Dielectric Properties of Certain Biological Materials at Microwave Frequencies

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In the medical field, microwaves play a larger role for treatment than diagnosis. For the detection of diseases by microwave methods, it is essential to know the dielectric properties of biological materials. For the present study, a cavity perturbation technique was employed to determine the dielectric properties of these materials. Rectangular cavity resonators were used to measure the complex permittivity of human bile, bile stones, gastric juice and saliva. The measurements were carried out in the S and J bands. It is observed that normal and infected bile have different dielectric constant and loss tangent. Dielectric constant of infected bile and gastric juice varies from patient to patient. Detection and extraction of bile stone with possible method of treatment is also discussed.

Key Words: Biological materials, Permittivity, Cavity Resonators, Perturbation Technique

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The great affinity of microwaves for absorption in biological objects is well known [Schwan, 1957; Tran and Stuchly, 1987; Gandhi and Chen, 1995; David Dunn et al., 1996]. Biological effects of microwaves and the application of microwaves in medicine represent strongly developing areas of research. Availability of sophisticated microwave systems and components of smaller size at lower cost makes microwave applications in medicine more attractive. Microwaves are used in cardiac therapy, cancer therapy and hyperthermia treatment.

Detailed studies on the medical application and the effects of microwaves on tissues have been reported by a number of researchers [Livesay and Chen, 1974; Anderson et al., 1984; Teng et al., 1995]. Different types of applicators have been used for microwave prostatic hyperthermia [David Despretz et al., 1972]. Distribution of maximum microwave power for heating off-centre tumors was described by Rappaport and Morgenthaler [1987]. Various methods of analysing focussed pulse-modulated microwave signals inside the biological tissues were described by Konstantina et al. [1996] and Najafabadi and Peterson [1996]. The effect of microwave absorption in the human head from handheld portable radio and mobile telephones were also reported [Gandhi et al.,1996; Cleveland and Athey, 1989]. Polk and Postow [1995] give a comprehensive background on investigations of the interaction of microwaves with the nervous system. Microwave imaging in medical applications is an emerging area of recent research [Murch and Chan, 1996; Souvorov et al., 2000].

For any type of microwave treatment, initial conditions of the object under treatment should be known. This involves determination of the complex permittivity and conductivity of the object. Because of many constraints such as high dielectric loss and faster decay rate of biological materials, the studies on the dielectric properties on these materials are seen very seldom in the literature. Also, much care should be taken in handling the infected biological samples like bile, bile stones etc. Though various methods are available for permittivity measurement, the cavity perturbation technique has unique advantages and is the most accurate method.

Sample Collection

Biological samples were collected from the Digestive Disease Centre of P.V.S Memorial Hospital, Cochin, India. In this center, research, diagnosis and treatment are done. Internal organs were examined with an advanced medical technology, endoscopy. The modern endoscope, Videoendoscope, has an endoscope, CPU and a monitor. A charge-coupled device at the tip of the shaft transmits the image data to a TV monitor. The handle of the endoscope has control knobs for maneuvering the tip and also controls to regulate irrigation water, air insufflation and suction for removing air and secretions. Also, there is an instrument channel allowing the passage of biopsy forceps, snares for removing polyps and foreign bodies or devices to control bleeding. In routine Upper Gastro Intestinal (UGI) Endoscopy, the entire esophagus, stomach and the proximal duodenum are examined. Some of the common conditions that are routinely diagnosed by endoscopy include Gastroesophageal reflux disease, Peptic ulcer and cancer of the UGI tract. During this investigation, biles and bile stones are collected. Usually bile stones are removed by ERCP (Endoscopic Retrograde Cholangio Pancreatography) surgery. This is a variation of UGI endoscopy, combining endoscopic and radiological techniques to visualize biliary and pancreatic duct systems. With a side-viewing instrument, after being placed into the descending duodenum, the papilla of Vater (where bile duct and pancreatic duct opens into GIT) is cannulated and contrast medium injected, thus visualizing the pancreatic duct and the hepato biliary tree radiographically. It is useful in the diagnosis of stones and cancer of bile duct and also pancreatic disorders like chronic pancreatis and pancreatic malignancy. Therapeutic potentials include removal of bile duct stones and palliation of obstructive jaundice by placing stents to bypass obstructing lesions. Pancreatic juice, pancreatic stone and gastric juice can be collected in this way. All the biological samples were preserved at freezing temperature to avoid the possibility of deterioration. The dielectric measurements were done at 25°C.

