 1. INTRODUCTION

Breast cancer is the most common type of cancer among women in the United States regardless of race and ethnicity, and it is the second most common cause of death among women (American Cancer Society, 2014). According to a report from the Centers for Disease Control and Prevention, in 2010 in the United States, 206,966 women were diagnosed with breast cancer. The American Cancer Society (2014) reported 232,670 new cases by the end of 2014. Researchers have conducted many types of clinical studies on preventing, detecting, and treating breast cancer, and those advances have contributed to early diagnosis and efficient treatment methods, thus reducing the number of deaths. Women with breast cancer undergo several different types of treatment depending on the severity and stage of the disease (Fentiman, 1999). Most general treatment options involve radiation, chemotherapy, or surgery.

Hyperthermia is a noninvasive treatment used in combination with conventional treatments like chemotherapy and radiotherapy. Hyperthermia, exposes cancer tissue to external radiation to increase the temperature to around 42 ºC; temperatures between 41 ºC and 44 ºC negatively affect cancer cells (Ahmed & Zaidi, 2013). Elevating the temperature of cancerous regions increases blood circulation and, therefore, causes more perfusion and oxygenation. This helps drugs better penetrate tumor cells in chemotherapy and makes those cells more sensitive to ionized radiation (Korkmaz, Isik, & Nasoor, 2013). Medical researchers (Ahmed & Zaidi, 2013; Zee et al., 2002; Zee et al., 1999) found that hyperthermia allows lower doses of drugs and radiation to have the same effect. According to Ahmed et al. (2013), hyperthermia combined with other treatments significantly reduces the size of tumor cells.

Hyperthermia treatment is applied using single or multiple antennas radiating microwaves or radio waves, or via ultrasound. An antenna is a unit that radiates radio waves or microwaves within a hyperthermia applicator. Over the past several years, applicators have been developed for efficient hyperthermia treatments (Moros, 2013; Chichel, Skowronek, Kubaszewska, & Kanikowski, 2007). However, equipment and reliable treatment methods have not yet been standardized. This research addressed the materials, equipment, and procedures for testing the feasibility of printed antennas that can be incorporated into a wearable applicator. Fabricating smaller, lighter, and more flexible antennas that fit into a wearable applicator is the ultimate goal. Conventionally, hyperthermia devices have come in various sizes and forms, whereas all applicators have been large and rigid (Moros, 2013). In addition, the therapeutic depth attainable using these applicators is only a few centimeters, and their use is limited to those parts of the human body with flat, regular surfaces. This means convex shapes such as breasts and tumors located deep in the breast have been a challenge in hyperthermia treatments. The antenna is a major element in the hyperthermia device, so miniaturizing the antenna itself could lead to smaller and lighter hyperthermia applicators. Moreover, research has shown that radiation efficiency of antennas can be increased as antenna dimensions become light and smaller (Moros, 2013). Further, small, conformable applicators would be helpful to target specific tumor cells (Gupta & Singh, 2006), which, in turn, would minimize exposure of surrounding tissues to radiation. A device that better fits the convex shapes of the body also could minimize power loss due to gaps between antennas and tumor tissue. Therefore, designing a wearable device that snugly fits body contours is desirable.

Miniaturizing the antenna is mandatory for the latest advances in wearable antennas. In the last few decades, for example, miniaturized wearable antennas have been developed for telecommunication and for entertainment. Indeed, integrating radio frequency systems into clothing in telecommunication has become very popular, leading to flexible, compact, and lightweight antennas. However, wearable antennas have been used to constantly monitor respiration and heart function in patients, but little effort has gone into developing wearable antennas for cancer treatment. Clinically, hyperthermia treatment requires one hour to bring the tumor temperature up to 42ºC. The patient lies down for a prolonged time in an uncomfortable position to expose the cancerous region to the device. A wearable device could increase a patient's comfort level throughout treatment.

The long term goal of this project is to develop a wearable device for delivering hyperthermia treatment to the breast, while the purpose of this research was to evaluate the feasibility of integrating printed antennas into a wearable format. The study used conductive ink consisting of silver particles printed on a flexible surface. This wearable antenna, consisting of smaller and more flexible components, could help in developing next generation applicators. Antennas printed on a flexible substrate would weigh less, and such an antenna would be simple to fabricate and customize, unlike conventional metal antennas. In addition, the cost to manufacture low profile antennas would be much lower than for other metal antennas. Therefore, wearable antennas could be a significant advantage to the manufacturer who can develop lightweight, low profile, cost-effective hyperthermia devices and to the patients at cancer clinics. No research was found that focused on a wearable hyperthermia applicator specifically for breast cancer. Previous studies (Trembly, 1985; Wust, 2002; Stauffer, 2007; Curto, 2006) focused on antenna arrays and alternate types and shapes of antennas but not on modifying the applicator as a unit.

Micro strip patch antennas used in this research consisted of a ground plane and a patch (rectangular thin copper plate). A thin copper plate is mounted over the ground plane. Ground plane was printed on a flexible substrate. The ground plane was tested for physical and electrical performance, which varies significantly depending on shape and the conductivity of the ink. This is important because radiation efficiency and conductivity of an antenna depend on how well conductive ink is deposited during the printing process.

Initially, printed traces were tested with a single layer, but satisfactory conductivity was not achieved. Therefore, the ground plane of the antenna was printed multiple times in stacked layers (multi-layers). This multi-layering technique ensured the printed particles connected together and allowed continuous current flow and thus preventing short circuits. Also, consecutive layer printing decreased resistance and increased the conductivity of the antenna. However, printing multiple layers requires more ink, thus increasing the cost of producing the antenna.

This research was divided into two experimental design stages. The first stage of the experiment was designed to evaluate how much the conductivity improved in printed traces after repeated printing. Antenna performance was assessed in the second stage of the experiment. To determine where the significant difference exists between the number of printed layers and the performance of the antenna, following research questions were addressed:

Research Question 1. How does repeated printing improve the conductivity of printed trace?

Research Question 2. How does the number of printed layers on ground plane affect antenna performance?

Inadequate research on the wearable hyperthermia applicator is a major limitation of this study, many other variables could affect treatment efficiency, which may affect the interpretation of our results. Further, sample size was controlled because of financial and equipment limitations. Therefore, statistical interpretations should not be generalized. Additionally, once the implementation stage is reached, different sizes of applicators are required according to patient's breast size and tumor location.

Definition of Terms

Capacitance - Capacitance is expressed as the ratio of stored charge in coulombs to the impressed potential difference in volts.

Conductivity- The degree to which a specified material conducts electricity, calculated as the ratio of the current density in the material to the electric field that causes the flow of current. It is the reciprocal of the resistivity. Unit of conductivity is siemens per meter (S/m).

Conductive ink – Metallic particles shaped as flakes are blended into an ink. Metallic particles touch and overlap, creating a continuous conductive trace.

Detuning – shift of antenna resonant frequency from the incoming signal frequency.

Dielectric – Insulating material or a poor conductor of electric current. Electron flow will occur for voltage above a threshold level (Khan & Rajesh, 2012).

Impedance - the degree to which an electrical circuit resists the flow of electric current when a voltage is impressed across its terminals. Unit of impedance is ohm (Ω).

Printed Trace – silver conductive ink printed on a flexible substrate

Relative permittivity - relative permittivity is the ratio of the capacitance of a capacitor using that material as a dielectric, compared to a similar capacitor that has vacuum as its dielectric. Unit of relative permittivity is measured in farads per meter (F/m).

Resistance - Property of an electric conductor by which it opposes a flow of electricity and dissipates electrical energy away from the circuit. Measure of resistance is given in ohm (Ω).

Resistivity - Resistivity is an intrinsic property of a material that quantifies how strongly a given material opposes the flow of electric current irrespective of its shape and size. Unit of resistivity is expressed in ohm-meters.

Return loss (S_{11}) - Measure of the effectiveness of power delivery from a transmission line to a load. If the power incident on the antenna is P_i and the power reflected back to the source is P_r, the degree of mismatch between the incident and reflected power in the travelling waves is given by the ratio P_i / P_r, expressed in dB

Specific absorption rate (SAR) - a measure of the rate at

which energy absorbed per mass of tissue when exposed to a radio frequency electromagnetic field. Unit of SAR is watts per kilogram (W/kg).

CHAPTER 2. LITERATURE REVIEW

Developing a small, flexible, and wearable antenna is important in treating cancer tumors with hyperthermia, as is reducing the weight of the hyperthermia applicator. Wearable antenna could be printed on a textile surface or other flexible material, which would be simple to fabricate and customize, compared to conventional metal antennas. In addition, such antennas would have a lower profile than metal antennas, and printed antennas would be much cheaper to manufacture. Further, lightweight, compact antenna would facilitate clinical use and provide comfort to patients. Overall, wearable antennas for hyperthermia treatment could provide the advantages of lighter weight, lower profile, and lower manufacturing costs.

2.1 Hyperthermia Devices

The hyperthermia device includes an applicator, single or multiple antennas, and a water bolus. While the antenna releases heat by radiating radio waves or microwaves within the applicator, the water bolus improves coupling and reduces heat on the skin surface. Ultimately, however, the efficiency of treatment depends on the radiation characteristics. Thus, radiation pattern, radiation directivity, return loss, and specific absorption rate are the important characteristics to evaluate for efficiency of radiation. Review of the literature revealed that both the applicator design and antenna design influence radiation efficiency.

Different types of antennas have been evaluated for frequency and return loss, and based on those results, both square and circular patch antennas have been used in clinical treatments. Various printed antennas such as dipole, mono pole, circular loop, and inverted-L have also been investigated for effects of antenna design on human lossy tissue which has higher water content than other tissues in the body (Alam, 2013; Alomainy, 2007).

Wearable antennas, which integrate a radio frequency system into clothing, have become popular in the telecommunications field. Research shows patch antennas are the best among small wearable antennas (Sharma, Bhushan, Gupta, & Kaur, 2013). The advantage of this type of antenna is that it is lightweight with a low profile and cost effective. The following section describes applicators, the bolus, and power levels used in hyperthermia treatment as well as reviewing both printed and metal patch antennas to identify those most efficient for hyperthermia treatment.

2.1.1 Applicators

Typical applicators for local hyperthermia treatment include waveguide, spiral, and current sheet types, none of which are currently wearable. The therapeutic depth of these applicators is only a few centimeters and limited to regions with a regular surface. Specifically, commercially available micro strip applicators range from 7.3 cm × 19.8 cm to 19.8 × 19.8 cm (Moros, 2013). At frequency levels between 150 - 430 MHz, the emitting radiation will be 15 cm, which allows 30 mm therapeutic depth (Wust et al., 2002).

A. Waveguide applicator

A waveguide applicator (Figure 1) has been preferred for hyperthermia treatments because other types of inductive applicators tend to cause excessive heating to non-cancerous areas such as the skin and fat. The electric field created by waveguide applicators generates little heat in the body’s fat layers, concentrating it instead in the muscle layers (Paglione, Sterzer, Mendecki, Friedenthal, & Botstein, 1981). However, this applicator is relatively large, and the shape of the aperture does not work well for irregular body surfaces where heat must be delivered to tumor depths ranging from 6 to 15 mm (Togni, Vrba, & Vannucci, 2010).

Figure 1. Waveguide applicator. Adapted from “Hyperthermia in combined treatment of cancer” by Wust, P., Hildebrandt, B., Sreenivasa, G., Rau, B., Gellermann, J., Riess, H., Felix,R.,Schlag, P.M, 2002, *The Lancet Oncology*, *3*, p.489.

B. Spiral applicator

Spiral applicators are more flexible and smaller than waveguide applicators (Figure 2) and can be used to treat large areas (Patummakasorn, Tangwachirapan, & Thongsopa, 2008; Jacobsen, Rolfsnes, & Stauffer et al., 2005). The performance of spiral applicators is based on the parameters of the antenna, which is the main element in this applicator. Specifically, spiral antennas depend on spiral wire diameter, the space of adjacent spiral circles, and the number of spiral circles of the antenna. Notably, the distribution of the electromagnetic field decreases when the width of spiral wire decreases (Du, Xi, & Guo, 2011). This phenomenon restricts the dimension of spiral applicators, which is a disadvantage.

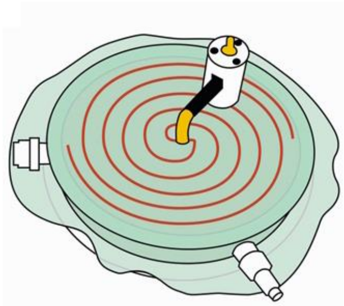


Figure 2. Spiral applicator. Adapted from “Hyperthermia in combined treatment of cancer” by Wust, P., Hildebrandt, B., Sreenivasa, G., Rau, B., Gellermann, J., Riess, H., Felix, R., Schlag P.M, 2002, *The Lancet Oncology*, 3, p.489.

C. Current sheet applicator

The current sheet applicator consists of arrays of thin metal plates placed on and conforming to the ground plane (Figure 3). The highly conductive flat sheets are bent in a 'U' shape, and a resonant circuit is created by capacitance plates (electrically charged sheets) placed between the arms of the U. The effective radiation produced by a pair of these sheets is continuous even if other sheets are placed perpendicular or parallel to the direction of current flow. Also, the coupling among elements eliminates any inductive coupling from the ground plane (Moros, 2013). Current sheet applicators are smaller than waveguide applicators and have a larger heating area, both of which are advantages. However, one practical limitation is that only Very High Frequency (VHF) and Ultra High Frequency (UHF) bands can be used with a current sheet applicator. Thus, heating deep-seated tumors is difficult. Other limitations include its rigid structure and of the need for a separate mounting system.

