Performance Evaluation of Dipole versus Modified Bow-Tie in Annular Phased Array Applicators

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Abstract— Phased arrays are the common type of applicators for deep hyperthermia systems to heat tumors selectively while keeping healthy tissues at normal temperatures. Annular array applicators with dipoles and water bolus have been improved in several studies to deposit energy efficiently in head and neck tumors. In this study we investigate the performance of a modified Bow-Tie antenna versus half-wave dipole as single elements in annular phased array applicators to heat tumors in head and neck region. Hyperthermia quality indicators have been calculated for each case to quantify the quality of treatment outcome in two different tumor positions in a head-and-neck phantom. The obtained results indicates that dipoles are appropriate phased array elements to heat superficial tumors, while modified Bow-Ties are more suitable in heating big deep-seated tumors.

1. INTRODUCTION

Combination of hyperthermia with chemotherapy and radiotherapy has proven to improve overall survival for different tumor locations [1]. The idea of hyperthermia treatment is to achieve adequate temperature increase at the tumor site while keeping temperature in healthy tissues below critical values. The required temperature increase in the tumor location depends on the ability of the hyperthermia applicator to heat the tumor efficiently.

In phased arrays the wave focusing in the tumor is given by constructive wave interference of the surrounding antennas. This can be achieved by finding the optimal excitation amplitude and phases of the antenna elements in the applicator, which is called treatment planning. The optimization methods have been used to determine the antennas amplitudes and phases, are either based on optimal SAR distribution or optimal temperature distributions.

Besides the hyperthermia treatment plans, the specific design of the applicator such as the number of antennas, number of rings and frequency has a direct effect on the final SAR pattern in the tumor and surrounding tissues. The most common applicator for treatment of head and neck tumors are phased arrays, which composed of antenna elements arranged in circular or elliptical array. To have an applicator capable of treating both shallow and deep-seated tumors, wide-band antenna design are necessary. This way the frequency of operation can be adjusted according to the size and position of the tumor. To this purpose, we have designed and analyzed a wideband Bow-Tie antenna to be used as the antenna elements in a hyperthermia applicator. The antenna has a wide-band performance over 433–900 MHz [2].

In this study 3D time-reversal focusing method is used to find the excitation settings. The advantages of this method are being fast, patient-specific and applicable to wide-band hyperthermia applications [3]. The implementation used the finite-difference time-domain (FDTD) to solve the Maxwell's equations. In a previous study, we investigated the effect of different parameters as the input settings of a 3D code, based on the time-reversal focusing method, for optimal heating of tumor models in a head-and-neck phantom [4]. There we compared the performance of dipoles and hard sources as the antenna elements of the hyperthermia applicator in the 3d code. Based on our results dipole antennas with ominidirectional radiation pattern performed better than hard sources in terms of the average absorbed power in two tumor models.

In this paper the aim is to study the behavior of the modified wideband Bow-Tie and dipole in hyperthermia treatment of two tumor models in a head-and-neck phantom. To evaluate the performance of each antenna, treatment planning outcome of Bow-Tie antenna applicator were compared with that of the half-wave dipole applicator. The efficacy of these two antennas in heating the tumors were then evaluated in terms of hyperthermia treatment quality indicators.

2. METHOD

To be able of comparing Bow-Ties and dipoles as antenna elements of a phased array, 3d time reversal method was implemented in CST commercial software. The virtual source which was placed in the center of tumors, considered as a half-wave dipole at frequency of 500 MHz. Based

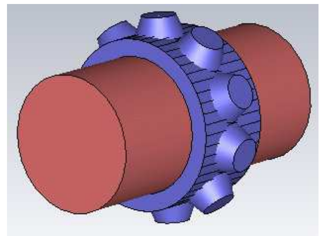


Figure 1: One-ring antenna applicator with homogeneous phantom.

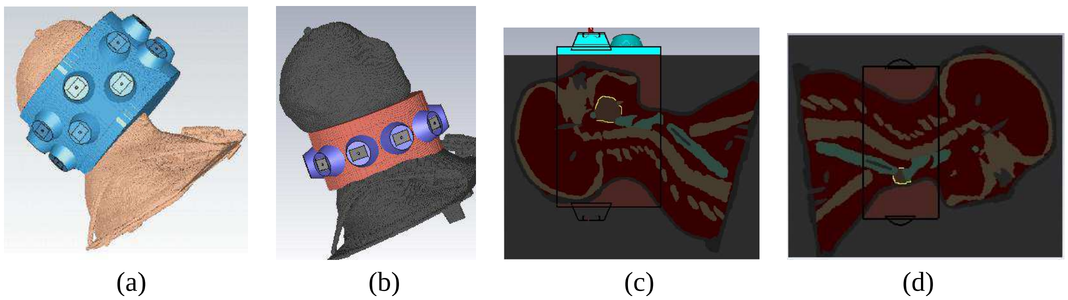


Figure 2: (a) and (b) Antenna applicators for the tongue and laryngeal tumors, (c) and (d) the position of the tongue and laryngeal tumors in the head-and-neck phantom, respectively.

on the expected target volumes in the available head-and-neck phantom, 500 MHz was considered a suitable frequency. This frequency is a good compromise between good focusing and desired penetration depth for two tumor models in our analysis.