Experimental Setup and Method of Measurement

The principles and resonant cavity perturbation method were described previously [Raveendranath and Mathew, 1995]. However, the experimental setup was modified to accommodate different types of samples. The basic principle in the cavity perturbation technique is the field perturbation by the samples and the determination of the resonant frequencies and 3dB bandwidths of the cavity resonator. The cavity resonator is constructed with a portion of a transmission line (waveguide or coaxial line) with one or both ends closed. The cavity resonator can be either transmission or reflection type. There is a coupling device to couple the microwave power to the resonator. The cavity resonator is connected to a HP 8510C Network Analyzer, HP 83651B Sweep Oscillator and HP 8514B S-parameter test set as shown in Figure 1. For this study, S and J band rectangular cavity resonators were used. The length of the resonator determines the number of resonant frequencies. The cavity resonator is excited in the TE_{10p} mode. A typical resonant frequency spectrum of the cavity resonator is shown in Figure 2. The field within the cavity resonator is perturbed by the introduction of the dielectric samples. For the measurements of complex permittivity of biological liquids, a capillary tube (radius less than 0.5 mm) made of low loss fused silica is used. The empty tube is cleaned, dried and inserted in the cavity resonator. One of the resonant frequencies is selected and the tube is adjusted for the position of maximum perturbation where the resonant frequency and 3dB bandwidth are determined. The empty tube is then taken out and filled with the biological liquid and the measurement is repeated to determine the

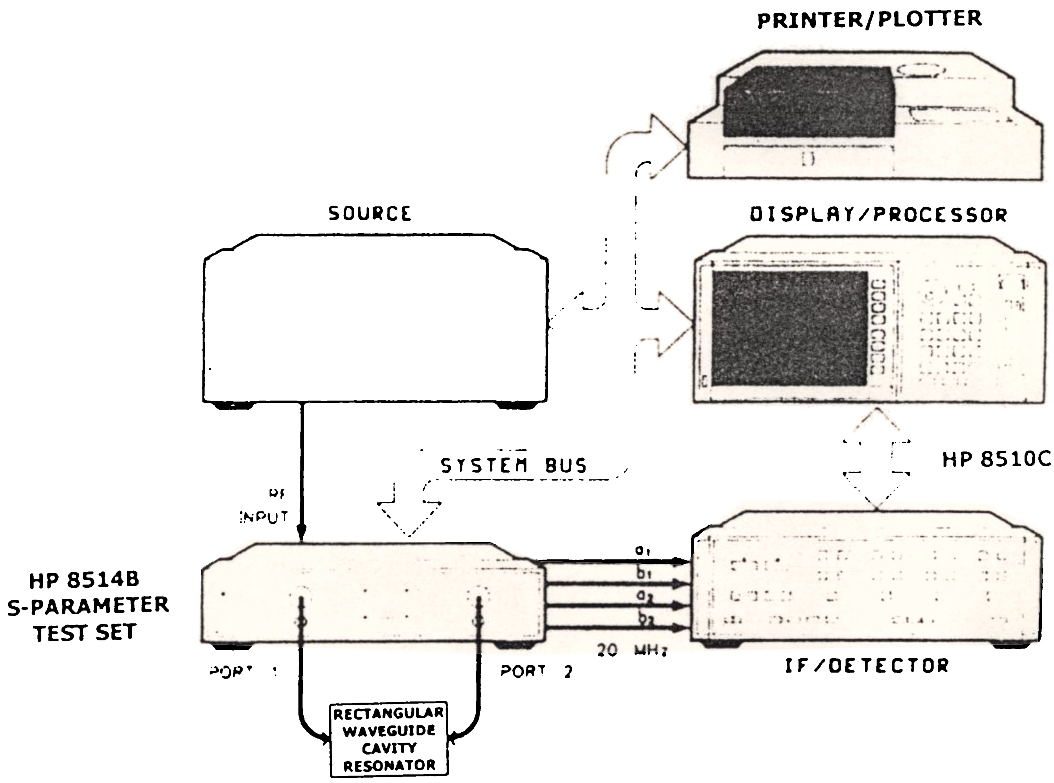

FIGURE 1: Schematic diagram of the experimental setup.

new resonant frequency and 3dB bandwidth. The procedure is repeated for all other frequencies. Measurements were made for different types of bile, gastric juice and saliva.

