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High Temperature Control Woven Fabric for Women

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***Abstract-** Breast hyperthermia is a non-invasive cancer treatment, where breast temperature is mildly elevated by a localized electromagnetic (EM) irradiation to deactivate and damage cancer cells. The emerging needs associated with this medical modality include the development of a highly wearable microwave applicator with a low power requirement to enable a more patient-friendly and continuous hyperthermia therapy. As a potential solution, we propose a textile antenna that consists of a copper-plated woven polyester fabric as a radiating patch and a ground plane and a woven polyester fabric as a dielectric substrate and a padding layer. The porous nature of these textile materials enables construction of a lightweight and flexible antenna with a low dielectric loss for a more comfortable hyperthermia treatment. By incorporating a synthetic breast tissue for a model study, the temperature rises were measured to be 3.3 °C and1.9 °C at 5 mm and 15 mm depths, respectively, after 15 min of heating (input power of1 W). This suggests that the textile-based approach could be an effective solution for comfortable and long-term applications of breast hyperthermia therapy.*

***Indexed Terms-** Smart textiles, e-textiles, Wearable medical thermotherapy, Breast hyperthermia, Woven fabric antenna, Electromagnetic, Thermal simulations*

I. INTRODUCTION

Breast cancer is the most common type of cancer diagnosed for women in the United States, accounting for approximately 30% of all cancer diagnoses in women, and the treatment of breast cancer is one of the most active research areas in health sciences (Gradishar 2017; Mukai 2016; Siegel et al. 2017). As a supplementary technique of treating breast cancers, microwave hyperthermia has been featured in recent research. Microwave hyperthermia is a non-invasive cancer treatment where body temperature is locally raised to 39–45 °C by a focused electromagnetic (EM) radiation to deactivate and damage cancer cells (Pang and Lee 2016). Within this temperature range, it has been proven by both cytological studies (Song et al. 1984) and clinical trials (Pang and Lee 2016) that malignant (cancerous) tumors substantially shrink while normal tissues could withstand the heat for an extended period of time owing to their superior blood flow that allows a rapid thermal dissipation. Heat produced during the breast hyperthermia treatment could accelerate the deactivation and damage of tumorous cells when radiotherapy (Zagar et al. 2010) and chemotherapy (Klimanov et al. 2018) were performed in combination.

Current microwave hyperthermia research focuses primarily on aperture antennas(waveguides) (Van Der Zee et al. 2010). Aperture antennas are relatively easy to operate, but because they are rigid and bulky, patient discomfort is a significant challenge fora continuous treatment (Curto et al. 2018; Mukai 2016). Thus, development of a more comfortable, personal microwave device is highly encouraged for widespread acceptance of hyperthermia treatment (Curto et al. 2018; Curto and Prakash 2015; Mukai 2016).

In order to reduce the antenna size for a wearable device, various compact antenna structures have been proposed and tested in literature. For instance, (Montecchia 1992) ;(Singh 2015) and (Singh and Singh 2015) examined the performance of planar antennas built on printed circuit boards (PCBs). Although these antennas were small and designed specifically for on-body hyperthermia applications, they would not conform to the body contour owing to the highly rigid nature of PCB materials.

More wearable forms of hyperthermia devices were discussed by (Curto et al. 2015), (Curto and Prakash 2015) and (Curto et al. 2018) with patch antennas embedded inwater bolus systems. The proposed antennas had water boluses that ease antenna impedance matching, reduce the applicator size and cool both the antenna and the skin surface (Curto and Prakash 2015). It was also claimed that a flared ground plane improved the radiation efficiency and the conformability of the applicator, which led to satisfactory heating (Curto and Prakash 2015).

There are, however, notable drawbacks to have a water bolus (Curto et al. 2018, 2015; Curto and Prakash 2015). Water is a highly lossy dielectric at microwave frequencies (Skaar 1988) and thus brings about low efficiency. Consequently, the input power requirement for the antenna was as high as 50 W (Curto et al. 2018). Moreover, an additional power is required to circulate water for cooling. Because the power source needs to be physically carried by patients to run the wearable systems, this high-power requirement is a critical disadvantage. These large, heavy and non-breathable applicators with water boluses would deteriorate the wearability.