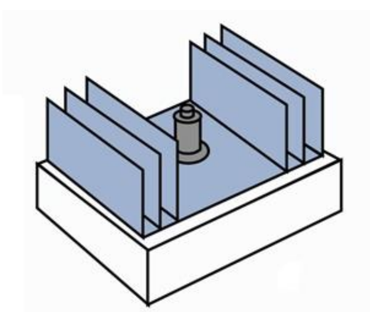


Figure 3.Current sheet applicator. Adapted from "Hyperthermia in combined treatment of cancer" by Wust, P., Hildebrandt, B., Sreenivasa, G., Rau, B., Gellermann, J., Riess, H., Felix, R., Schlag P.M, (2002). *The Lancet Oncology*, 3, p. 489.

2.1.2 Antenna

As units for radiating radio waves or microwaves in hyperthermia applicators, antennas are categorized into patch, loop, and print antennas depending on fabrication method and geometry. The following sections analyze different types of antennas and identify conditions affecting antenna performance.

A. Patch Antenna

The micro strip patch antenna is preferred in telecommunications because of its diverse polarization, light weight, and low profile. The low profile makes it suitable for incorporating onto flat planar surfaces. These antennas are constructed by mounting different shapes of flat metal sheets (patch) over a dielectric sheet (substrate). The patch can be fabricated by electroforming metal mesh or commercial conductive fabrics. The ground plane is constructed on the other side of the dielectric sheet. According to Balanis (2005), the performance of the antenna varies according to the geometry of the patch and the thickness of the substrate.

Sharma et al. (2013) analyzed the performance of square, elliptical, annular ring, and triangular shape patch antennas (Figure 4). Their research showed all patch antennas, whether square, elliptical, or triangular, had very similar return losses although the annular ring showed a still lower return loss than the others. The annular ring also had outstanding reflection property, reflecting back a smaller portion of an input signal than the other types of antenna. The bandwidth of the patch antennas showed a return loss of -10dB in this research, and the elliptical and square antennas were similar at 47.6 MHz and 46 MHz, respectively. Sharma et al. (2013) argued that this might be due to a ratio nearly equaling for major versus minor axis in the elliptical antenna.

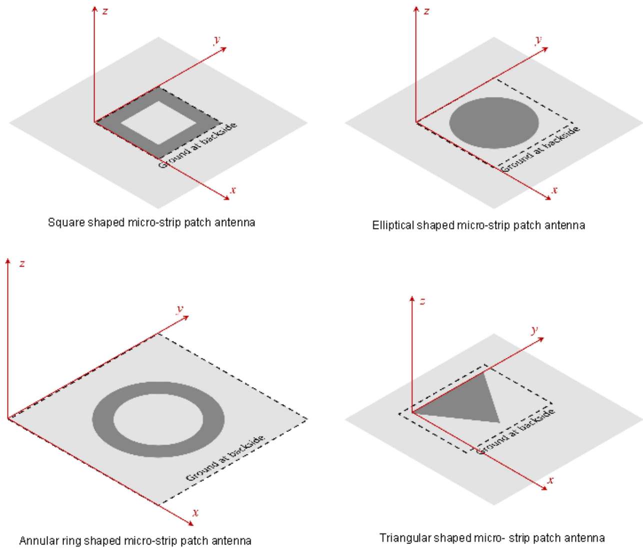


Figure 4. Different shapes of micro strip patch antenna. Re-drawn from “performance comparison of micro strip antenna with different shape of the patch’’ by Sharma, S., Bhushan, B., Gupta, S., Kaur, P., 2013,*International journal of u -and-e*, (6)3, p14.

B. Loop Antenna

Loop antennas are linear and constructed simply and inexpensively. A small loop antenna functions much like a minute magnetic dipole antenna because both have the same mathematical form for a radiation field. Researchers have found that the orientation of the loop antenna mounting on the substrate affects antenna performance (Balanis, 2005).

Curto et al. (2006) analyzed three-dimensional electromagnetic interaction between loop antennas and biological tissue, finding that loop antennas on the XY plane (Figure 5) had better return loss but lower efficiency, so more interaction between the antenna and tissues could take place. Conversely, other orientations (YZ and XZ planes) showed higher radiation efficiency and lower SAR. Tested for depths of 5, 40, and 95 mm inside muscle tissue, SAR distribution was highest when the loop was placed parallel to the muscle. These findings mean research is needed on 3D arrays of antennas, which can improve the efficiency of hyperthermia treatment. In addition, the performance of a wearable antenna would vary according to specific angles and distance from the body (Figure 5 and Table 1).

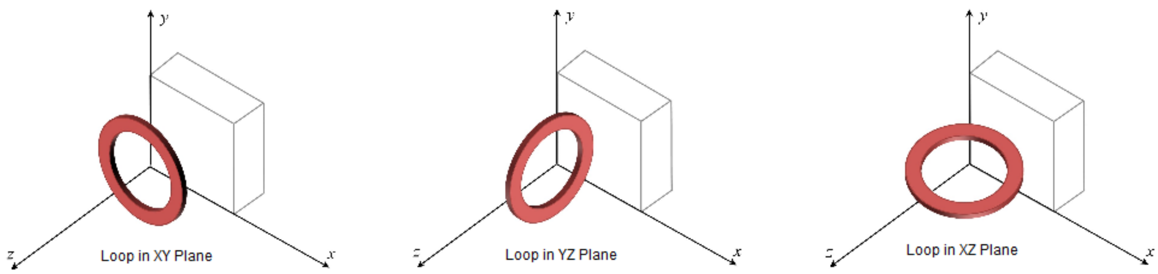


Figure 5. Loop antenna. Re-drawn from "Compact patch antenna for electromagnetic interaction with human tissue at 434 MHz" by Curto, S., McEvoy, P., Bao, X., & Ammann, M. J, (2006), *microwave and optical technology letters,* 48, p.2419.

Table 1.Radiation characteristics for different orientations of antennas

	Radius (mm)	Return loss (- dB)	Directivity (dBi)	Gain (dBi)	Efficiency (ŋ, %)	Max, SAR 5 mm depth into tissue (W/Kg)
Loop in free space	114.5	5.99	3.69	3.56	96.6	-
Z-axis (Loop in XY Plane)	110.5	12.32	7.27	3.11	42.7	0.36
X-axis (Loop in YZ Plane)	99.5	9.52	4.62	3.73	80.8	0.10
Y-axis (Loop in XZ Plane)	95.5	5.94	3.06	2.70	88.3	0.01

Reprinted from "Compact patch antenna for electromagnetic interaction with human tissue at 434 MHz" by Curto, S., McEvoy, P., Bao, X., & Ammann, M. J, (2006), *microwave and optical technology letters*, 48, p.2420.

From the literature review, we see that the applicator design mainly depends on how the antenna is fabricated and particularly on the shape and dimensions of the antenna. Therefore, the choice of the fabrication type will affect treatment. Moreover, at lower frequencies, heat penetrates more deeply, which is useful for deep tumors. However, fabrication method and size of antenna both restrict the possibility of lowering the frequency. In addition, fabrication techniques, particularly with patch and loop antennas, influence antenna proximity to tissue. Compared to other fabrication methods, the patch antenna has different radiation patterns depending on the dimension and shape of the antenna (Sharma et al., 2013), which affect the amount of radiation reaching a deep tumor. Thus, the required proximity of antenna to body affects the choice of fabrication technique.

Proximity must be evaluated for both efficiency and frequency detuning (Boyes, 2013). The literature review reveals that ground plane antennas were less prone to change in proximity to the human body (Alomainy, 2007). Also, researchers observed that frequency detuning varies according to specific angles and distance from the body because antennas placed closer to the human body significantly affect characteristic impedances and loss of radio frequency. However, lighter weight antennas using low frequencies requires increasing the size of applicators to remain efficient. This is one major reason that all applicators have been large. Finally, the location of the tumor in the body and the surrounding anatomy are critical to designing a wearable device.

Clearly, antenna design, structure of applicator, and treatment conditions should be carefully considered in choosing the design of a wearable device. Antenna geometry and necessary frequency level should also be carefully considered in wearable antenna design.

2.1.3 Water bolus

Typically, in hyperthermia applicators, the antennas are embedded in a distilled water bolus to obtain a better coupling between the irradiated electromagnetic fields and tissues. The water bolus reduces the size of the antenna with respect to resonant frequency. It serves also to cool the skin surface, preventing burns. The thickness of the bolus significantly changes the performance of the antenna. Therefore, to obtain uniform heating throughout body tissue, the spacing between antenna and human tissue should remain consistent. A water bolus specifically designed for a hyperthermia applicator needs to take into account the curvature of the breast, which makes building a bolus more complex.

2.1.4 Power

The power range for hyperthermia treatment is from 10-500 Watts for a single microwave applicator at frequencies ranging from 915 MHz to 2450 MHz (Cheung and Neyzari, 1984) although maximum clinical power level for a single antenna is limited to 30 Watts (Arunachalam, Maccarini, Juang, Gaeta, & Stauffer, 2008). The required power can be reduced by using several antennas in an array.

However, because higher power can melt printed conductive ink and the substrate, the input power required careful consideration in this project. Elevated power, with losses due to antenna resistance, may heat up the antenna itself, possibly degrading its performance.

2.2 Conductive Printing

Antennas can be made by printing conductive ink directly on dielectric substrates. This type of antenna can be produced more accurately, which is a point in its favor. Indeed, complicated shapes like spiral or multi-cornered antennas can only be achieved through printing. The conductivity, viscosity, and adherence as well as post-printing processes are critical for successful conductive printing (Suh, Carroll, Grant, & Oxenham, 2013). Printed antennas have been studied for various research purposes, but little research has focused on printed antennas for applying hyperthermia treatments.

2.2.1 Printing Method

Conductive printing is used for flexible electronics like sensors, antennas, capacitors, and circuit boards in part because it is straightforward and easily produces electronic tracks in commercial production. Inkjet technology prints patterns onto a substrate in response to an electrical signal. The printer head ejects tiny droplets of liquid one at a time onto a substrate. This process is data driven; a computer determines where each droplet is deposited. The first form of inkjet, the continued jet technique, charged and deposited individual droplets via the electrostrate yielding patterns on the substrate (Fuller, 2002). The Drop on Demand (DOD) technique is the most recent development. The differential pressure produced between chambers causes valves to open whereupon ink is supplied through nozzles. Since the DOD technique is also data driven, this application led to three dimensional prototyping, with examples including semiconductors, semiconductor mountings, and organic light emitting diodes formed by droplets (Fuller, 2002). The higher resolution of this technique makes electronic fabrication feasible. Commercially available inkjet conductive inks are water-based, oil-based, or solvent-based; they may also be UV curing ink (Woods, 2003). Importantly, inkjet printing can print any number of layers over curved and flexible areas.

Unfortunately, printing conductive ink on fabrics leads to loss of textile properties. Specifically, the flexibility and drapeability of textile material is lost as it becomes more conductive and brittle. The ink printed on fabric also tends to peel when fabric is stretched or bent. Moreover, ink penetrates the fabric substrate, using large amounts of ink but leaving only a thin layer of ink on the surface. Suh (2011) noted that the conductivity of printed media is optimized when conductive ink remains on the surface, which makes fabric substrate still more of a challenge. It is also a challenge to cure ink at high temperatures without damaging the fabric. In fact, to get higher conductivity, temperatures between 90 ºC and 180 ºC have been suggested to cure silver ink (Suh, 2011; Smith, Shin, Stringer, Derby, & Reis, 2006).

The multiple-layering technique used to create wearable electronics like the medical MRI (magnetic resonance imaging), the receiver coil (Mager, 2012), and the printed coil for RFID (radio frequency identification) tags (Salmeron, 2014) showed good conductance in several studies (Salmeron, 2014; Mager, 2012). The conductivity of the ink was influenced by the curing temperature. Therefore, commercially available ink that can be cured at low temperatures would be best for printing on flexible film because it is stable at low temperatures.

Another consideration for our study is that, as layers are added, the line and shape of the print is destroyed because of the contact angle (Mager, 2012). Therefore, an optimal number of layers and thickness must be identified.

2.2.2 Printed Antennas

The antennas printed on dielectric substrates in wearable devices are primarily for network communication. Whatever the application, though, a printed antenna showed significant changes in performance when it was placed close to the human body (Alomainy et al., 2007), which acted as a ground plane and influenced the radiation pattern. On six different shapes of antennas tested (Figure 6), researchers observed that frequency was detuned as the antennas were placed closer to the human body and that distances less than 0.5 mm from the body have a significant effect on characteristic impedances and loss of radio frequency (RF) interconnections (Alam, Sillanpaa, & Makinen, 2013).