For the measurement of resonant frequency and 3dB bandwidth of solid samples (bile stones) a specially designed cavity resonator was constructed. Because of large sample size, the measurements were done in the S band only. A rectangular slot of size 4 cm x 3 cm was cut at the top of the cavity resonator for the introduction of the sample and a slot of sufficient length was made at the bottom of the cavity resonator to permit movement of the sample for maximum perturbation. The opening was made on the non-radiating wall of the waveguide and this was exactly fit when the metal cover was put back. It was experimentally observed that there was practically no shift in resonant frequency or quality factor due to the rectangular opening. The sample is usually irregular and can be shaped by applying low pressure. A small cup made of low-loss polystyrene rests on a rod of the same material and can slide along the slot. After placing the cup in the cavity resonator, the rectangular slot of the waveguide is closed with a metal piece of correct size so that it forms a part of the waveguide. As before, the resonant frequency and 3dB bandwidth of the cavity resonator with empty cup were determined. Then the experiment was repeated with a sample in the cup. The schematic diagram of the cavity resonator for measurement of bile stone is shown in Figure 3.

For S and J bands, different types of cavities

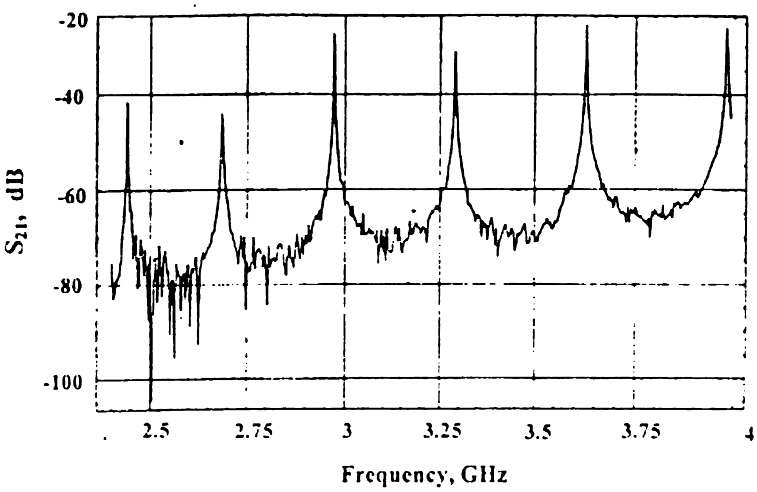

FIGURE 2a: Resonant frequency spectrum of S-band cavity resonator.

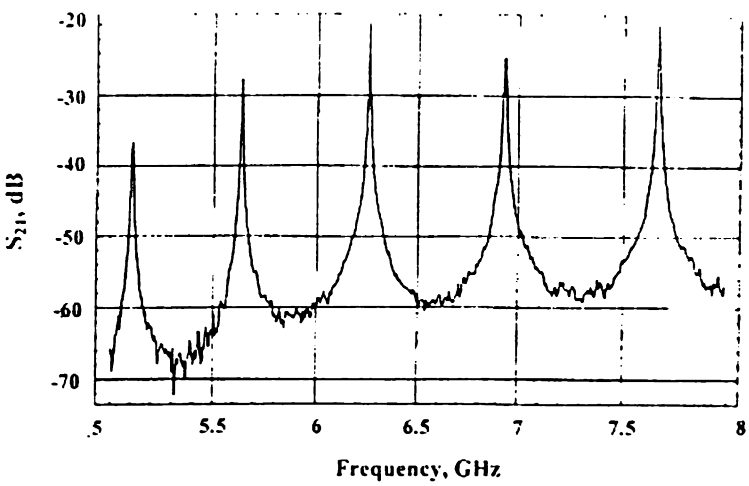

FIGURE 2b: Resonant frequency spectrum of J-band cavity resonator.

were constructed. Since all biological materials are high loss dielectrics, the volume of samples should be small in order to satisfy the requirements for the perturbation measurements. Hence, capillary tubes of small diameter were used. Another very important point is the very precise measurement of the radius of the capillary tube. A slight error in the diameter measurement makes drastic changes in the results.