The objective of this research was to present a wearable conformal patch antenna fabricated with textile materials for a more comfortable breast hyperthermia therapy. The proposed textile antenna followed a hemispheric contour and consists of copper-plated woven polyester for a radiating patch and a ground plane and a woven polyester fabric for a substrate and a padding. The textile antenna is lightweight, breathable and flexible, and therefore, can be inherently embedded into clothing such as a brassiere or a slip (Ghahremani Honarvar and Latifi 2017; Ramasamy et al. 2018). Moreover, due to the porous nature of textiles, the proposed antenna benefits from a dielectric permittivity close to air, and that results in a high gain and a high efficiency (Mukai et al. 2018a, 2020; Mukai and Suh 2020; Salvado et al. 2012). Thanks to this, the power requirement could stay considerably low.

II. METHODS

As a model study, a hemispheric breast phantom was incorporated in this research, and the dimensions of the textile antenna were optimized using a 3D full-wave EM simulation software. The reflection coefficient of the antenna and the distribution of specific absorption rate (SAR) in the breast phantom were also calculated by using the EM software for theoretical analysis. A transient thermal simulator examined the heat distribution under thermal diffusion. After prototyping, the performance of the textile antenna was experimentally evaluated to verify its feasibility as a wearable hyperthermia applicator

Table 1 Materials properties of the breast phantom

Properties	Values	References
Specific heat ($J\ g^{-1}\ K^{-1}$)	3.63	Ito et al. (2001)
Thermal conductivity ($W\ m^{-1}\ K^{-1}$)	0.55	Ito et al. (2001)
Density ($Kg\ m^{-3}$)	900	Ito et al. (2001)
Complex permittivity at 2.45 GHz	48.5–23.28 j	Zajicek and Vrba (2010)

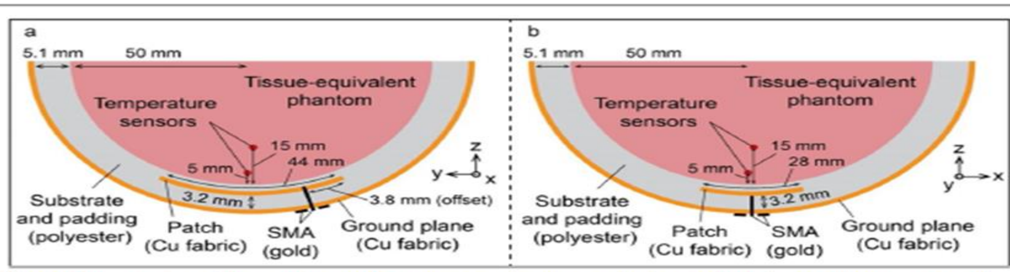

Fig. 1 Cross-sections of the textile patch antenna conforming to the hemispheric breast phantom; **a** yz-slice and **b** zx-slice (not to scale)

III. BREAST MODEL

In microwave breast hyperthermia, the expected treatment effect varies depending on biophysical (perfusion and dielectric) and dimensional (breast size and tumour location) characteristics of treating breasts (Curto et al. 2018). However, these breast characteristics differ significantly from individual to individual, and therefore, a microwave applicator will need to be customized for each patient in clinics (Curto et al. 2018; Pangand Lee 2016). As a model study, a simple homogeneous breast phantom was employed in this work. The breast phantom (density of 900 kg·m−3 (Ito et al. 2001)) had a hemispheric shape with a radius of 50 mm and its thermal and dielectric properties are given in Table 1.

