AN ATTEMPT OF HIGH-SPEED IMAGING OF THE CHIRP RADAR-TYPE MICROWAVE COMPUTED TOMOGRAPHY

Michio Miyakawa and Toyohiko Hayashi

Dept. of Information Eng., Faculty of Eng., Niigata University, Japan

ABSTRACT

Methods for a high speed imaging of the chirp radar-type microwave computed tomography have been investigated to show the feasibility of biological imaging. Electronic scan of the array antennas is a major scheme to reduce the data acquisition time. However, quick sweep of the chirp pulse microwave signal and data acquisition in time domain are also useful for the purpose. By adopting those techniques, data acquisition time of the chirp radar-type microwave computed tomography can be reduced to approximately one forty of the prototype system.

INTRODUCTION

A chirp radar-type microwave computed tomography in which the diffracted or reflected waves can automatically be removed from projections by its hardware-based signal processing, was developed as a tool for non-invasive thermometry of the human body[(1),(2)]. Since the effects of diffraction or reflection of microwaves are removed, tomographic images can easily be obtained by applying a simple algorithm used in an X-ray CT. However, the prototype system requires approximately 100 minutes for the tomographic measurement. This is mainly responsible for its simplified experimental setup which has only one set of the transmitting- and receiving-antenna. Therefore, mechanical scan of the antenna is needed for tomographic measurement in the prototype system. To show possibility of clinical application of the tomography, high-speed imaging techniques are inevitable. Otherwise, biological imaging using some animals is impossible.

Prior to discussion on the high speed imaging, measurement principle of the chirp radar-type microwave computed tomography is explained briefly. Chirp pulse signal from 1 GHz to 2 GHz is radiated from the transmitting antenna toward the object placed in a bolus tank filled with saline solution. The transmitted signal is detected by the receiving antenna which is placed on the opposite side of the transmitting antenna. Frequency of the beat signal between the input signal and the transmitted signal reflects the transmission path length between those two antennas. Therefore, the signal component which transmitted on a straight path between those two antennas is discriminated from multipath signals by spectral analysis of the beat signal generated by a mixer. The prototype system detects the signal component with a FFT analyzer, that is, measures the signal amplitude at a specific frequency corresponding to the straight path. The object is scanned by mechanically translating the antennas and the microwave attenuation is measured at 128 equidistant points along the translational axis. The complete set of projection data is obtained by repeating the translational scan 50 times at 3.6° intervals. It takes approximately 100 minutes for the tomographic measurement when sweep time of the chirp pulse signal is 200 ms. Since the attenuation constant of biological tissues shows temperature dependence, distribution of temperature change is visualized by subtracting a image from another one which are obtained before and after the temperature change.

We have already reported that the roughly estimated spatial resolution is approximately 1 cm and tomographic measurement of 0.7°C temperature change is possible[(3),(4)]. Those estimates were obtained in our preliminary study using a phantom model. Figure 1 is an example of the image showing temperature change by 1°C. In this experiment, three cylindrical phantoms filled with 0.39% saline solution are placed in a bolus tank which is filled with the same saline solution as phantoms. At first, temperature of three phantoms and bolus saline solution are kept at 32°C for the first tomographic imaging. After increasing temperature of the right-upper cylinder by 1°C and decreasing temperature of the left cylinder by 1°C, the second tomographic imaging is performed by keeping temperature of the right-lower cylinder at 32°C. Temperature change is measurable as shown in this figure, however, approximately 100 minutes data acquisition time must be improved for practical application of the computed tomography used for a noninvasive thermometry of biological targets.

As mentioned above, it takes roughly 100 minutes to collect all the attenuation data at 6,400 points (128 points along translational axis x 50 angles). Measurement using the chirp pulse microwave signal is a cause of its long data acquisition time, because the sweep time is inevitable. Spectral analysis with a FFT-analyzer which is used to identify the straight path between two antennas is also responsible for it. However, the analysis is not necessarily needed during the measurement. By recording the beat signal directly via an A/D converter, time required for Fourier transform is excluded from the measurement time. Fourier transform required for straight