Gaussian pulse in the frequency range of 400–1200 MHz considered as the antennas excitation. The mesh density was about 11 cells per wavelength to have a good compromise between accuracy and simulation time. In all the simulations each antenna in the applicator was immersed in a conical shape water bolus of dimension $a = 20$ mm, $b = 30$ mm and $h = 25$ mm, as the upper and lower radii and the height of the truncated cone. In the first analysis a homogeneous spherical tumor was located in 3 different positions of a homogeneous phantom with radius 80 mm. In the applicator, 10 Bow-Ties and dipoles were placed over a water-bolus of outer radius 100 mm and arranged in a one-ring setup, respectively, Figure 1. First excitation amplitudes and phases were found by the time reversal method. Then using these excitation settings, the absorbed power density in the phantom was calculated for each applicator.

In the second analysis voxel data of an available head-and-neck phantom of $430 \times 290 \times 364$ cells, was imported into CST commercial software. Here the analysis is based on two irregular-shaped tumor models in tongue and larynx. The applicator for the tongue tumor was an elliptical applicator of radii 104 and 114 mm, which consists of 16 antennas arranged in two-ring setup. For the laryngeal tumor 10 antennas were arranged in one ring. The positions of the tumors respect to the phantom and applicators are shown in Figure 2, with yellow color showing the tumor boundary. Dielectric properties of the modeled tissues in the phantom at 500 MHz are similar to those given in [4].

To evaluate the ability of the hyperthermia applicators to heat the specified tumors, the hot-spot target coefficient (HTQ) [5] and target coverage$_{25\%}$ [6] were computed for each applicator and each tumor. HTQ index shows the hot spot SAR to tumor SAR quotient, while target coverage$_{25\%}$ indicates the percentage of the tumor volume which is covered by 25% of the maximum SAR value in the patient model.

3. RESULTS

The behavior of a single Bow-Tie antenna and a single half-wave dipole, immersed in a conical shape water bolus, has been studied in the presence of a homogeneous human phantom in [4]. Recalling the analysis results of the antennas radiation at 500 MHz, the Bow-Tie antenna presented a wider bandwidth and higher effective field size than half-wave dipole over the range 0.4–1 GHz. This higher effective field size is useful for heating deep-seated larger tumors. To have a reliable measure of applicators heating efficiency, SAR distributions of the applicators were computed in the homogeneous spherical phantom, Figure 1. The quality indicators were calculated then for two tumor radius of 10 and 20 mm at 3 different distances to the surface of the phantom,d. The analysis results are given in Table 1.

As it is shown in Table 1, for tumor at position 1, Bow-Tie antenna applicator performs better than dipole antenna applicator in terms of HTQ index. This result is independent of the tumor radius or the tumor size. For the tumor closer to the surface at position 2, while $TC_{25\%}$ are comparable for both applicators, dipole antenna applicator presents a lower HTQ index than the Bow-Tie. Finally for the shallowest tumor at position 3, dipole antenna applicator shows lower HTQ indexes for both tumor sizes.

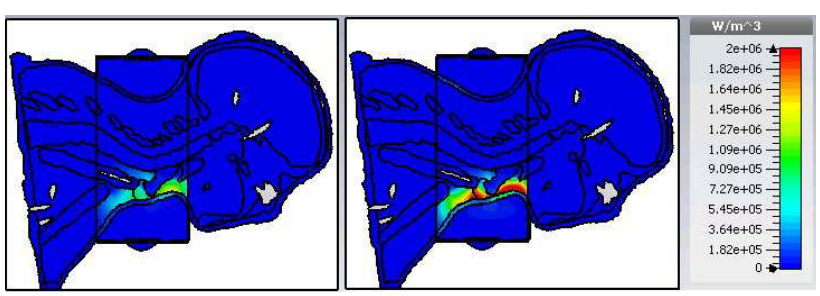
In the second analysis, two tumors in larynx and tongue were radiated by Bow-Tie and dipole antenna applicators. As it was expected from the first analysis results, the dipole antenna applicator delivered more power into the shallow and small laryngeal tumor than Bow-Tie. This is a clear result from the calculated lower HTQ index and higher tumor $\text{coverage}_{25\%}$, Table 2. For the tumor in tongue with larger size and more distance to the phantom surface, HTQ index and tumor $\text{coverage}_{25\%}$ are comparable for both applicators. However Bow-Tie antenna applicator presented higher value of maximum absorbed power in 2d plane of the tumor center which indicates more heating efficiency than dipole antenna applicator, Table 2.