IV. ANTENNA DESIGN

The patch antenna was designed with a conductive patch and a ground plane mounted on a dielectric substrate (Fig. 1). The patch and ground plane were made of a 0.08 mm-thick copper-plated woven polyester fabric (Fig. 2a). Being in a plain weave, this fabric had a basis weight of 80 g/m2 and a highly dense (360-by-280threads-per-inch) structure. This helped to attain a low sheet resistance (sheet resistance of 0.03 Ω/sq., Less EMF Inc.) required for the microwave application. The dielectric substrate was a 0.32 mm-thick woven polyester fabric with a basis weight of 192 g/m2 (Fig. 2b). Woven with 64-tex warp and 57-tex weft yarns in a relatively loose plain-weave construction (45 ends per inch and 33 picks per inch), this fabric had a high porosity (56%) and hence a low complex permittivity (1.55 − 0.014 j). This would be suitable to produce an antenna with a high gain and a wide bandwidth (Mukai et al. 2018a, b). A padding layer made of the same dielectric polyester fabric was also included in the antenna design to protect the conductive patch from corrosive environments such as skin secretions, and a 50 Ω SMA connector was incorporated to feed a 1 W input power.

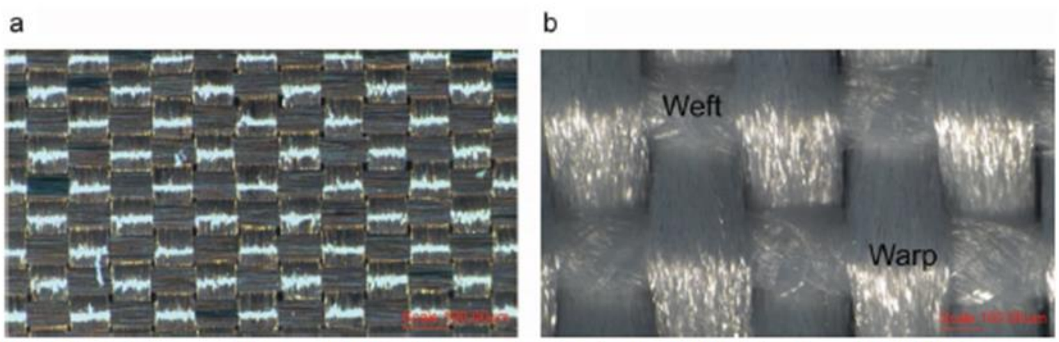

Fig. 2 Optical images of the **a** conductive (copper-plated) polyester and **b** dielectric polyester fabrics

In this antenna geometry, the microwave radiation is achieved by the fringing fields that are generated by the non-uniform distribution of electric fields between the patch and the ground plane (Balanis 2012, 2016). The conformal ground plane serves as a back reflector, and the maximum radiation is directed in the normal direction from the center of the patch (Bancroft 2009). This could be ideal for hyperthermia applications since the focused microwave beam would deposit a concentrated microwave (thermal) energy in the target tumor (Curto and Prakash 2015). The dimensions of the antenna (Fig. 1) were optimized by using a 3D EM simulator with a finite element solver (Ansys HFSS®). The patch sheet was designed to be44 mm by 28 mm, and the optimized thicknesses of the substrate and padding were3.20 mm and 1.92 mm, respectively.

V. THEORETICAL EVALUATION

In order to theoretically evaluate the EM performance of the proposed hyperthermia applicator, 3D full-wave EM simulations were performed by using Ansys HFSS®. The reflection coefficient of the designed antenna and the SAR distribution within the tissue were computed with an input power of 1 W. Since the phantom had ahigh thermal conductivity (0.55 W m−1

K−1), 3D transient thermal analysis was also performed by using the Ansys Transient Thermal simulator.

VI. PREPARATION OF BREAST PHANTOM

The breast phantom was prepared as follows (Ito et al. 2001). 10.46 g of agar (LIVINGJIN Co., Ltd.), 3.76 g of sodium chloride (Sigma-Aldrich Corporation), 0.20 g of sodiumazide (Sigma-Aldrich Corporation) were completely dissolved in 337.50 g of deionized water, followed by heating on a stove. Once the solution reached the boiling point, heat was immediately removed and 8.44 g of TX151 (Oil Center Research Inc.) and 33.75 g of polyethylene powder (Sigma-Aldrich Corporation) were sprinkled and mixed uniformly. The liquid was then poured into a 3D-printed breast mold and then cooled at room temperature for 24 h to form the hemispheric shape (Fig. 4). The phantom was maintained sealed by a plastic wrap at room condition for preservation.