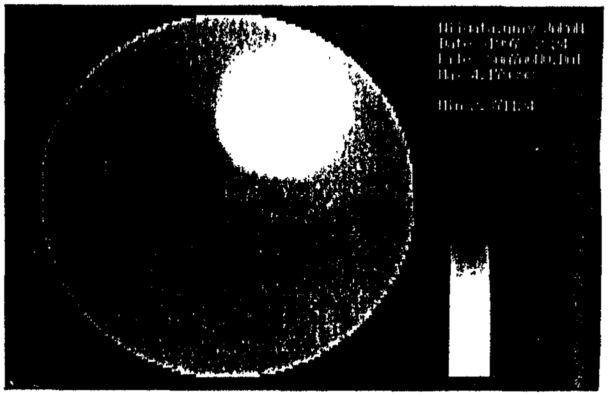

Fig. 1 CT image obtained for 1°C temperature change

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path discrimination should be done after the measurement. The way of recording is referred to as "data acquisition in time-domain" in the paper. In this study, the sweep time has been shortened to 20 ms from 200 ms in the prototype system and data acquisition in time-domain has been adopted.

As compared to electronic scan which is very popular in medical imaging, much time is required for a mechanical scan of the antenna. Thus, electronic scan of the antennas is quite useful for reducing the data acquisition time. In the study, electronic scan has been attempted by using a dipole array antenna, or by applying the modulation scattering technique[5] to attenuation measurement.

ELECTRONIC SCAN USING A DIPOLE ARRAY ANTENNA

A dipole array which is composed of 12 small dipole elements and used as the transmitting- or a receiving-antenna has been developed. As shown in Fig. 2, the length is 20 mm and each element is 22 mm apart from the adjacent elements. Four additional dipoles which are not connected to the circuitry are arranged on both sides of the array antenna. This is to keep the input impedance at constant, regardless of the element position. Only a 12-pole RF-switch is available in this study, so that mechanical translation of the dipole array is also needed for tomographic measurement.

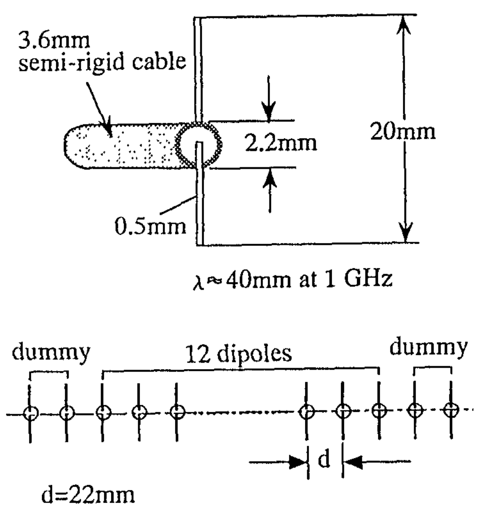

Fig. 2 Configuration of a dipole array antenna

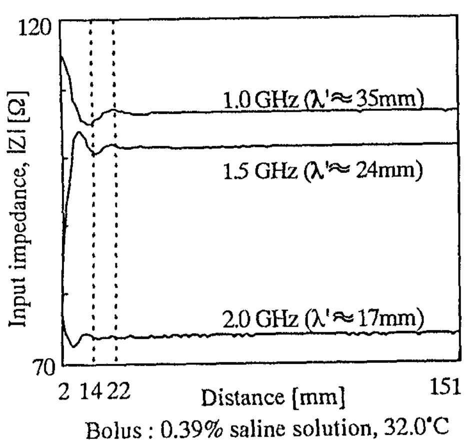

Fig. 3 Mutual coupling between two dipole antenna elements

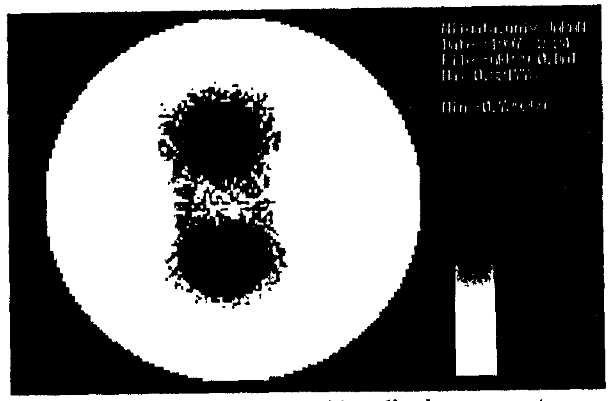

Fig. 4 CT image obtained with a dipole array antenna

Whenever we think of an array antenna, the mutual coupling effect of those elements becomes a matter of great concern. In this case, the smaller the coupling effect becomes, the more the image quality is improved. Figure 3 shows a relationship between the input impedance of the dipole element and distance between adjacent two dipole elements. One of the dipole elements which constitute the array antenna is fixed perpendicularly in the bolus saline solution. The element is connected to a network analyzer to measure the input impedance. Another dipole element which is also held perpendicularly in the saline solution and then is moved to change the distance between them. As shown in Fig. 3, the mutual coupling effect becomes negligible small when the adjacent dipoles are separated more than 22 mm. Consequently, we have developed the array antenna as shown in Fig. 3. The isotropic feature comes from the directivity of a dipole antenna .