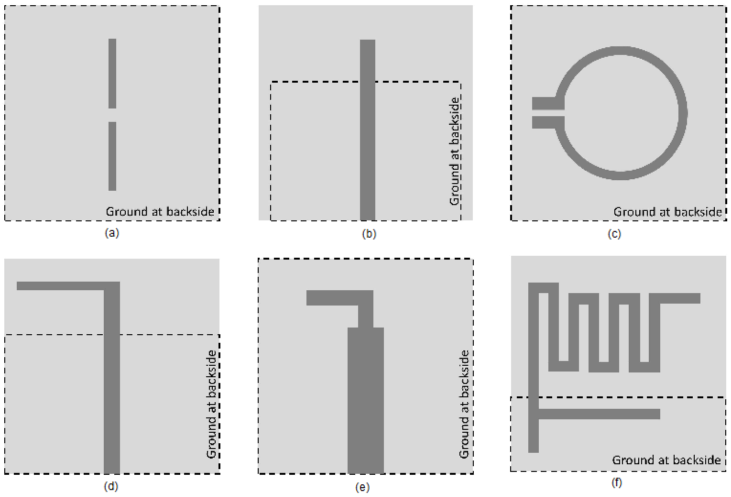


Figure 6. Printed antenna. (a) dipole,(b) monopole,(c) circular loop, (d) inverted L,(e) parasitic L (f) wiggle antenna. Re-drawn from "Parametric Study of Wearable Antennas with Varying Distances from the Body and Different On-Body Positions" by Alomainy, A., Hao, Y., and Davenport, D., 2007, p.85.

According to Alomainy et al. (2007), among antenna shapes, the return loss of printed monopole and parasitic L antennas showed less detuning than the dipole antenna. Alomainy et al. (2007) argue that this could be explained by different percentages of substrate being exposed to the lossy tissue, caused by the presence of the ground plane. In a parasitic L antenna, detuning from free space resonance was apparent, but the variations in distance from the body had less apparent effects than the dipole antenna. Monopole and inverted L antennas were least affected by distance. Clearly, small discrepancies between on-body and free space resonances greatly influenced system reliability and efficiency. Table 2 shows the antenna types and their main operating parameters at 2.4, 2.44, and 2.48 GHz. Monopole and dipole antennas demonstrated excellent performance although parasitic L and wiggle antennas showed decreased antenna bandwidth and radiation efficiency due to coupling between the multiple elements of each.

Table 2. Free space antenna parameters related to antenna type and dimensions

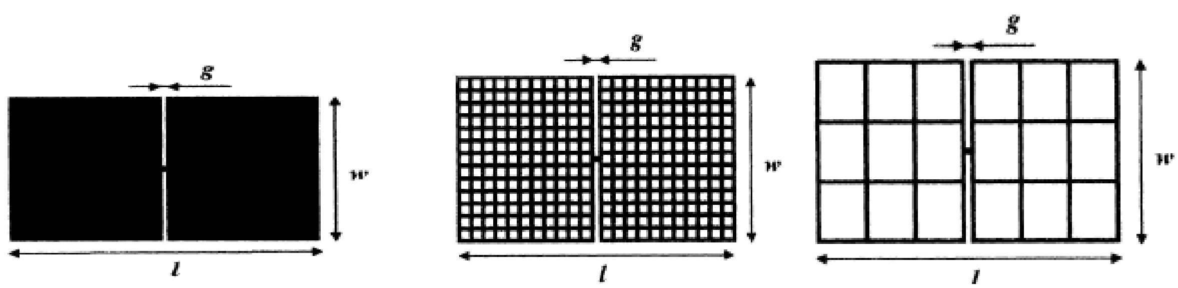
Antenna	Size (mm^2)	Gain (dBi)			Radiation Efficiency (%)		
		2.4GHz	2.44GHz	2.48GHz	2.4GHz	2.44GHz	2.48GHz
Printed dipole	10×55	1.8	1.9	2.0	95	97	99
Printed monopole	80×70	3.3	3.2	3.3	100	99	100
Circular loop	60×60	2.9	2.9	3.0	97	98	99
Inverted L	50×45	3.3	3.2	3.0	100	100	99
Parasitic L-shaped	30×20	1.5	1.6	1.9	81	83	87
Wiggle antenna	25.6×23	-4.8	-5.7	-6.7	18	17	14

Reprinted from "Parametric Study of Wearable Antennas with Varying Distances from the Body and Different On-Body Positions" by Alomainy, A., Hao, Y., and Davenport, D., 2007, p. 86.

2.2.3 Performance

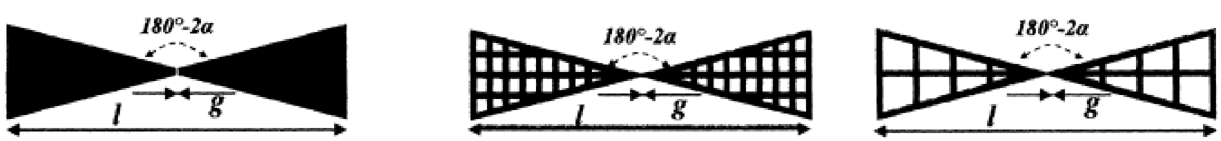
Antenna radiation efficiency and resistivity depend on the thickness of each ink layer and layer thickness throughout the structure of antenna. Radiation efficiency also depends on the total amount of ink used, and the silver particles mixed in the ink determine the electrical properties of an antenna. Silver ink is more expensive than other inks, so traditional high-density solid designs will cost more than other designs (Figure 7a). One objective of this study was to reduce the cost of the hyperthermia applicator, so we sought alternatives in the research on different antenna printing techniques and different geometries to reduce the cost. Research on flexographic printing found that a halo effect is created during the printing process. The halo effect involves squeezing ink outside the printing area because of pressure in the flexo plate. The halo effect occurs when antenna lines are printed less than 1mm wide (Siden, Olsson, Koptioug, & Nilsson, 2005). The halo effect also creates anisotropy (directional) conductivity, which resists uniform conductivity. However, studies have shown that wide and grid dipole antenna designs reduce the amount of ink needed per antenna while maintaining antenna parameters (Clasen & Langley, 1999; Sidén et al., 2005).

In the communications field, researchers have found that, for gridded antennas, modifications of the length to width ratio permit good antenna properties while reducing ink usage. The grid designs for common antenna geometries have been compared with solid antenna geometries for performance (Figure 7b & 7c). In 2005, Sidén et al. found that half the ink could be saved by substituting grid antennas for solid antennas. Siden et al. (2005) also analyzed bow type antennas for very low density grids (Figure 8). Their findings revealed that different antenna geometries used different amounts of ink. Thus, the grid antenna can save on ink, but it creates directional conductivity when a thin layer of ink is applied.



(a) (b) (c)

Figure 7. Square shape antennas with solid and grid prints. Adapted from ''Reduced Amount of Conductive Ink with Gridded Printed'' by Sidén, J., Olsson, T., Koptioug, A., & Nilsson, H. (2005). Antennas. *5th international conference on polymers and adhesives in microelectronics and photonic,* p.86.



(a) (b) (c)

Figure 8. Bow shape antennas with solid and grid prints. Adapted from ''Reduced Amount of Conductive Ink with Gridded Printed'' by Sidén, J., Olsson, T., Koptioug, A., & Nilsson, H. (2005). *Antennas. 5th international conference on polymers and adhesives in microelectronics and photonic,* p. 88.

However, few experiments on printed antenna for hyperthermia treatment exist. This indicates a need for a study of printed antenna characteristics to determine their efficiency in hyperthermia treatment.

Based on the literature review, antenna design is critical in hyperthermia treatment. Antenna heavily influence hyperthermia parameters like targeting the tumor, depth of heat penetration, and time needed to reach a tumor temperature of around 42 ºC.

This study analyzed how multiple layers of conductive print influence performance based on expected hyperthermia treatment parameters. Further, this study determined optimum ink usage to retain antenna properties required for hyperthermia treatment. Clearly, an antenna close to the skin should deliver less power to prevent overheating. Overheating of the antenna may also destroy the flexible film. Therefore, power handling capacity of printed antennas was also evaluated in this study.

CHAPTER 3. METHODOLOGY

The goal of this research was to develop a proof of concept prototype for a wearable hyperthermia device. The prototype antenna consisted of a copper thin plate and a ground plane printed with silver conductive ink. In the initial stage, the antenna was tested using simulation by Comsol Mutiphysics Software (Comsol, Inc., Burlington, MA) to determine optimal performance. The simulation provided guidance on choosing the dimensions of the antenna, including both conductive printed ground plane and copper thin plate. The actual prototype was then produced and tested to verify the expected performance. The number of printed layers on the ground plane were modified in the first experimental phase, and thickness, resistance, and resistivity of those printed layers on the ground plane were statistically analyzed to determine how significantly conductivity could be improved by repeated conductive printing. The statistical results provided the optimal number of printed layers. Then, in the second phase of the experiment, the antenna was fabricated using the selected ground planes. Antenna return loss, power handling capacity, and temperature elevation were tested for the selected antenna.

3.1 Research question

To verify the feasibility of the proposed antenna for hyperthermia treatment, the study addressed the following research questions:

Research Question 1. How does repeated printing improve the conductivity of printed trace?

Research Question 2. How does the number of printed layers on ground plane affect antenna performance?

To answer the research questions, following six hypotheses were tested.

Hypothesis I (null): there is no significant difference in thickness of printed ground plane by increasing the number of printed layers

Hypothesis II (null): there is no significant relationship between thickness and resistance.

Hypothesis III (null): there is no significant relationship between thickness and resistivity.

Hypothesis IV (null): antenna return loss does not change by the number of printed layers on ground plane

Hypothesis V (null): power handling capacity of antenna does not have significant difference between the numbers of printed layers on ground plane.

Hypothesis VI (null): temperature elevation does not have significant difference between the number of printed layers on ground plane.

3.2 Materials

This section describes all the materials used in this study: silver conductive ink, PET printing substrate (Polyethylene terephthalate), inkjet printer, and silicon protective coating.

3.2.1 Conductive Ink

Metalon JS- B25P silver conductive ink (Novacentrix., Austin, TX), which contains 25% silver nano particles, was used in this experiment. Silver conductive ink was used to print the ground plane of the antenna. The resistivity of this ink on thin film was 5 μΩ.cm, and it is electrically conductive when printed on Novele porous substrate (Novacentrix., Austin, TX). The ink is formulated for inkjet printing. It is water based, which means the printed trace needed a protective coating to protect the print trace from water.

3.2.2 Printing substrate

A Novele™ IJ-220 Printed Electronics Substrate (Novacentix., Austin, TX) was used as the substrate for the ground plane. The ground plane was printed in a rectangular shape, 32.5 mm × 17.0 mm traces. Novele is a PET film (polyethylene terephthalate) with a surface specially treated with mesoporus on one side for conductive ink. The substrate is 0.14 mm thick, and the film weighs 175 g/m^2.

3.2.3 Printer

The inkjet printer used to print the ground plane is the Epson C88+ ink jet printer (Novacentix., Austin, TX). The printer has 4 cartridges: one black and three color cartridges. The conventional black ink cartridge was replaced with a cartridge containing conductive silver ink, and the three color cartridges were replaced with Epson aqueous inkjet vehicle solution.

To maximize the conductivity of the printed ground plane, printing quality was controlled using advanced settings. The printer was set to gray scale and to the best photo option; quick print was turned off to allow the printer to apply as much ink as possible. The best resolution was achieved using a vector-based file format. The printer head and the printing substrate were maintained at room temperature. The same printing settings were maintained throughout the research to ensure homogeneity of the printed layers. Ground planes were printed up to 5 times without complete curing between consecutive printings to better align printing and bond silver particles together (Salmeron, 2013).

3.2.4 Protective coating

Initially, two types of coating materials were selected: silicon conformal coating 422B (Mouser Electronics., Mansfield, TX) and silicon adhesive (DAP Products Inc., Baltimore, MD). The silicone conformal coating and silicon adhesive were tested to evaluate physical and chemical reactions with the Novele porous substrate. The coating was applied with a brush. The silicone conformal coating was clear, neat, and shiny, also a thinner than the silicon adhesive coating. The silicon conformal coating discolored the substrate and left a white patch on the back side of the film. No such reaction occurred, however, when the silicon conformal coating was applied over the printed ink antenna, so the experiment was conducted with conformal coating.

An SMA connector (Pasternack Enterprises, Inc., Irvine, CA) was glued to the ground plane with conductive epoxy (AI Technology, Inc., Princeton Junction, NJ) before the coating was applied. The silicon conformal coating was applied to protect the printed ground plane and ensure electrical performance, protecting the conductive ink when in contact with water. In addition, the coating protected the printed ground plane from physical damage. The coating was cured for 48 hours at room temperature following manufacturer's instructions.

3.3 Measurement

The thickness, DC resistance, and resistivity of the printed layers on the ground plane were statistically analyzed in the first phase of the experiment. Thickness and resistance was measured in order to calculate the resistivity and to evaluate the conductivity. Antenna return loss, power handling capabilities, and temperature elevation were measured in the second phase. The purpose of these measurements was to identify the effect of repeated printing on the antenna performance because antenna properties relevant to heating body tissue influence both the pattern of radiation and return loss (Moros, 2013). Return loss is also influenced by the power input to the system, so the power level was also tested.

3.3.1 Thickness

The thickness of printed layers was measured using thickness gauge 543-683BS series, (Mitutoyo Corporation, Kanagawa, Japan). Samples of the printed ground plane were replicated 20 times for each set of print layers (single, double, triple, quadruple, and quintuple). For exact measurement, printing was done on 32.5 mm ×17.0 mm ground planes, and the thickness gauge was placed exactly in the middle of the printed ground plane (Figure 9).