VII. ANTENNA FABRICATION

In order to fabricate the textile antenna in the hemispheric shape (Fig. 2), the conventional flat-pattern method was employed. By following (Thyssen 1997), the optimized (Fig. 5). For the substrate and the padding, 10 and 6 layers of the polyester were respectively stitched together by using a lockstitch machine (ISO 301) to attain the designed thicknesses of 3.20 mm and 1.92 mm, respectively. The patch, ground plane, substrate and padding layers were cut by a laser cutter (Universal Laser Systems VLS 6.60) into the intended dimensions (Fig. 5) after immersed in water to prevent burn marks (Haagensonet al. 2015; Mukai et al. 2018b).

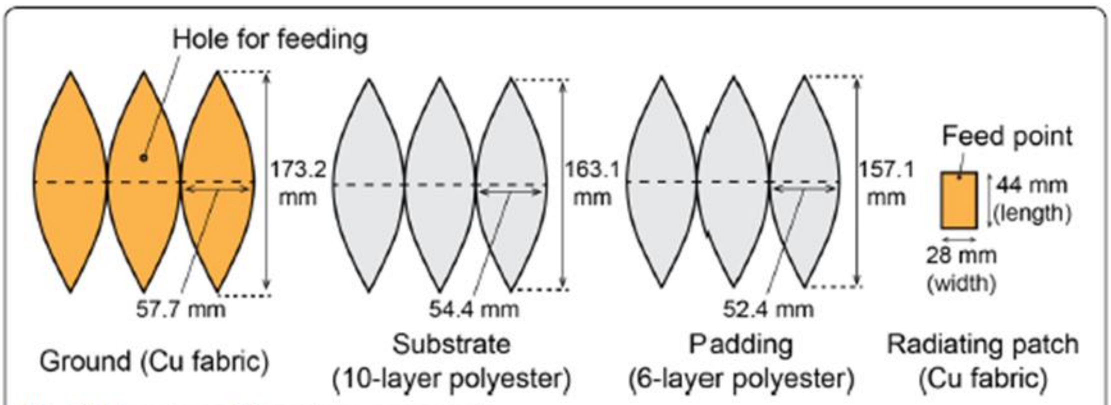

Fig. 5 Flat patterns of the antenna components

Next, the patch and ground plane were mounted on the substrate with a polyamide fusible web (Bostik Inc.). A 50 Ω panel-mount SMA connector (Amphenol Corp.) was soldered to the patch and ground plane, and the connection was reinforced with a silver conductive epoxy for better electrical conduction (MG Chemicals Ltd.). The antenna prototype is shown in Fig. 6a.

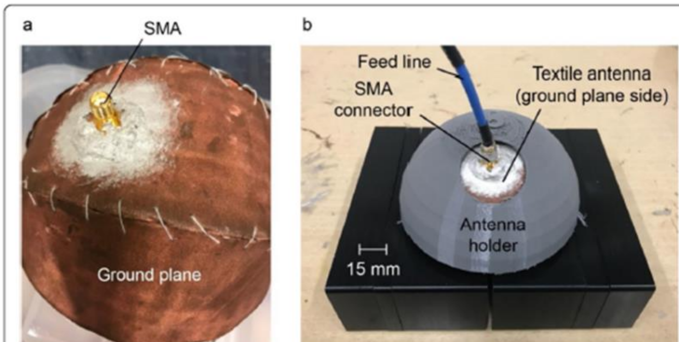

Fig. 6 Antenna sample (**a**) placed in an antenna holder (**b**) for measurements

VIII. EXPERIMENTAL EVALUATION

A calibrated VNA (Agilent E5071C ENA Series Network Analyzer) was used to validate the antenna design. Based on the two-port scattering (S)-parameter network (Huangand Boyle 2008), the reflection coefficient (S11) of the antenna prototype was measuredin the frequency range of 1–6 GHz to evaluate the impedance matching.