Theory

The real and imaginary parts of the relative complex permittivity of the biological samples are given by [Raveendranath and Mathew, 1995; Mathew and Raveendranath, 1999]

$$\varepsilon_r' - 1 = \frac{f_t - f_s}{2f_s}\left(\frac{V_c}{V_s}\right) \tag{1}$$

$$\varepsilon_r'' = \frac{V_c}{4V_s}\left(\frac{Q_t - Q_s}{Q_t Q_s}\right) \tag{2}$$

Here, $\bar{\varepsilon}_r = \varepsilon_r' - j\varepsilon_r'' \cdot \bar{\varepsilon}_r$ is the relative complex permittivity of the sample, ε_r' is the real part of the relative complex permittivity, which is usually known as dielectric constant and ε_r'', the imaginary part of the relative complex permittivity, which is associated with the dielectric loss of

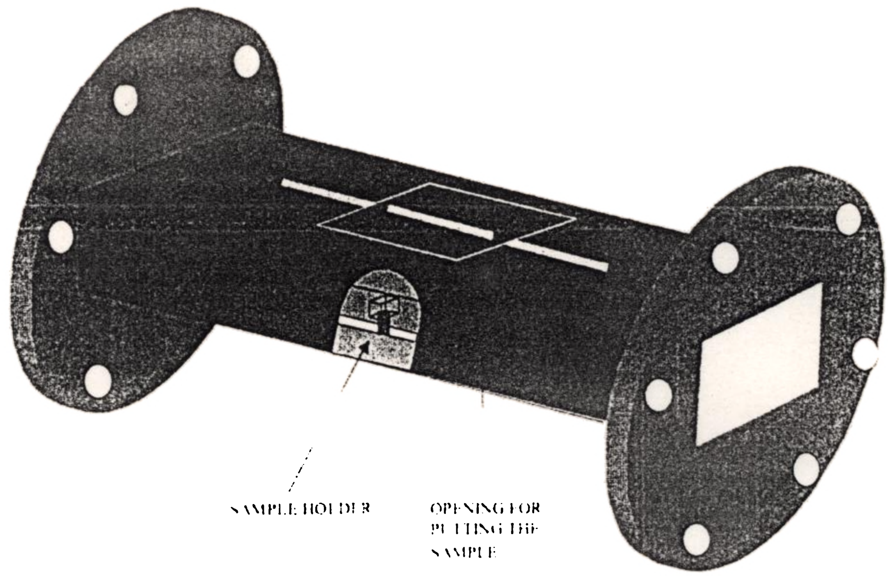

FIGURE 3: Schematic diagram of cavity resonator for bile stone measurement.

the material. V_s and V_c are the volumes of the sample and the cavity resonator respectively. From equations 1 and 2, it is observed that the real part of complex permittivity depends on the resonant frequency shift and the imaginary part depends on the quality factors.

Results and Discussion

Bile

The complex permittivities of normal and infected biles were found to differ. The dielectric constant of normal bile varies from 61 to 53 (±2) in the frequency range from 2 GHz to 8 GHz. Depending on the nature of the disease, the infected bile has a dielectric constant greater or less than that of normal bile. Infected bile with high dielectric constant indicates that it has more water content than normal bile. Three infected samples were collected from the following and the respective complex permittivity was measured:

1. a patient suffering from a stone in the gall bladder and the bile duct (Cholelithiasis and Choledocholithiasis). Gall bladder and Common bile duct stones were removed by ERCP (sample 1)
2. a patient suffering from a bile duct stone (Choledocholithiasis) alone (sample 2)
3. a patient suffering from Cholestatic Jaundice (Primary Sclerosing Cholangitis), which is an inflammatory bowel disease. As a result, the bile ducts become narrowed and irregular. The gall bladder of this patient was removed by laproscopic cholecystectomy (sample 3).

Real and imaginary parts of the relative complex permittivity of infected biles of these persons are shown in Figure 4.