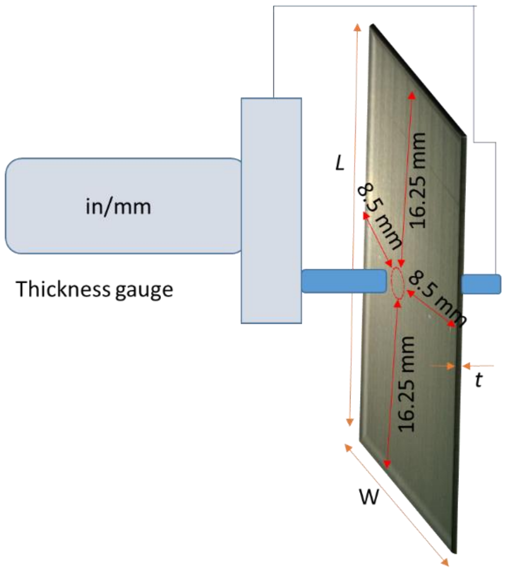


Figure 9. Schematic showing the positioning of thickness gauge

3.3.2 Resistance and Resistivity

Resistance (R) is defined as the property of an electric conductor that opposes a flow of electricity. The resistance of the ground plane depends on the amount of deposited conductive ink during the printing process. The average direct current (DC) resistance was measured by a digital multi meter. The average resistance was obtained from 20 replicated samples of each different numbers of printed layers on the ground plane. Two probes from the digital multi meter were placed on exactly the same position of each printed ground plane (Figure 10).

Resistivity (ρ) is an intrinsic property of a material irrespective of its shape and size. Resistivity is the reciprocal of conductivity. The conductivity of printed trace influences the current flow in the ground plane. The resistivity (ρ) of the ground plane was calculated using the following equation:

$$\rho = \frac{RWt}{L} \tag{1}$$

where, ρ = resistivity, R = resistance, W = width of printed ground plane, L = length of printed ground plane, and, t = thickness of the printed ground plane.

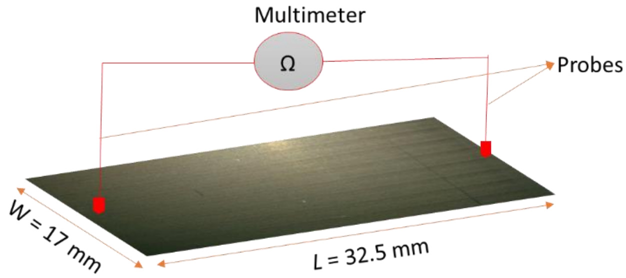


Figure 10. Schematic showing the positioning of multi meter probes

3.3.3 Return loss and power handling capacity

Return loss, a measure of how well the antenna matches the transmission line, refers to the portion of the signal that cannot be absorbed by the end of line transmission, which affects radiation efficiency. The magnitude of S_{11} versus frequency is also referred to as return loss. S_{11} is an indication of reflection coefficient at the port channel, and it must be minimal for optimal antenna performance. Return loss is expressed as a negative number in dB. In general, -10 dB is an acceptable level of return loss (Balanis, 2005). For instance, if the incident power is 10W and the reflected power is 1W, then the S_{11} is -10 dB. Values of incident power and reflected power were recorded from the power meter (Bird Technologies., Angola, NY) and return loss was calculated using the following equation:

$$S_{11} = 10 \times log10\,(P_r \,/\, P_i) \qquad (2)$$

where, P_r = reflected power and P_i = incident power.

The lowest possible return loss allows maximum transfer of energy to tissue. More energy reflected from the antenna also leads to reduced tissue heating and creates excess heat in antenna components. Therefore, antennas with a printed ground plane were tested to determine the return loss (S_{11}) at 915 MHz.

Power was tested as a function of time to determine how much power the printed antennas can withstand before their performance degrades. These tests were conducted at 915 MHz with a return loss less than -10 dB because antennas become unstable and the power amplifier may reduce output power if the antenna bandwidth is higher than -10dB (Balanis, 2005). An HY3020C series DC power amplifier (RSR, Colorado) was used to input power while an HP 8648C series signal generator (ANKO Electronics, San Diego) was used to set the signal frequency. Power at 15 W was supplied for 10 minutes to evaluate the average antenna power handling capacity against time. Power level was restricted to 15 W for treatment volumes (T>41°C) and depths of 2.79 cm^3 and 19.72 mm for the flat ground plane configuration (Curto, Ramasamy, Suh, & Prakash, 2015).

3.3.4 Temperature

The aim of hyperthermia treatment is to increase tumor temperature to between 41 ºC – 44 ºC. Temperature of a breast model was measured to evaluate how well the antenna performed in heating tissue. Fiber optic temperature probes (Neoptix, Canada) 2cm deep measured meat temperature for 10 minutes. Chicken breast tissues were used as phantom for biological tissue to measure the internal tissue temperature in medical experiments (Krotov, Zhadobov, & Reyman, 2003). Fiber optic probes are used because these probes are immune to electromagnetic interference and do not conduct electricity, so they can be used in place of metal probes (Chichel, 2007; Stauffer, 2005). Otherwise, antenna radiation interference will give inaccurate temperature measurements. The probe was placed precisely in the middle of the breast model, which was made with chicken meat (Figure 11).

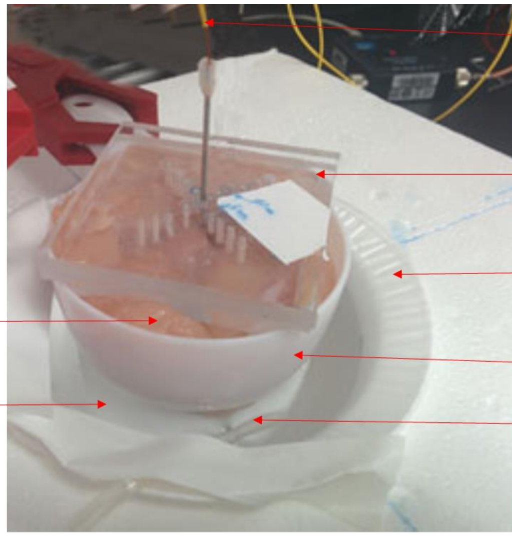


Figure 11. Schematic drawing showing the position of temperature probes

3.4 Experimental design

This research had two stages to test the hypotheses. The first stage was designed to evaluate the conductivity of the ground plane. The thickness, resistance, and resistivity of up to five layers of conductive printing were tested. Based on the results from the first stage, an optimal number of printed layers was selected for fabricating the antenna. In the second phase, antennas were tested for hyperthermia performance: return loss, power handling capacity, and temperature elevation in tissue.

3.4.1 Experimental design I

The primary goal of the first experiment design was to test the first research question: how does repeated printing improve the conductivity of the printed trace on the ground plane. Thickness, resistance, and resistivity of the ground plane were analyzed in this stage.

Cost and the length of the printing process meant we could experiment with up to quintuple layers of print. Traces were printed on a ground plane with dimensions of 32.5 mm ×17 mm.

Twenty replications of each layer type were printed, and the thickness was analyzed using ANOVA. Resistance and resistivity were analyzed using a regression model.

The single layer did not consistently allow continuous current flow because the deposition of ink was not homogeneous, leaving space between silver particles. The conductivity of a printed trace depends on silver particles mixed in the solvent and their connections to one another in printed state.

3.4.2 Experimental design II

The second experiment design tested the second research question: how does the number of printed layers on the ground plane affect antenna performance? Antenna performance was determined by analyzing return loss, power handling capacity, and temperature elevation in tissue.

The optimal number of printed layers on the ground plane was selected using the results of the first experiment stage in terms of resistance and thickness. The same ground planes used in first experiment were used to fabricate the antenna. Based on the result of the first experiment, antenna prototypes with triple and quintuple layered ground planes were replicated three times.

The antenna used in this study consisted of a thin copper plate and a printed ground plane using dimensions based on software simulation results. The dimension of the copper plate was 13.7 mm × 3.9 mm, and the dimension of the ground plane was 32.5 mm×17.0 mm. Conductive epoxy (Prima Solder EG 8050) with electrical resistivity of 4×10^{-4} Ω - cm was used to glue the connector to ground plane and copper plate. The connection was cured for 120 hours at 25 ˚C (Figure 12).

A PE 4099 series SMA straight connector (Pasternack Enterprises, Inc., Irvine) was installed 3.3 mm away from ground plane and 0.25 mm from the edge of the copper plate. The connector was 27.43 mm long, 12.70 mm in diameter, and 12.70 mm high; it weighed 20.72 g.

The frequency range of the connector was DC to 18 GHz, and the impedance was 50 Ω. The body of the connector was stainless steel and gold plate, and the contact material was beryllium copper mixed with gold plate. Figure 13 shows the antenna structure and dimensions.

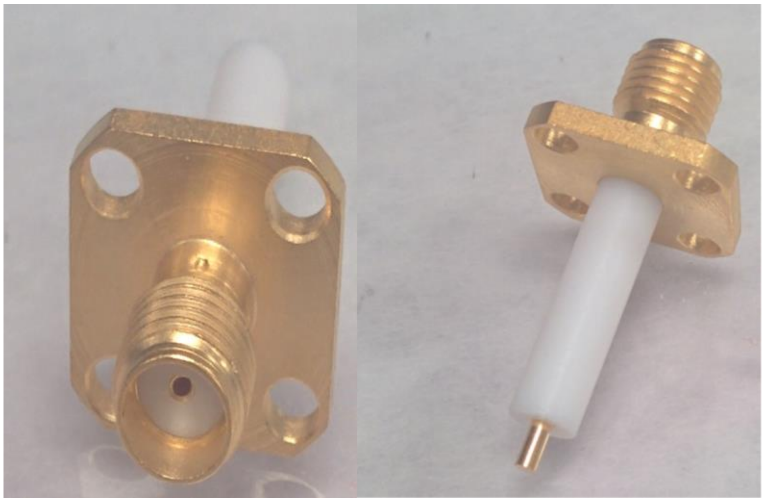


Figure 12. A PE 4099 series SMS straight connectors

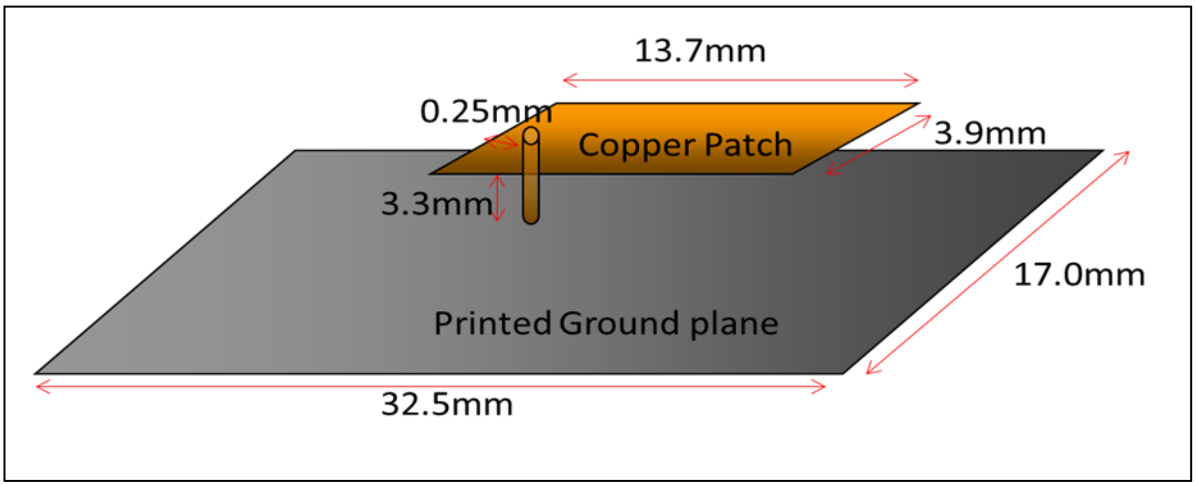


Figure 13. The schematic of antenna design. The antenna consisted of silver conductive ink printed on the ground plane with a patch made of thin copper plate

The antenna must be immersed in water (water bolus) to cool the antenna components and skin during hyperthermia treatment. This also helps reduce the antenna size and the operating frequency (Curto et al., 2015; Trefná, Vrba, & Persson, 2010). Therefore, the antenna was fixed to a polystyrene foam cup, and then 200 ml (approximately 3 cm depth) of deionized water was poured into the cup. The polyurethane cup with water represented a water bolus (Figure 14). Permittivity (*εr)* of 79.95 F/m and conductivity (*σ)* of 0.20 S m^{-1} was continuously maintained for the water. The water was continuously circulated through a water pump. The water inlet and outlet were manually controlled to keep the water level consistent. The water circulation prevented overheating the skin and maintained the temperature of the water (Stauffer et al., 2005; Trefná, Vrba, & Persson, 2010).

A breast model was used to mimic breast tissue to get a clear results of hyperthermia in a clinical setting. Chicken meat was used to represent breast tissue. Meat was stacked into a thin fabricated plastic cup to build a breast shape (Figure 14). The cup was shaped in a hemisphere; the diameter was 8 cm, and height was 4 cm.

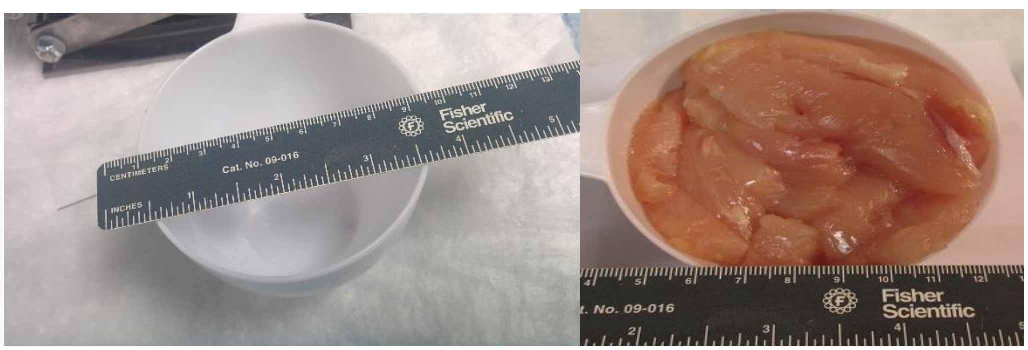


Figure 14. The breast model prepared by stacking meat in a hemispherical cup

The midpoint of the breast model was positioned over the middle of the antenna, 5 mm above the copper plate. The meat was heated in a water bath with circulating water to maintain the temperature of 33 ºC before each experiment. Three trials were conducted for triple printed layers and three trials for quintuple layers. A new meat sample of the same size was used for each trial. The antenna was connected to a power amplifier by a 50Ω coaxial cable, and the temperature probes were inserted to into the breast model (Figure 15).