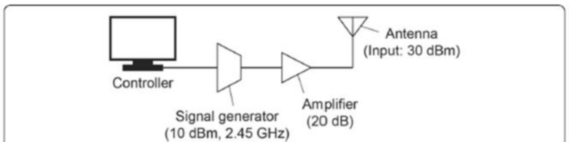

Fig. 7 Antenna powering setup for temperature measurement

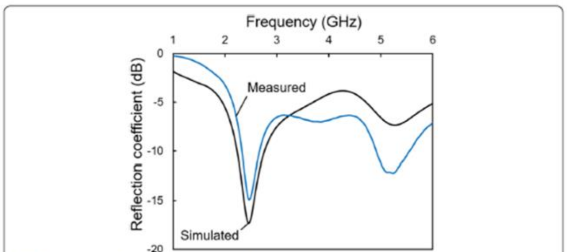

Fig. 8 Simulated and measured reflection coefficient of the wearable textile antenna

For the evaluation of heating performance, the antenna prototype was placed over the breast phantom and housed inside the plastic template (Fig. 6b) to ensure dimensional stability throughout the measurements. This holder was incorporated merely for the purpose of accurate characterization and was not a part of the actual antenna system. A 20-dB gain block (Sireen 2.4 GHz 1 W High Gain Amplifier Module) was connected to a computer-controlled 10 dBm signal generator (Windfreak Technologies Synth NVRF Signal Generator) and supplied a power of 30 dBm (1 W) at 2.45 GHz to the antenna (Fig. 7). The temperature increment in the breast phantom was monitored by a thermometer (Fluke 52 II Dual Probe Digital Thermometer) at the two tissue locations (Fig. 1), in 5 mm and 15 mm depths for 15 min at the room temperature (~ 22 °C).

IX. RESULTS AND DISCUSSION

- Reflection coefficient

Figure 8 shows the simulated and measured reflection coefficients of the designed antenna. The impedance of the fabricated antenna was well-matched to the source impedance of 50 Ω at the operating frequency of 2.45 GHz. The measured S11 was− 14.7 dB which was comparable to the simulated value of − 17.3 dB. Also, accounting of the electromagnetically permeable (and hence low dielectric loss) nature of the porous textile fabric, the antenna showed a wide fractional bandwidth of 13.8% (measured) and20.4% (calculated) (|S11|≤ –10 dB). This successful impedance matching and the wide bandwidth at the target frequency (2.45 GHz) confirms that the proposed design of the wearable antenna is valid.

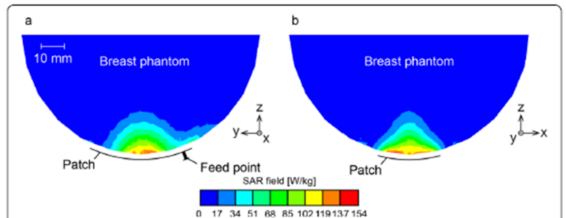

Fig. 9 Cross sections of the SAR distribution in the tissue simulated in HFSS

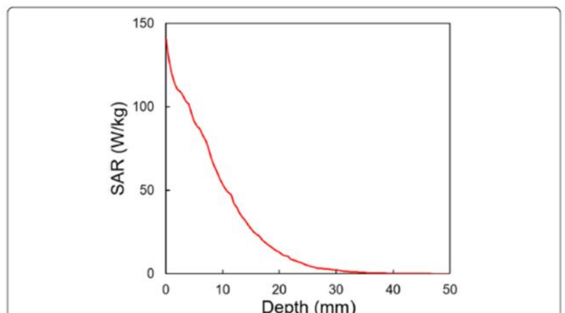

Fig. 10 Simulated SAR plotted as a function of the tissue depth

- SAR distribution

The SAR distribution in the breast phantom was successfully calculated and is shown in Fig. 9. It was found that there was a major microwave absorption (> 100 W/kg) near the center of the patch. The SAR as a function of the tissue depth along the normal direction of the center of the patch is given in Fig. 10. This plot illustrates that there was no significant energy absorbed in the deeper (> 30 mm) tissue, which indicates that the proposed system would be only effective to superficial tumors.