Bile Stone

Hard biological materials deposited in the gall bladder or the bile duct are generally known as bile stones (Cholithiasis and Choledocholithiasis). Such materials deposited in the pancreas are known as pancreatic stones. Bile stone is a fat like material. The complex permittivities of bile stones

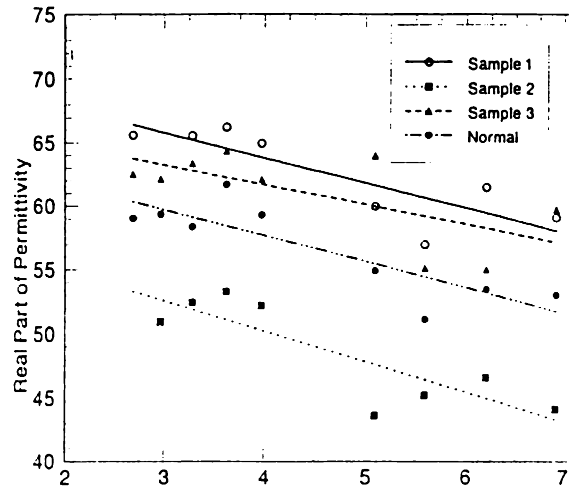

FIGURE 4a: Real part of relative complex permittivity of infected and normal biles at different frequencies.

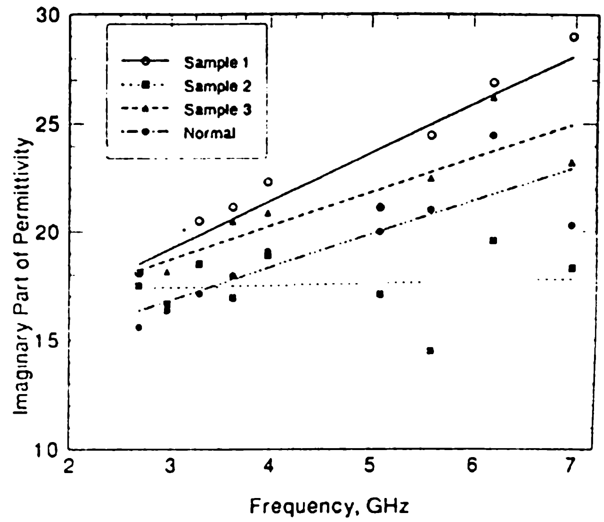

FIGURE 4b: Imaginary part of relative complex permittivity of infected and normal biles at different frequencies.

	Frequency (GHz)	ε_r'	ε_r''
Sample 1	2.44	4.0	0.18
	2.85	4.0	0.26
	3.34	4.2	0.14
	3.89	4.2	0.26
Sample 2	2.44	4.0	0.25
	2.85	4.2	0.35
	3.34	4.3	0.11
	3.89	4.3	0.24

TABLE 1: Complex Permittivity of Bile Stones.

collected from these patients were also studied. Its dielectric constant is found to be same as that of fat. Slight variations in the real and imaginary parts of the complex permittivity of different bile stones were observed. Table 1 shows the complex dielectric constant of bile stones collected from two patients.

Gastric Juice

Gastric juices of two persons were collected and complex permittivities of these samples were determined. The two persons were suffering from gall stone disease and artral erosion. They underwent the removal of the gall bladder, which contained multiple mixed stones. The dielectric constant and dielectric loss of gastric juice varies from patient to patient. This is clear from Figure 5.

Saliva

Both saliva and gastric juice have many similar functions. There is slight variation in the dielectric properties for these two biological materials. Saliva was collected from two healthy persons. Figure 6 shows the variation of real and imaginary parts of the complex permittivity with frequency.

Conclusions

The dielectric properties of tissue from human bodies, including bile, bile stone, gastric juices and saliva are presented. This is particularly impor-

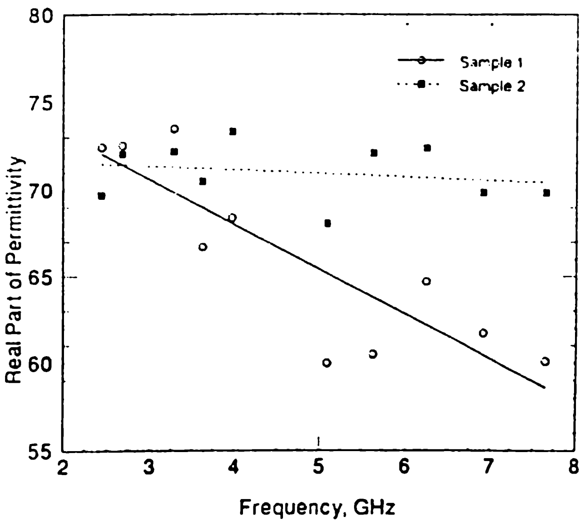

FIGURE 5a: Real part of relative complex permittivity of gastric juices at different frequencies.