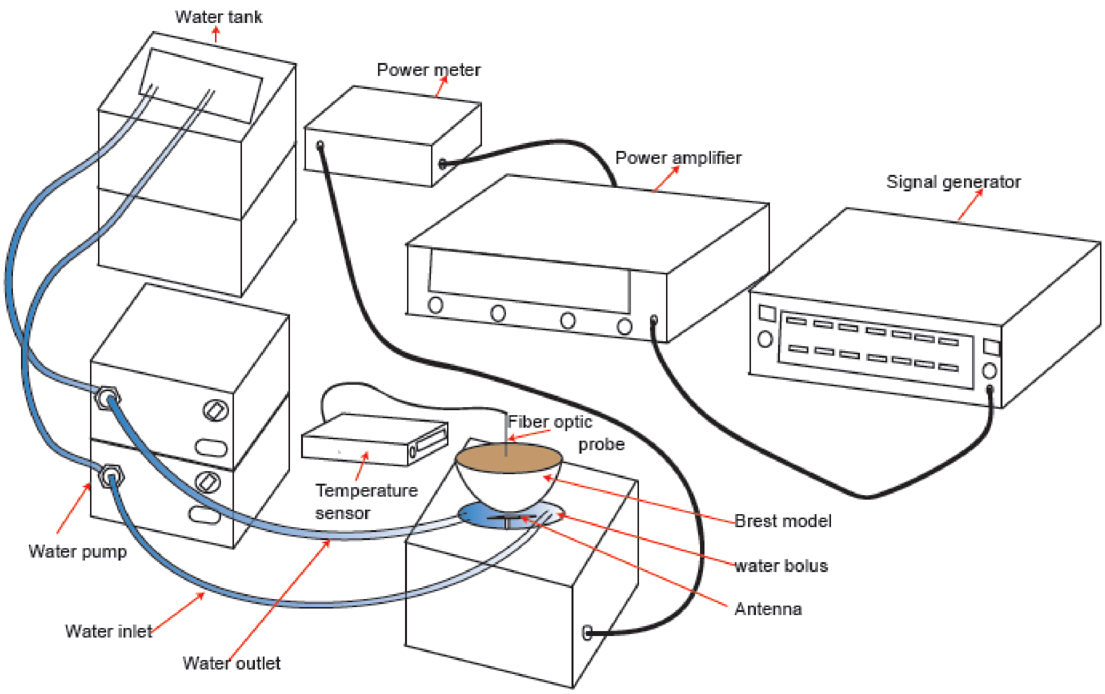


Figure 15. Schematic drawing of experiment setting

The second stage of experiments were designed to evaluate how well the antenna performed in hyperthermia treatment. All three variables, return loss, power handling capacity, and temperature elevation, were measured at 915 MHz while 15 watts of power were supplied for 10 minutes.

The value of return loss (S_{11}) of each antenna was measured based on Equation (2). The average S_{11} of both antennas, one with triple layers of printing and the other with quintuple, was compared to see if S_{11} improved. To evaluate power handling capacity against time, the average S_{11} over 10 minutes was analyzed. The reflection coefficient of the antenna must be lower to improve antenna performance. The reflection coefficient over time must, in addition, be consistent for stable antenna performance. The average temperature elevation of antennas with triple and quintuple printed layers was also measured to analyze antenna performance. Over 10 minutes, antennas were evaluated for the ability to elevate tumor temperature ($T > 41$ ˚C). Both antennas, with triple and quintuple printed layers, were compared to look for improvements in temperature elevation. Results were analyzed with repeated measure ANOVA.

CHAPTER 4. RESULTS & DISCUSSION

The purpose of this study was to explore the possibility of incorporating conductive printing into a wearable hyperthermia applicator, specifically investigating antenna performance and the effect of multiple layers of printing on a ground plane. The research questions in this study focused on the electrical performance of printed antenna. Experiments tested changes in thickness and performance due to the number of printed layers. One way ANOVA was adapted to test thickness of multiple layers. Simple linear regression was used to evaluate resistance and resistivity of the printed ground plane, and repeated measure ANOVA was used to analyze the return loss (S_{11}) and power handling capacity of the antenna and temperature elevation in tissue. This chapter presents the results of the data analysis of the six hypotheses introduced in Chapter One.

4.1 Experimental design I

Experimental design I investigated the relationship between numbers of printed layers and thickness, resistance, and resistivity on a ground plane. The following section presents the descriptive and ANOVA results for the electrical performance of the ground plane. The ground plane had up to quintuple printed layers to investigate the relationship between the number of layers and electrical performance.

4.1.1 Thickness of printed layers

In the first experiment stage, thicknesses of printings with varying numbers of layers were measured. Table 3 provides the descriptive statistics of all printed samples and Figure 15 shows the trend in mean thickness versus number of layers. Thickness increased dramatically between double and triple layers and again between triple and quadruple layers of consecutive printing.

Table 3. Descriptive statistics for thickness of printed ground plane by number of printed layers

Layers	N	M (μm)	SD	Minimum	Maximum
Single	20	1.75	0.44	1.00	2.00
Double	20	1.80	0.41	1.00	2.00
Triple	20	2.40	0.50	2.00	3.00
Quadruple	20	3.20	0.41	3.00	4.00
Quintuple	20	3.55	0.51	3.00	4.00

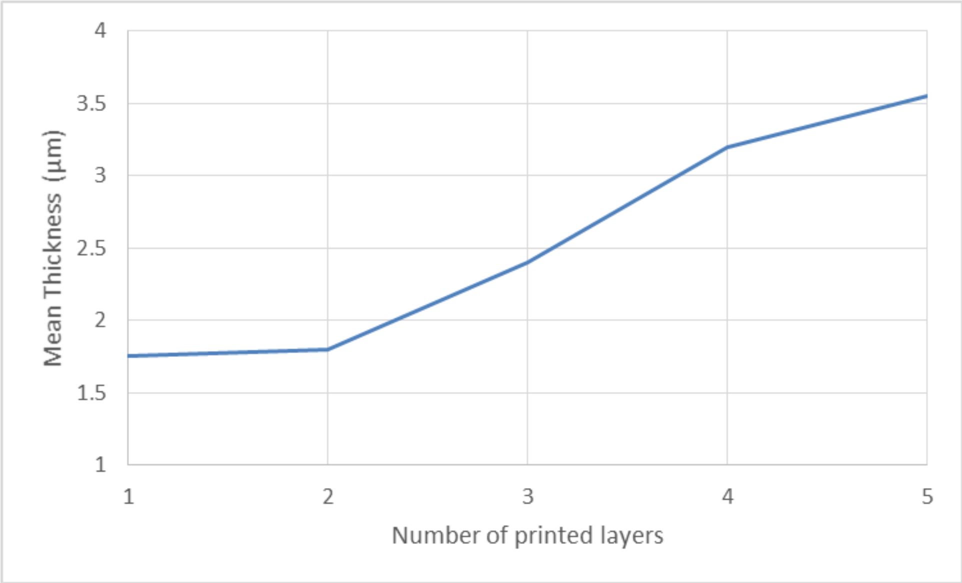


Figure 15. Thickness of layers with consecutive printing

One way ANOVA and Tukey's post hoc method were used to analyze the thickness of the ground plane for all twenty replications to test Hypothesis I for any significant differences in the means.

Hypothesis I (null): There is no significant difference in thickness of printed ground plane by increasing the number of printed layers

A one way ANOVA compared the mean scores of thickness (lowest = 1.75 µm; highest = 3.55 µm) for single to quintuple layers, showing a statistically significant difference among number of printed layers: $F (4, 95) = 63.18, p < 0 .001$ (Table 4). However, Tukey's post hoc test shows no significant difference in thickness between single and double layers (p = 0.997) and no significant difference in thickness between quadruple and quintuple layers (p = 0.119). For mean thickness, layers could be grouped into three distinct groups; Table 5 shows a homogeneous subset of the group. These results show no consistent variation in thickness in consecutive printings.

At the initial stage, inconsistent ink deposition and porosity was observed in single layer print; the second consecutive layer may have filled the spaces between ink particles. Consequently, no significant piling up of ink particles during the printing process occurred when the second layer was applied. Moreover, no significant increase in thickness was observed. This may explain why resistance improved with double printing; that is, the silver particles connected to each other in parallel and bridged the spaces between silver particles. Silver particles are responsible for conductivity of the ink, so bridging the spaces formed in single layer print would be helpful. Moreover, silver particles align in parallel, so they do not tend to pile up, and thickness will not increase.

Unexpectedly, thickness was not significantly different between quadruple and quintuple layers either, probably because the ink flowed down at the edges of the printed trace. However, the silver particles may also mix well with the ink solvent, combining well with the previously printed layer and restraining any increase in thickness.

Table 4. ANOVA results for thickness by number of printed layers

Sources	df	N^2	F	Sig
Between Groups	4	13.23	63.182	0.000*
Within Groups	95			
Total	99			

P < 0.001*

Table 5. Thickness of printed ground plane for different layers

	Subset for alpha = 0.01		
Layers	1	2	3
Quintuple	3.55		
Quadruple	3.20		
Triple		2.40	
Double			1.80
Single			1.75

4.1.2 Resistance

Conductivity of the ground plane was evaluated by analyzing the resistance of the printed ground plane, which was directly measured using a multimeter. Table 6 shows the means and standard deviations of resistance. Resistance decreased dramatically between a single layered print and double layered print (Figure 16).

Table 6. Descriptive statistics for resistance of printed ground plane by number of printed layers

Layers	N	M(Ω)	SD	Minimum	Maximum
Single	20	2.26	0.45	1.60	3.20
Double	20	0.85	0.16	0.70	1.20
Triple	20	0.75	0.05	0.60	0.80
Quadruple	20	0.62	0.04	0.50	0.70
Quintuple	20	0.61	0.05	0.50	0.70

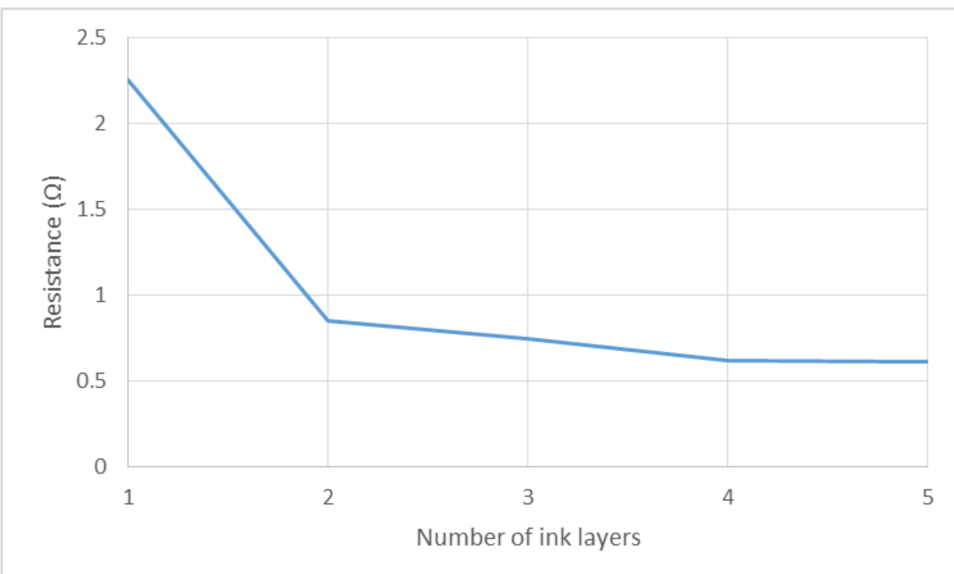


Figure 16. Resistance for consecutive printings

A one way ANOVA compared the mean scores of resistance (lowest = 0.61Ω; highest = 2.26Ω) for single layer through quintuple layers; differences in resistance were statistically significant among printed layers: $F\ (4, 95) = 212.48,\ p < 0\ .001$ (Table 7). However, Tukey's post hoc showed only three homogeneous subsets within the group using mean resistance (Table 8). Based on the post hoc test, resistance showed no significant differences among triple, quadruple and quintuple layers. This may be due to inconsistency in depositing silver particles so that thickness variation did not increase proportionally with consecutive printing. For instance the triple layers range from 2µm to 3µm thickness, and quadruple layer range from 3µm to 4µm thickness. Therefore, samples of both triple and quadruple layers each have some 3µm thickness of printed layers. This means resistance would not show much significant difference. A simple linear regression model was established to further investigate the relationship between predicted resistance and thickness.

Table 7. ANOVA result for resistance by number of printed layers

Sources	df	N^2	F	*Sig*
Between Groups	4	9.891	212.475	0.000*
Within Groups	95			
Total	99			

$P < 0.001^*$

Table 8. Resistance of printed ground plane for single through quintuple printed layers

	Subset for alpha = 0.01		
Layers	1	2	3
Quintuple	0.61		
Quadruple	0.62		
Triple	0.75	0.75	
Double		0.85	
Single			2.26

The second hypothesis examined the regression relationship between thickness and resistance.