- Temperature increment

The simulated temperature distribution after 0, 300 and 900 s are given in Fig. 11. A significant thermal diffusion was observed in the tissue due to its high thermal conductivity (0.55 W m−1 K−1), which contributed to a wider spread of the heat. Figure 12 shows the calculated and measured temperature rises at the 5 mm and 15 mm depths. According to the calculation, the temperature was elevated by 6.7 °C and 3.5 °C, respectively, after 900 s of heating (Table 2). However, the measured temperature increments were significantly less than the simulated values–the measured temperature rises in the 5 mm and 15 mm locations were 3.3 °C and 1.9 °C, respectively (Table 2).

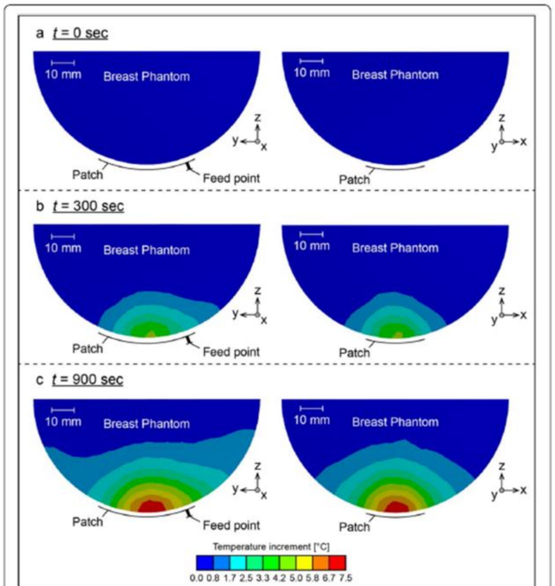

Fig. 11 Cross sections of the simulated temperature distribution in the phantom at different heating times

There are several possible reasons for these differences between the simulated and measured temperature rises. The first reason would be the heat leakage into the ambient air from the tissue, which was not considered in the calculations. Because the air flow promotes thermal dissipation, this might have contributed to the difference. Another attribute could be the limited fabrication accuracy of the antenna sample. In the simulation nmodel, the antenna was assumed to perfectly conform to the hemispheric contour of the breast phantom. In prototyping, however, the textile antenna did not perfectly conform to the hemispheric surface since it was constructed from flat patterns of the multi-layered woven fabric. As the radiation performance of patch antennas is reported to be highly sensitive to its geometry (Balanis 2016; Mukai et al. 2018b; Xu et al. 2017), this imperfection could have lowered the radiation efficiency. Also, the cold solder joint of the conductive fabric and the SMA connector could have led to a radiofrequency (RF)power loss at the insertion. Although the silver epoxy adhesive was applied over the solder to help the electrical conduction, the imperfect electrical connection could have lowered the efficiency.

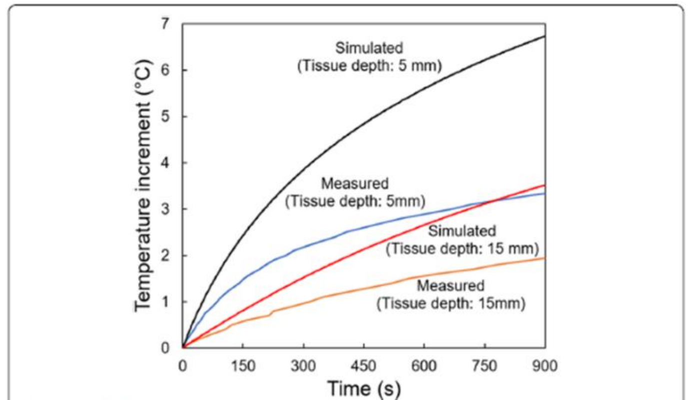

Fig. 12 Simulated and measured temperature increments at the 5 mm and 15 mm locations in the breast phantom

Table 2 Temperature rises after 15 min of heating

Depth	Simulated temperature rises (°C)	Measured temperature rises (°C)
5 mm	6.7	3.3
15 mm	3.5	1.9