Table 1: Quality indicators calculated for Bow-Tie and dipole antenna applicators at frequency of 500 MHz, applicator setup is shown in Figure 1.

		Bow-Tie antenna applicator		**Dipole antenna applicator**	
Tumor position (mm)	**Tumor radius (mm)**	HTQ	$TC_{25\%}$	HTQ	$TC_{25\%}$
Position 1	10	1.21	100	1.26	100
($d = 80$ mm)	20	1.71	95	1.79	92
Position 2	10	1.47	97	1.46	97
($d = 40$ mm)	20	1.73	60	1.7	60
Position 3	10	0.95	100	0.93	100
($d = 24$ mm)	20	0.87	70	0.84	71

Table 2: Quality indicators calculated for Bow-Tie and dipole antenna applicators at frequency of 500 MHz. The maximum power loss density in 2d plane of the tumor center is shown with PLDmax, $(\mathrm{W/m^3})$.

	Bow-Tie antenna applicator			**Dipole antenna applicator**		
Tumor type	HTQ	$TC_{25\%}$	PLDmax	HTQ	$TC_{25\%}$	PLDmax
Laryngeal	1.11	78	3e6	0.61	84	4.6e6
Tongue	0.85	72	3.41e6	0.84	70	2.74e6



(a) (b) (c)

Figure 3: (a)–(c) Power absorption distribution radiated by Bow-Tie and dipole in the laryngeal tumor, shown in the sagittal plane.

4. CONCLUSION

Bow-Tie antenna and half-wave dipoles have been evaluated as the antenna elements in two different applicators for head and neck tumors. According to the calculated quality indicators in a homogeneous cylindrical phantom, Bow-Tie antennas with wider EFS performed better in heating deeper tumors while dipole-antenna applicator performed better for shallower tumors. For two specific tumors in larynx and tongue of a head-and-neck phantom conforming results were achieved. Bow-Tie-antenna applicator presented more heating into the larger, deeper tongue tumor, while dipole-antennas delivered more power to the smaller, shallower laryngeal tumor. Although Bow-Tie antennas with wideband characteristics give us the capability to adapt the treatment planning for different tumor sizes and positions, half-wave dipole antennas with lower EFS can result in a better treatment outcome for superficial tumors at the single design frequency of the dipole. Thus development of a separate hyperthermia applicator to treat superficial tumors is an alternative solution to achieve high quality treatments for all tumor types.

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REFERENCES

1. Moros, E. G., *Physics of Thermal Therapy: Fundamentals and Clinical Applications*, Taylor and Francis Group, CRC Press, 2013.
2. Takook, P., H. Dobšíček Trefná, and M. Persson, "A compact wideband antenna for microwave hyperthermia system over 0.4–0.9 GHz," *ESHO 2013*, Munich, 2013.
3. Dobšíček Trefná, H., J. Vrba, and M. Persson, "Time-reversal focusing in microwave hyperthermia for deep-seated tumors," *Phys. Med. Biol.*, Vol. 55, No. 8, Apr. 2010; Vol. 26, 185–197, 2010.
4. Takook, P., H. Dobšíček Trefná, A. Fhager, and M. Persson, "Evaluation of the 3D time reversal method for hyperthermia treatment planning in head and neck tumors," *9th European Conference on Antennas and Propagation*, Apr. 2015, Accepted, to be Published.
5. Canters, R. A. M., P. Wust, J. F. Bakker, and G. C. Van Rhoon, "A literature survey on indicators for characterization and optimization of SAR distributions in deep hyperthermia, a plea for standardization," *International Journal of Hyperthermia*, Vol. 25, No. 7, 593–608, 2009.
6. Rijnen, Z., J. F. Bakker, R. A. M. Canters, P. Togni, G. M. Verduijn, P. C. Levendag, G. C. Van Rhoon, and M. M. Paulides, "Clinical integration of software tool VEDO for adaptive and quantitative application of phased array hyperthermia in the head and neck," *International Journal of Hyperthermia*, Vol. 29, No. 3, 181–193, May 2013.