Hypothesis II (null): There is no significant relationship between thickness and resistance

Equation (3) provides a linear regression model adopted for resistance(R) .

$$\frac{1}{R} = \beta_0 + \beta_1 D_1 + \beta_2 D_2 + \beta_3 D_3 \tag{3}$$

where, R = resistance; β_0 = intercept; D1 = 1μm; D_2 = 2μm; D_3 = 3μm;

β_1 = the difference between the reciprocal of average resistance of layer with thickness 1μm and the reciprocal of average resistance of layer with thickness 4μm;

β_2 = the difference between the reciprocal of average resistance of layer with thickness 2μm and the reciprocal of average resistance of layer with thickness 4μm;

β_3 = the difference between the reciprocal of average resistance of layer with thickness 3μm and the reciprocal of average resistance of layer with thickness 4μm.

Dummy variables were included in the regression model because the independent variable (thickness) in this experiment is a categorical variable. Regression analyses are conducted for numerical variables. Numerical variables are interval or ratio scale variables with directly comparable values. Thickness as a categorical variable dummy variable was included for a better fit for regression analysis (Table 9).

Table 9. Set of dummy variables for categorical predictor of thickness

Thickness (µm)	D_1	D_2	D_3	D_4
1	1	0	0	0
2	0	1	0	0
3	0	0	1	0
4	0	0	0	0

D_1 = 1µm; D_2 = 2µm; D_3 = 3µm; D_4 = reference variable

The reciprocal of resistance was adopted as the transformation model for analysis because the general regression model did not validate the regression assumptions. However, the transformation model passes the assumptions of constant variance and also of normality distribution. Figure 17 shows the scatterplot for normality assumption.

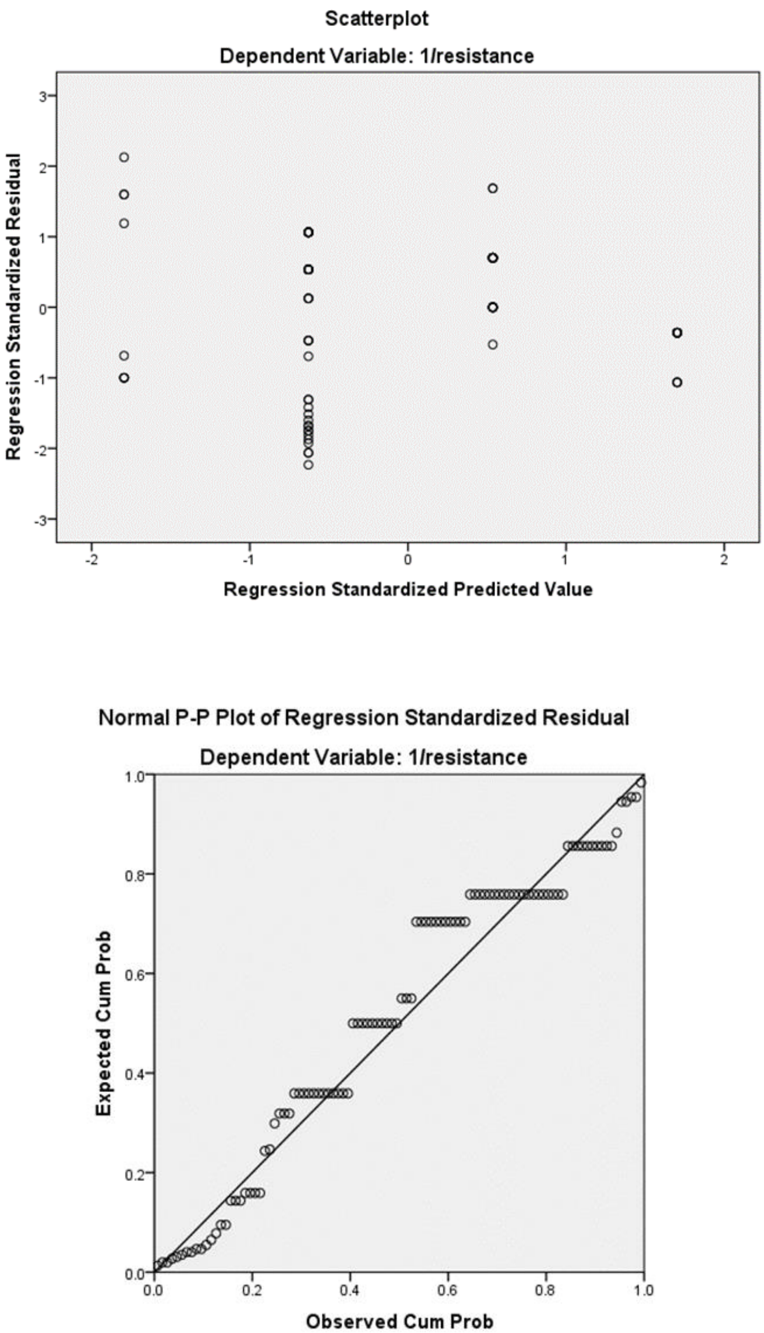


Figure 17. Normality distribution of variance

The effect of thickness on resistance was significant (Table 10). The regression results showed thickness and resistance had both a significant regression relationship and an inverse relationship ($F(3, 96) = 38.14$, $p < 0.001$). Therefore, the null hypothesis was rejected, and the alternate was accepted.

Table 10. Regression model on 1/resistance with thickness differences

	df	*Sum of Squares*	*Mean Squares*	*F*	*Sig.*
Regression	3	11.249	3.750	38.140	.000*
Residual	96	9.438	0.098		
Total	99				

p < 0.001*

The coefficient results showed no significant differences in resistance between thicknesses of 4 µm and 3 µm ($p = 0.863$) but does show a strong significant difference in resistance between 4 µm and 2 µm thick layer and between 4 µm and 1µm thick layer (Table 11).

Table 11. Coefficient results of sheet resistance of printed ground plane on different thicknesses

Model	*B*	*Beta*	*t*	*Sig*
Constant	1.619		19.998	.000*
D_1	-0.842	-0.530	-6.366	.000*
D_2	-0.639	-0.695	-6.791	.000*
D_3	-0.017	-0.018	-0.174	.863

$p < 0.001^*$

The estimated regression equation follows:

$$\frac{1}{R} = 1.619 - 0.842D_1 - 0.639D_2 - 0.017D_3 \tag{4}$$

In the regression equation, D_1 is significant to the regression model ($p < 0.001$), and the coefficient was calculated as - 0.842. The difference between the reciprocal of average resistance of layers that are 1µm thick and the average resistance of layers that are 4µm thick is - 0.842. This indicates that the average resistance of a 4µm thick layer is less than the average resistance of a 1µm thick layer

The average resistance of a 4µm thick layer is less than the average resistance of a 2µm thick layer because that the difference between the reciprocal of the average resistance of a 2µm thick layer and the average resistance of a 4µm thick layer is - 0.639. Also the derived regression equation shows D_2 is significant ($p < 0.001$) with a coefficient of - 0.639.

The regression model shows that resistance of a 4µm thick layer and 3µm thick layer were not significantly different ($p = 0.863$). To that end, we conclude that layers of 3µm and 4µm thickness had statistically the same impact on sheet resistance.

4.1.3 Resistivity

Generally, resistivity of a particular material is consistent because resistivity is intrinsic to a material irrespective of shape and size. Table 12 shows the descriptive statistics for resistivity of printed samples. Unexpectedly, however, we observed a significant drop in resistivity of the printed ground plane between a single layer and double layers (Figure 18).

Table 12. Descriptive statistics for resistivity of printed ground plane by layers

Layers	N	M (Ω-μm)	SD
Single	20	2.03	0.57
Double	20	0.81	0.26
Triple	20	0.93	0.17
Quadruple	20	1.03	0.16
Quintuple	20	1.13	0.21

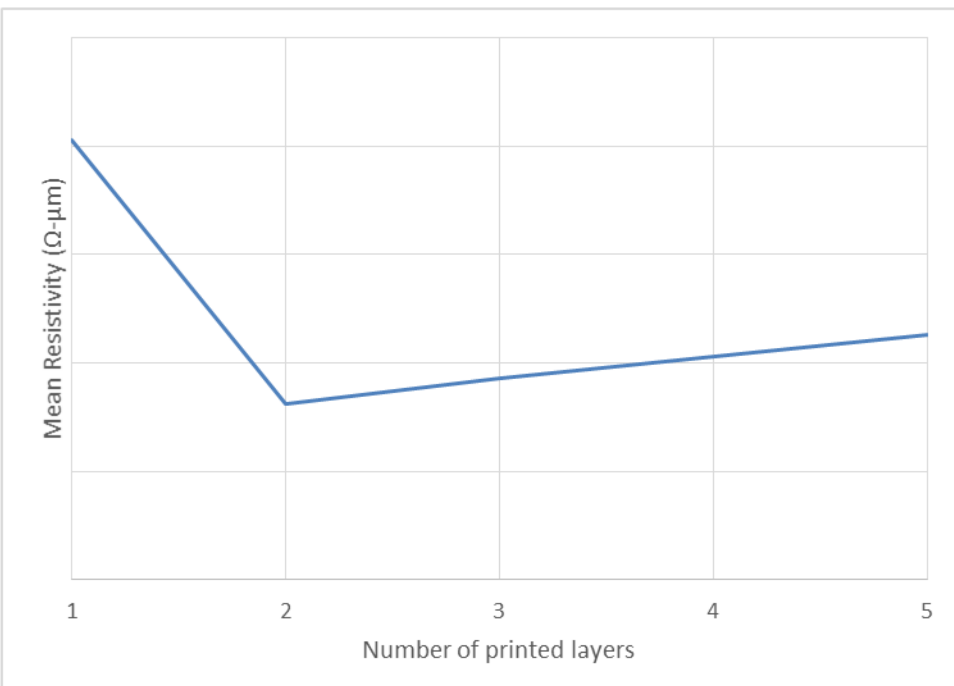


Figure 18. Resistivity of consecutive printing

This drop resistivity from single layer to double layer may be due to the significant decrease in resistance from single to double layer. As shown in the equation (1); $\rho = \frac{Rtw}{l}$, when width and length are consistent, any increase in thickness would proportionally decrease resistance, therefore keeping resistivity consistent. However, this experiment showed no decrease in resistance proportional to increases in thickness. Therefore, double layer showed significant decreases in resistivity.

One way ANOVA was used to compare the mean scores of resistivity (lowest = 0.81Ω-µm; highest = 2.03Ω-µm) for single layer through quintuple layers; Table 13 shows a statistically significant difference among layers: $F\ (4, 95) = 48.28,\ p < 0\ .001$. However, Tukey's post hoc test showed that the only significant difference in resistivity was between single and any of the other layers. In fact, resistivity results show layers can be divided into two groups; Table 14 shows a homogeneous subset of the groups. This result is consistent with the relationship between layer and thickness. While no significant differences in thickness appeared between single and double layers, a decrease in resistance will decrease resistivity. Therefore, for resistivity, resistance has more influence than thickness. Consequently, resistivity can be reduced without much impact on thickness. However, ANOVA results showed that resistivity of triple, quadruple and quintuple layers increased. An increase in thickness may be relatively insignificant in decreasing resistance. That is, beyond the triple layer, no further decreases in resistivity occurred.

Table 13. ANOVA result for resistivity by printed layers

Sources	Df	N^2	F	Sig
Between Groups	4	18.92	48.275	0.000*
Within Groups	95			
Total	99			

$P < 0.001^*$

Table 14. Resistivity of printed ground plane for different thicknesses

	Subset for alpha = 0.01	
Layers	1	2
Quintuple	0.81	
Quadruple	0.93	
Triple	1.03	
Double	1.13	
Single		2.03

A linear regression model was established to test Hypothesis III;

Hypothesis III (null): there is no significant relationship between thickness and resistivity

A simple linear regression predicted resistivity based on thickness of the printed layers. The linear regression model for resistivity (ρ) is given below:

$$logarithm\, \rho = \beta_0 + \beta_1 D_1 + \beta_2 D_2 + \beta_3 D_3 \quad (5)$$

where, ρ = resistivity; β_0 = intercept;

β_1 = difference between the average logarithm (log) resistivity of a 1µm thick layer and the average log resistivity of layer 4µm thick layer;

β_2 = difference between the average log resistivity of a 2µm thick layer and the average log resistivity of a 4µm thick layer

β_3 = difference between the average log resistivity of a 3µm thick layer and the average log resistivity of a 4µm thick layer

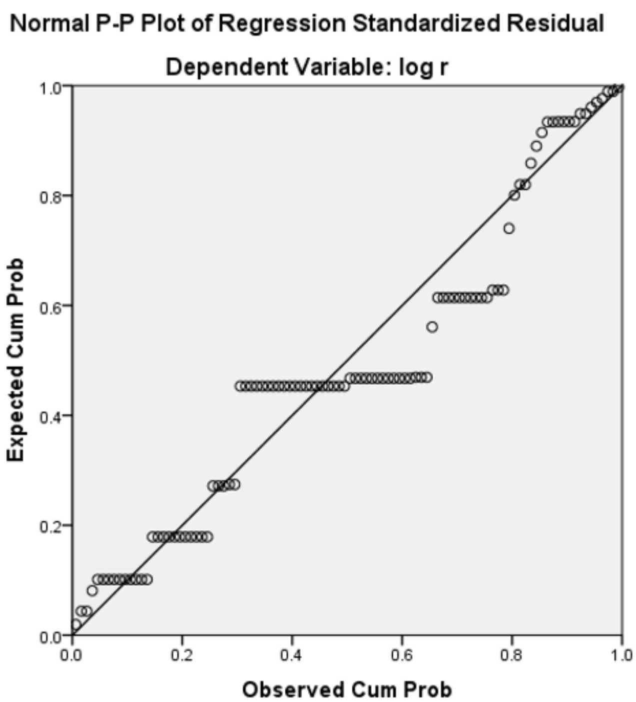
As with resistance, dummy variables were included for regression analysis (Table 15).