CONCLUSION

A textile conformal antenna was designed and fabricated with woven polyester fabrics, and the EM and heating characteristics were simulated and measured using a tissue equivalent phantom. From the simulations, it was found that the effective heating is limited to a superficial region (< 30 mm) due to the high EM dissipation of the tissue. According to the measurements with the antenna sample, up to 3.3 °C and 1.9 °C temperature elevation was observed at 5 mm and 15 mm depths, respectively, after 15 min of heating. Considering the normal body temperature of 37° and the target range of39–45 °C in hyperthermia treatment (Pang and Lee 2016), the reachable temperatures by the proposed textile antenna would be in the lower side. Although this was not experimentally elaborated in the current work, a higher temperature is achievable by increasing the input power. It is in theory that the temperature rise is nearly linear to the increase of the input power (Biagi et al. 2011).

Based on these observations, this paper concludes that satisfactory heating would be possible for a hyperthermia treatment of superficial tumors with a polyester-based textile antenna. Being flexible, lightweight and low dielectric loss owing to the porous textile structure, the presented textile-based approach sheds light on a more patient friendly and a long-term solution in cancer treatment.

It needs to be noted, however, that there are a couple of limitations in this work. Firstly, the presented textile antenna was produced from flat patterns and hence they had limited conformity with curved surfaces. As a potential alternative, advanced fabrication methods, such as 3D knitting (Narayanan et al. 2018), could be incorporated. Enablingan intrinsic construction of curved surfaces in a single step, the 3D knitting option would further improve the wearability while reducing the production-related workload.

Secondly, the results obtained in this research are not intended to directly apply to the case of human tissues. The actual tissues have a number of internal components such as fat and blood vessels with various dielectric properties, and the energy deposition and the temperature elevation could vary depending on such biophysical and dimensional factors. In this context, future work is also recommended with a more realistic phantom to further investigate the potential use of the textile-based wearable microwave applicator.

REFERENCES

[1] Balanis, C. A. (2016). Antenna theory: analysis and design (4th ed.). Hoboken: Wiley.

[2] Bancroft, R. (2009). Microstrip and Printed Antenna Design. IET Digital Library. https ://doi.org/10.1049/SBEW0 48E.

[3] Biagi, P. F., Righetti, F., Maggipinto, T., Maggipinto, G., Ligonzo, T., Schiavulli, L., et al. (2011). Apparatus for \textasciigrave\textasciigravein vivo\textquotesingle\textquotesingle exposure at 1.8 GHz microwaves. Journal of Instrumentation, 6(07), T07002–T07002. https ://doi.org/10.1088/1748-0221/6/07/T0700 2.

[4] Curto, S., & Prakash, P. (2015). Design of a compact antenna with flared ground plane for a wearable breast hyperthermia system. International Journal of Hyperthermia, 31(7), 726–736. https ://doi.org/10.3109/02656 736.2015.10631 70.

[5] Ghahremani Honarvar, M., & Latifi, M. (2017). Overview of wearable electronics and smart textiles. The Journal of The Textile Institute, 108(4), 631–652. https ://doi.org/10.1080/00405 000.2016.11778 70.

[6] Gradishar, W. (2017). Optimizing breast cancer management. Berlin Heidelberg: Springer.

[7] Haagenson, T., Noghanian, S., de Leon, P., & Chang, Y. (2015). Textile Antennas for Spacesuit Applications: Design, simulation, manufacturing, and testing of textile patch antennas for spacesuit applications. IEEE Antennas and Propagation

[8] Magazine, 57(4), 64–73. https ://doi.org/10.1109/MAP.2015.24538 90.

[9] Klimanov, M. Y., Syvak, L. A., Orel, V. E., Lavryk, G. V., Tarasenko, T. Y., Orel, V. B., et al. (2018). Efficacy of combined regional inductive moderate hyperthermia and chemotherapy in patients with multiple liver metastases from breast cancer. Technology in Cancer Research and Treatment, 17, 1533033818806003. https ://doi.org/10.1177/15330 33818 80600 3.

[10] Montecchia, F. (1992). Microstrip-antenna design for hyperthermia treatment of superficial tumors. IEEE Transactions on Biomedical Engineering, 39(6), 580–588. https ://doi.org/10.1109/10.14119 6.