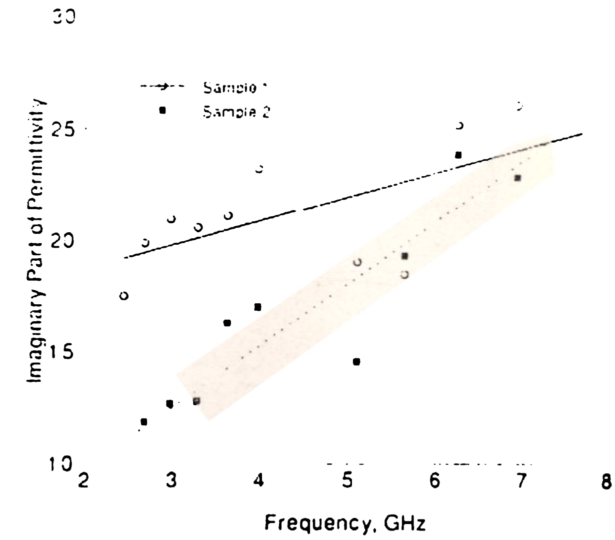

FIGURE 5b: Imaginary part of relative complex permittivity of gastric juices at different frequencies.

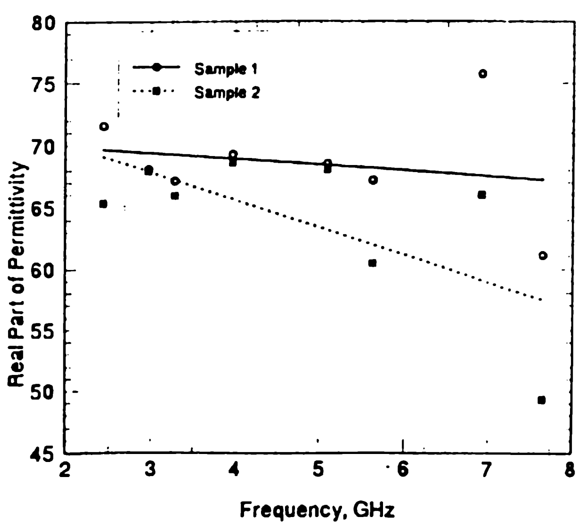

FIGURE 6a: Real part of relative complex permittivity of saliva at different frequencies.

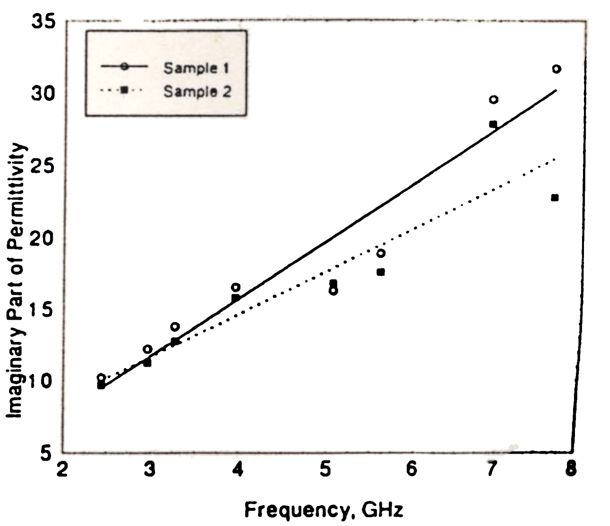

FIGURE 6b: Imaginary part of relative complex permittivity of saliva at different frequencies.

tant since the samples are collected from the internal organs of human beings and are not easily available. Because these samples are available only in small quantities, the cavity perturbation technique is suitable for their dielectric properties determination. This study suggests th at the deviation of dielectric properties for different tissues of a healthy person and a patient may be related to the presence of disease in the patient. More study is needed to establish the differences and their significance.