Table 15. Set of dummy variables for categorical predictor of thickness

Thickness (µm)	D_1	D_2	D_3	D_4
1	1	0	0	0
2	0	1	0	0
3	0	0	1	0
4	0	0	0	0

D_1 = 1µm; D_2=2µm; D_3 = 3µm and D_4 = reference variable

A transformation model was adopted for analysis because logarithm of resistivity model follows the assumptions of constant variance and of normality. Figure 19 shows the scatterplot for normality.



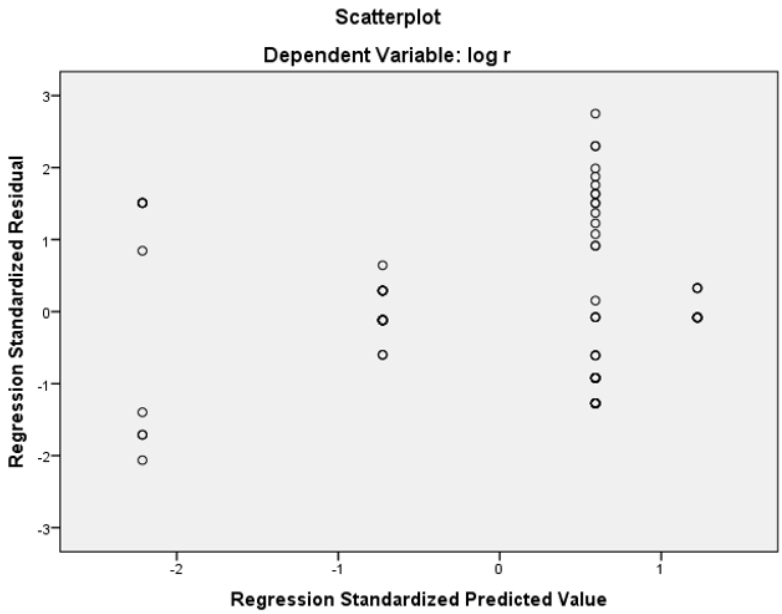


Figure 19. Normality distribution of variance

The regression model showed that the effect of thickness on resistivity was significant (Table 16), revealing a significant regression relationship between thickness and resistivity ($F(3, 96) = 4.573$, $p = 0.005$). Therefore, the null hypothesis was rejected, and the alternate was accepted.

Table 16. Regression model of differences between logarithmic resistivity and thickness

	df	Sum of Squares	Mean Squares	F	Sig.
Regression	3	1.958	.653	4.573	.005
Residual	96	13.702	.143		
Total	99				

The coefficient results showed no significant differences in average log resistivity of 2μm thick layers and 4μm thick layers ($p = 0.435$). We found no significant regression relationship between average log resistivity of 3μm thick layers and 4μm thick layers ($p = 0.022$). However, the average log resistivity of 4µm thick layers was significantly different from 1µm thick layers (p = 0.003). Table 17 shows coefficient results.

Table 17. Coefficient result for resistivity of printed ground plane on different thickness

Model	B	Beta	t	Sig
Constant	0.258		2.648	.000*
D_1	-.483	-.350	-3.034	.003*
D_2	-.089	-.111	-.784	.435
D_3	-.274	-.326	-2.330	.022

$P < 0.01^*$

The estimated regression model for logarithm (log) resistivity (ρ) is given in Equation (6) :

$$logarithm\ \rho = 0.258 - 0.4832D_1 - 0.089D_2 - 0.274D_3 \quad (6)$$

As shown in the regression model, D_1 is significant (p = 0.003), and the estimated coefficient was -0.4832. This means that the difference between the average logarithm resistivity of a 1µm thick layer and the average logarithm resistivity of a 4µm thick layer is $e^{-0.483}$.

The average resistivity of a 4µm thick layer is lower than a 1µm thick layer. Moreover, the regression model shows that resistivity of 4µm thick layers and 3µm thick layers are not significantly different. To that end, we conclude that 3µm and 4µm thick layers have the same impact on resistivity.

4.2 Experimental design II

The second experimental stage was designed to investigate the relationship between numbers of printed layers on the ground plane and the electrical performance of the antenna. Based on the results of the first experiment stage, antennas were fabricated using triple and quintuple layers of ground plane. Triple layered ground plane was chosen in terms of optimum level of thickness;

the ground plane with quintuple layers was chosen for minimal resistance and resistivity. Repeated measure ANOVA was conducted to compare the electrical performance of antennas with triple and quintuple layered ground plane. Three antennas with triple layers and three with quintuple layers were tested for S_{11}, power handling capacity, and temperature elevation.

4.2.1 Return loss

On each sample of antennas with both triple and quintuple layers, a total of six samples, S_{11} at initial stage was calculated. Forwarded and reflected power was measured by supplying 15 watts of power and generating a signal at 915 MHz. Both types of antenna successfully resonated at 915 MHz with an average return loss below -10dB.

Table 18 provides the descriptive statistics for S_{11} for antennas printed with triple and quintuple layered antennas.

Table 18. Descriptive statistics for S_{11} of antennas with triple and quintuple layers

Layers	N	M (dB)	SD
Triple	03	-13.76	4.99
Quintuple	03	-14.53	2.15

Although antennas with triple and quintuple layers statistically do not differ in S_{11} significantly, both types resonated with different average return losses of -13.76 dB for triple layers and -14.53 dB for quintuple layers.

One-way ANOVA was used to determine any significant differences between the means of S_{11} among two types of antenna. The hypothesis IV was proposed to examine the impact of number of printed layers on ground plane to the antenna return loss.

Hypothesis IV (null): Antenna return loss does not change by the number of printed layers on ground plane.

The ANOVA results showed that the number of printed layers on the ground plane had no significant effect on antenna return loss: *F (1, 4) = 0.059*, *p = 0.820* (Table 19). Return loss refers to the portion of the signal that cannot be absorbed by the end of line transmission, which affects radiation efficiency. These findings show that radiation efficiency does not depend on the number of printed layers on ground plane, which demonstrates that Hypotheses IV was accepted. This could be that radiation efficiency depends on total amount of ink used to print the trace than the number of printed layers on the ground plane. Previous research does show similar results (Siden, 2007)

Table 19. ANOVA results for S_{11} for antennas with triple and quintuple layers

Sources	df	N^2	F	*Sig*
Between Groups	1	.874	.059	.820
Within Groups	4			
Total	5			

$P < 0.001$

4.2.2 Power handling capacity

The power handling capacity was evaluated by analyzing the S_{11} over time. Constant input power of 15 watts was supplied and forwarded, reflected power was measured at frequency level of 915 MHz over a 10 minute period. Three samples each of antennas with triple and quintuple layers were analyzed for S_{11}. The mean value of S_{11} for antennas with triple layers was -12.12dB over that 10 minute period; for quintuple layer the mean value was -14.51dB. The antennas with triple layers read -11.89dB for the lowest return loss and -12.92 for the highest; antennas with quintuple layers read -13.85dB for the lowest return loss and -15.19dB for the highest. This shows robust performance for both antennas during power input because, in general, -10 dB is recommended as an acceptable level of return loss (Balanis, 2005). This result indicated that printed antennas on a PET substrate can handle 15 watts of power and resonate at 915MHz with less than -10dB. Figure 21 provides the means plot showing the separate means for S_{11} over 10 minutes.

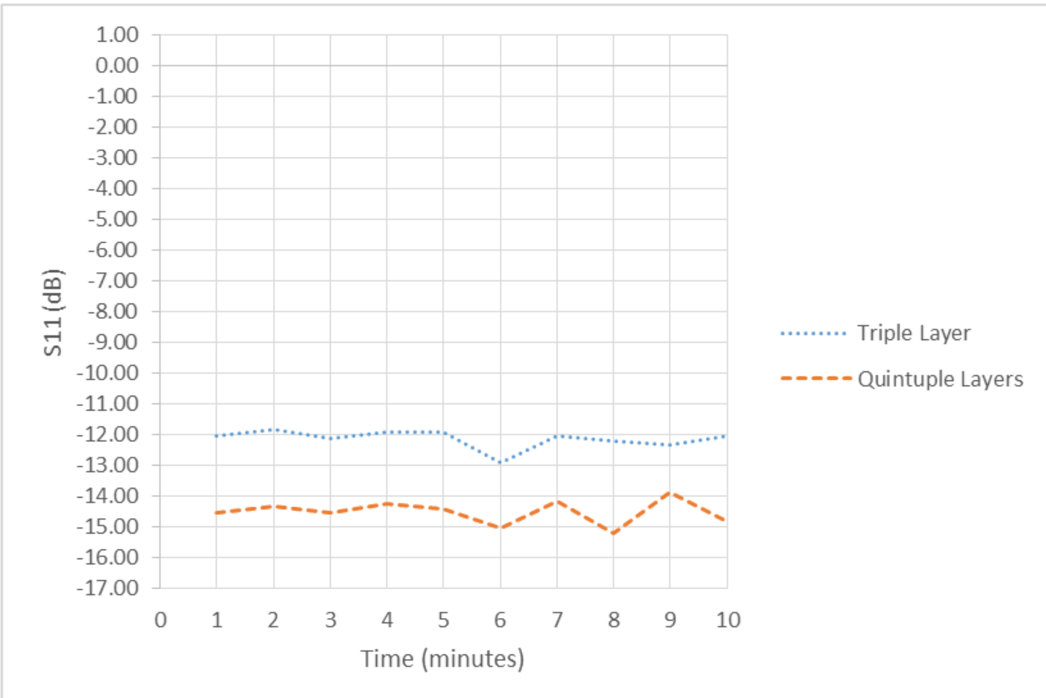


Figure 21. Return loss for antennas with triple and quintuple layers

The hypothesis V compared the overall significant difference between the means of S_{11} at the different time points through the repeated measure ANOVA.

Hypothesis V (null): Power handling capacity of antenna does not have significant difference between the numbers of printed layers on ground plane.

The antenna return loss was not significantly affected by number of layers throughout the 10 minutes period: *(F (1, 4) = 0.649, p = 0.466)*.Therefore hypothesis V was accepted. Table 20 shows the overall significant differences of mean S_{11}.

Table 20. Repeated measure ANOVA for S_{11} for antennas with triple and quintuple layer

	df	Mean Squares	F	*Sig.*
layers	1	85.038	*.649*	*.466*
Error(layers)	4	131.041		

The means plot shows S_{11} readings fluctuating. This fluctuation could be due to variations in water level during the experiment. Manual control of the water pump was a challenge. Because the two water tubes had different diameters to facilitate the experiments, the same speed control for both tubes was not easy to achieve. Circulating water is an important part of hyperthermia treatment to avoid overheating skin and maintaining a consistent temperature in the water bolus.

Thermal properties of water were maintained with a relative permittivity of 79.95 F/m, conductivity of 0.20 S/m, and 20 °C water temperature for the antenna to resonate at 915 MHz. Temperature changes in the water bolus would alter water properties and affected the forwarded and reflected power. Consequently, return loss for the antenna changed over the course of time. Changes in water temperature will also cause antennas to resonate at different frequencies, and accordingly reflected power may change.

Moisture absorption could also have a significant effect on the dialectic substrate as well as on antenna performance (Khan & Nema, 2012). Even so, the performance of the antennas did not degrade significantly over 10 minutes with an input power of 15Watts, and power handling capacity of antennas with triple layers later did not differ significantly from antennas with quintuple layers. This result is consistent with a previously tested hypothesis where resistivity of triple and quintuple layers on the ground plane did not differ significantly. Therefore forwarded and reflected is similar for antennas with both triple and quintuple layer at all the time points.

4.2.3 Temperature elevation

The temperature changes (41ºC – 44 ºC) in the breast model were evaluated using the same antennas with both triple and quintuple layers for this experiment. Temperature at depth of 2 cm was measured for 10 minutes. The probe was placed precisely in the middle of the breast model. Figure 22 shows the temperature rise at 2 cm deep.

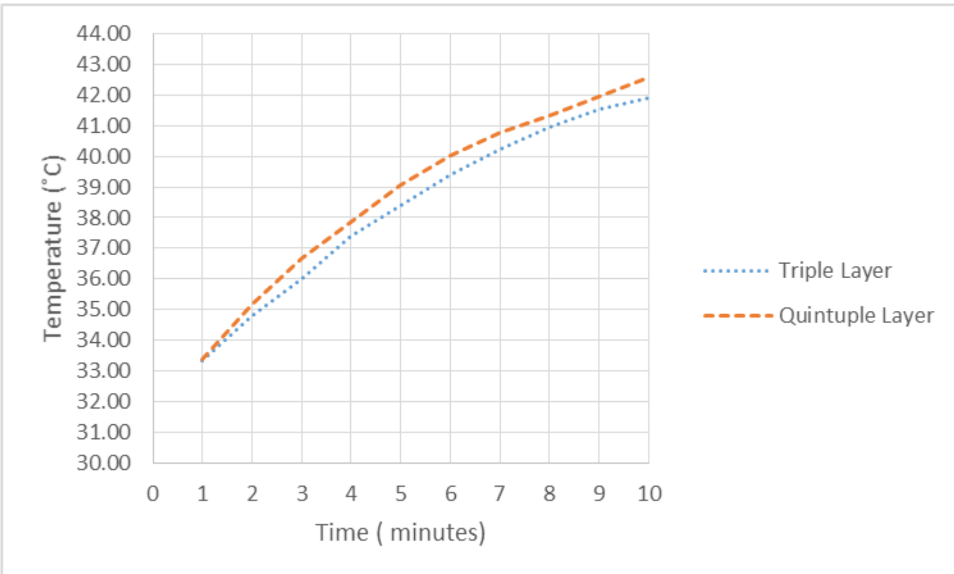


Figure 22. Temperature increases for antennas with triple and quintuple layers

Repeated measure ANOVA was used to assess the overall significant differences between the mean of temperature elevations at different points of time. Hypothesis VI was proposed to test the influences of number of printed layers on antenna performance

Hypothesis VI (null): Temperature elevation does not have significant difference between the number of printed layers on the ground plane.

The temperatures of triple and quintuple layers were compared at ten minute intervals (Table 21); the number of layers had no significant effect (F (1, 4) = 0.074, p = 0.799) on temperature elevation. A previous experiment showed that antennas with triple and quintuple layers did not differ significantly in return loss; this result, average rise in temperature did not differ significantly between triple and quintuple layers, is consistent with the previous results. To that end, we can conclude that although return loss fluctuated, it had no significant effect on antenna performance in heating tissue.

Table 21. Repeated ANOVA measurement results for temperature increase for triple and quintuple layers

	df	Mean Squares	F	*Sig.*
Layers	1	3.456	.074	.799
Error (layers)	4	46.849		

CHAPTER 5. CONCLUSIONS

This research investigated the feasibility of integrating printed antennas into a wearable hyperthermia device to improve the efficiency of hyperthermia treatment. Silver conductive ink was used to print the ground plane on a flexible substrate. Using printing facilitates smaller and flexible components, which in turn simplifies fabrication of antenna. Furthermore, printing on a flexible substrate could reduce the weight and size of the device. Also, a smaller, lighter weight applicator increases the efficiency of radiation. An antenna with a printed ground plane and a thin copper plate was fabricated. A multilayer technique was adopted to achieve good conductivity in ground planes to perform the hyperthermia treatment.

Achieving consistent ink deposition throughout the ground plane was a challenge with an inkjet printer. However, repeated printing produced a ground plane that significantly improved the electrical performance of antennas with additional layers of the ink. After repeated printing, the electrical properties of the printed ground plane were statistically analyzed. To improve the conductivity of the ground plane, this study used multiple ink layers in printing the ground plane, ranging from single layer to quintuple layers. This layering technique increased the silver particles deposited during printing and thus increased conductivity. This research was designed in two stages to evaluate feasibility of the proposed antenna for hyperthermia treatment. The first experiment stage was designed to test the conductivity of the printed trace on the ground plane. The test was conducted using 20 samples of printed ground plane with single, double, triple, quadruple and quintuple printed layers. To achieve this goal the following research question and hypotheses were addressed:

Research Question 1. How does repeated printing improve the conductivity of printed trace?

The thickness, resistance, and resistivity of up to five layers of conductive printing were tested to answer the first research question. Three hypotheses were tested to answer the first research question.

Hypothesis I (null): there is no significant difference in thickness of printed ground plane by increasing the number of printed layers

One way ANOVA analysis showed no significant increase in thickness when the layers were added (F=63.182, p<.000). Therefore the first hypothesis was accepted. Tukey's post hoc test showed no significant difference in thickness between single and double layers. There was no significant piling up of ink particles during the printing process when the second layer was applied because the second consecutive layer may have filled the spaces between the ink particles. There was no significant difference observed between quadruple and quintuple layers too, probably because the ink flowed down at the edges of the printed trace.

Hypothesis II (null): there is no significant relationship between thickness and resistance

The regression results showed thickness and resistance had both a significant and an inverse relationship ($F(3, 96) = 38.14$, $p < 0.001$). Therefore, the null hypothesis was rejected, and the alternate was accepted. The coefficient result indicated that the 4μm and 3μm thick layers were not significantly different. Therefore we can conclude that layers of 3μm and 4μm thickness had statistically the same impact on sheet resistance.

Hypothesis III (null): there is no significant relationship between thickness and resistivity

The regression model revealed a significant regression relationship between thickness and resistivity ($F(3, 96) = 4.573$, $p = 0.005$). Therefore, the null hypothesis was rejected, and the alternate was accepted. However, the coefficient result showed that the resistivity of 4μm and 3μm thick layers were not significantly different. Therefore, 3μm and 4μm thickness had the same impact on the resistivity.

In the first stage of our research, we discovered that printing triple layers of silver ink on the ground plane provided appropriate thickness and resistance for the antenna conductivity. Consecutive printing improved the resistance of the antennas. Specifically, thicker ink layers provided less resistance (R of 1μm < R of 4μm and R of 2μm < R of 4μm), although the differences in resistance between the ground planes of 3μm and 4μm was not significant. Moreover, thickness did not increase at the same rate because ink deposition was inconsistent on each consecutive printing, and the data showed that resistance of ground planes with triple, quadruple and quintuple layers did not differ significantly. Thus, different numbers of printed layers did not necessarily change thickness. In contrast to previous studies (Salmeron, 2014; Mager, 2012) we found no significant improvement in resistance and resistivity beyond the triple layers of prints. Resistance of the ground plane influences the antenna performance. Based on the results from the first stage, the triple and quintuple printed layers were selected in terms of resistance and thickness for fabricating the antenna. The second experiment was designed with the following research question and hypotheses:

Research Question 2. How does the number of printed layers on ground plane affect antenna performance?

Three antenna samples for the triple and quintuple layers were fabricated and evaluated for their antenna performance. Hypotheses 4-6 were tested to evaluate the antenna performance: return loss, power handling capacity, and temperature elevation in tissue. The antenna performance was measured by supplying 15 watts of power at 915MHz. The following hypothesis was proposed to test the impact of repeated printing on antenna return loss.

Hypothesis IV (null): antenna return loss does not change by the number of printed layers on ground plane

The ANOVA analysis showed that the number of printed layers on the ground plane had no significant effect on antenna return loss: *$F(1, 4) = 0.059$, $p = 0.820$*. Therefore, Hypothesis IV was accepted. This result demonstrates that radiation efficiency does not depend on the number of printed layers rather it depends on total amount of ink used to print the trace. Previous research does show similar results (Siden, 2007). The average return loss of the triple and quintuple layers were -13.76dB and -14.53dB respectively which is an acceptable level of return loss.

Hypothesis V (null): power handling capacity of antenna does not have significant difference between the numbers of printed layers on ground plane.

ANOVA results showed that return loss was not significantly affected by number of layers throughout the 10 minutes period: *($F(1, 4) = 0.649$, $p = 0.466$).*Therefore hypothesis V was accepted. This result is consistent where the conductivity of triple and quintuple layers did not differ significantly thus forwarded and reflected power was not significantly affected by number of layers. Fluctuations in return loss were observed due to the water circulation being manually controlled. However, overall return loss did not change over the time. The following hypothesis was proposed to test the influences of number of printed layers on temperature elevation in tissue samples:

Hypothesis VI (null): temperature elevation does not have significant difference between the number of printed layers on ground plane

The temperatures of triple and quintuple layers compared at ten minute intervals showed that number of layers had no significant effect ($F(1, 4) = 0.074$, $p = 0.799$) on temperature elevation, which demonstrates that Hypotheses VI was accepted. A previous experiment showed that antennas with triple and quintuple layers did not differ significantly in return loss and power handling capacity therefore transfer of energy to tissue did not differ significantly between triple and quintuple layers.

The second stage of this research successfully demonstrated that printed antennas with triple and quintuple layers on a PET substrate can handle 15 watts of power and resonate at 915MHz with less than -10dB. This is a new research finding on a silver conductive ink printed on a flexible substrate. The antennas consisting triple and quintuple layers also proved to be capable of increasing the tumor temperature to 41 ºC - 44 ºC within a 10 minute period without degrading the antenna components. According to Togni, Vrba, & Vannucci, 2010, expected heat penetration to tumors in irregular body surfaces was 6 to 15 mm. Experimented results showed that antennas consisting triple and quintuple layered ground planes are capable of delivering heat up to 2cm depth. Statistical analysis showed no significant differences in antenna performance between triple and quintuple layers. Thus, we can argue that radiation efficiency depends on the total amount of ink used to print the ground plane rather than on the number of printed layers. Moreover, the amount conductive ink deposited during printing affects the return loss. This also affects radiation efficiency, which is consistent with previous research on conductive printing electronics (Siden, 2007). These findings urge that an efficient method of printing is necessary to obtain consistent ink deposition. Therefore radiation efficiency can be increased without additional layers of prints and in turn this reduces the fabrication time for repeated printing.

The findings of this study verified the potential of printed antennas as a means of delivering heat for hyperthermia treatment. We successfully fabricated printed antennas for hyperthermia treatment that performed well in terms of temperature elevation and acceptable level of return loss. This study proved that ground planes printed with triple layers is optimum in terms of antenna performance for hyperthermia treatment. Also, testing the conductivity of the ground plane to select the ideal number of printed layers is critical because the results show that not more than a triple layer is required to increase the performance of the antenna.

There are many meaningful implications of this study. Conductive inkjet printing is a high technology that continues to advance with many printed electronics. However, adopting an inkjet printing method for the experiment, we lost conductivity by not using conventional metal antenna. Nevertheless, implementing multilayer technique, we were able to achieve better conductivity in ground planes. In our study, triple layers of printing were sufficient for fabrication of an antenna with a 13.79 dB return loss and 42 ˚C of temperature elevation.

The results of this study offered hyperthermia device manufacturers the opportunity to design alternatives to manufacture hyperthermia device with printed antennas. Antennas can be made by printing conductive ink directly on dielectric substrates. This type of antenna can be produced more accurately in short time compared to metal type antennas. Clearly, a wider range of printed wearable textiles and electronics is possible in medical treatment, although wearable electronics are used currently only for medical monitoring.

This study can help breast cancer patients undergoing hyperthermia treatment by demonstrating the necessity of a smaller and lighter weight applicator; such an applicator is achievable with wearable equipment when the antenna is printed on a flexible substrate. Compared to the dimensions of commercially available micro strip applicators which range from 7.3 cm × 19.8 cm to 19.8 cm × 19.8 cm, the antenna used in this experiments was only 3.25 cm × 1.7 cm big. The long term goal of this study was to develop a hyperthermia bra with printed antennas for applying heat to breast cancer tissues. Other clinical applicators exist, but the primary aim of this study is to increase the efficiency of hyperthermia treatment on a curved surface by integrating the printed antenna into the hyperthermia applicator.

The convex shape of the breast as well as the depth of tumors in the breast have been a challenge in conventional hyperthermia treatment. The result of this study showed that temperature reached to 2 cm depth within 10 minutes, while the conventional applicators are relatively large, and the aperture does not work well for irregular body surfaces where heat is expected to deliver to tumor depths ranging from 6 to 15 mm (Togni, Vrba, & Vannucci, 2010). Moreover, printing gives additional flexibility to print different shapes and accurate dimensions of the ground planes. Customization of antenna placement is necessary based on the tumor location. Printing can be utilized easily for this purpose.

A major limitation was a wearable water bolus not included in this research. We observed fluctuated readings in return loss due to inconsistent water level maintenance. The thickness of the bolus significantly changed the performance of the antenna. Therefore, to obtain uniform heating throughout body tissue, the amount of water between antenna and human tissue should have remained consistent. A water bolus specifically designed for a hyperthermia applicator needed to take into account.

Another limitation was the sample size in the second stage of the research which was not large enough. Due to equipment and financial constraints, only three samples were analyzed to evaluate power handling capacity and return loss. As a consequence, the statistical results for return loss and power handling capacity were not significant among different numbers of layers, which could change the study results; if one sample showed a weak performance due to handling, the average value dropped significantly.

The ink jet printer was a critical component in this study. Using a traditional printer was a challenge in achieving consistent ink deposition. Alternate printing methods and specialized printers could be more beneficial. An efficient printer is required to overcome the problem of uneven printing and in turn minimize the required number of layers. Identifying a method to optimize the number of printing layers while providing consistently low resistance would have much potential for future research.

Future research could focus on a wearable water bolus for an irregular contoured surface. The water bolus itself, which is one of the important components in the hyperthermia device, must be redesigned for a wearable applicator. Developing a water bolus for curved surfaces would increase the efficiency of a wearable applicator and antennas.

The bending properties of flexible substrate, deformations of printed trace could be potential variables for future studies. During the bending, physical damages such as cracks can occur in the printed traces and result in the discontinuity of current flow. Additionally, researchers can use the findings from this study to focus on other cancer regions such as the neck, thigh, and head, which also include highly curved surfaces.

In conclusion, the proposed antenna had low profile, lighter weight and offered significant advantages over a complex bulky applicator used in hyperthermia treatments for breast cancer. Incorporating the flexible printed ground plane will allow the wearable applicator to be in very close proximity to the breast, enhancing the radiation efficiency. This study showed a promising results in power handling capacity and the required tumor temperature elevation. This antenna design showed many potential features to be integrated into a wearable hyperthermia applicator.

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