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References

Alexandre E. Souvorov, Alexander E. Bulyshev, Serguei Y. Semenov, Robert H. Svenson. and George P. Tatsis. 2000. Two-Dimensional computer analysis of a microwave flat antenna array for breast cancer tomography. IEEE Trans. on Microwave Theory and Techniques 48: 1413-1415.

Anderson.J.B. et al. 1984. A hyperthermia system using a new type of inductive applicator. IEEE Trans. Biomed. Eng. 31: 212-227. Cleveland Jr, R.F. and Athey, T.W. 1989. Specific Absorption Rate (SAR) in models of the human head exposed to hand-held UHF portable radios. Bioelectromagn. 10: 173-186.

David Despretz, Jean-Christophe Camart, Christophe Michel, Jean-Jacques Fabre, Bernard Prevost, Jean-Pierre Sozanski and Maurice Chive. 1996. Microwave prostatic hyperthermia: Interest of urethral and rectal applicators combination-theoretical study and animal experimental results. IEEE Trans. on Microwave Theory and Techniques 44: 1762-1768.

David Dunn, Rappaport, C. and Andrew J. Terzuoli, Jr. 1996. FDTD verification of deep-set brain tumor hyperthermia using a spherical microwave source distribution. IEEE Trans. on Microwave Theory and Techniques 44: 1769-1777.

Gandhi, O.P. and Chen, J.Y. 1995. Electromagnetic absorption in the human head from experimental 6 GHz handheld transceivers. IEEE Trans. Electromag. Compat. 37: 547-558.

Gandhi, O.P., Lazzi, G. and Furse, C.M. 1996. Electromagnetic absorption in the human head and neck for mobile telephones at 835 and 1900 MHz. IEEE Trans. on Microwave Theory and Techniques 44: 1884-1897.

Konstantina .S. Nikita. and Uzonoglu, N.K. 1996. Analysis of focussing of pulse modulated microwave signals inside a tissue medium. IEEE Trans. on Microwave Theory and Techniques 44: 1788-1798.

Livesay, D.E. and Chen, K.M. 1974. Electromagnetic fields induced inside arbitrarily shaped biological bodies. IEEE Trans. on Microwave Theory and Techniques 22: 1273-1280.

Mathew, K.T. and Raveendranath, U. 1999. Sensors Update Vol. 7. Wiley VCH Publications. Germany.

Murch, R.D. and Chan, T.K.K. 1996. Improving microwave imaging by enhancing diffraction tomography. IEEE Trans. on Microwave Theory and Techniques 44: 379-388.

Musil, J. and Zacek, F. 1986. Microwave measurements of complex permittivity by free space methods and their applications. Studies in Electrical and Electronic Engineering 22, Elsevier Science Publishers. Amsterdam.

Polk, C. and Postow, E. 1995. CRC Handbook of Biological Effects if Electromagnetic Fields. CRC Press. Second Edition

Rappaport, C. and Morgenthaler, F. 1987. Optimal source distribution for hyperthermia at the center of a sphere of muscle tissue. IEEE Trans. on Microwave Theory and Techniques 35: 1322-1327.

Raveendranath, U. and Mathew, K.T. 1995. Microwave technique for water pollution study. J. Microwave Power and Electromagnetic Energy 30: 187-195.

Reza M. Najafabadi and Peterson, A.F. 1996. Focussing and impedance properties of conformable phased array antennas for microwave hyperthermia. IEEE Trans. on Microwave Theory and Techniques 44: 1799-1802.

Schwan, H.P. 1957. Electrical properties of tissue and cell suspensions. Advances in Biological and Medical Physics. Vol. 5. Academic Press.
Teng, J., Carton de Tournai, D., Duhamel, F. and Vander Vorst, A. 1995. Variations of the somatosensory evoked potentials due to microwave fields in the spinal cord. IEEE MTT-S Microwave Symp.: 295-298.
Tran, V.N. and Stuchly, S.S. 1987. Dielectric properties of beef, beef liver, chicken and salmon at frequencies from 100 to 2500 MHz. J. of Microwave Power 22: 29-33.