A typical image obtained with the array antenna is shown in Fig. 4. Saline solution phantoms whose salt concentration are 0.19% are placed in the bolus saline solution (0.39%). The diameter of the phantom cylinder is 60 mm and they are placed 30 mm apart to each other in the bolus. Since the mutual coupling of antenna elements is negligible in the system, no specific feature is observed in the tomogram. It takes approximately 4.5 minutes for the tomographic measurement, when the sweep time of the chirp signal is 20 ms. For practical reasons, a partial mechanical scan also must be used together, but data acquisition time is shorter than 5 minutes. This is not necessarily short enough for clinical applications, but at least, animal experiments will be possible.

ELECTRONIC SCAN BASED ON MODULATION SCATTERING

As mentioned above, the transmitted wave on the straight line between two antennas is discriminated from the multipath waves by analyzing the beat signal in our chirp radar-type microwave computed tomography. Another way of the electronic scan can be realized by making use of a modulation scattering technique for the beat signal measurement. Figure 5 shows a block diagram of the chirp radar-type microwave CT in which the modulation scattering technique is employed. Diode-loaded small dipoles are arranged in front of the receiving antenna in order to modulate the chirp signal by a low frequency signal. By supplying a low frequency signal, the transmitted chirp signal is modulated with those small dipoles in turn. From the modulated signals, attenuation of the transmitted wave on each straight path between a small transmitting antenna and the corresponding small is measured. As a matter of course, frequency range of the beat signal

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measurement shifts to that of the modulation signal which is higher than that of the beat signal. Thus, the object is electronically scanned and tomographic measurement can be performed. The SN-ratio decreases in this case.

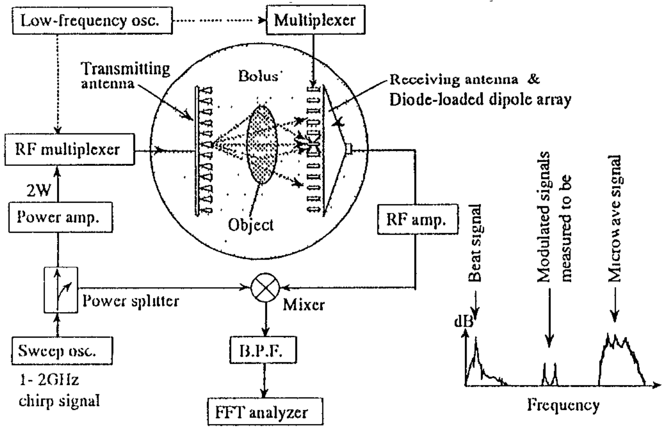

Fig. 5 Measurement principle of the modulation scattering method

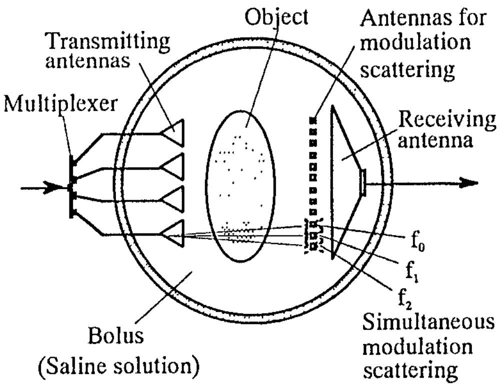

Fig. 6 A method for simultaneous modulation scattering

The electronic scan without using a high-frequency component such as an RF-switch is an advantage of the method. Easiness of simultaneous data sampling would also be a big advantage of the method. Figure 6 shows a principle of simultaneous data sampling based on the modulation scattering technique. Several dipoles for modulation scattering are excited with different frequency signals at the same time. By choosing appropriate modulation frequencies, all of the modulated beat signals is recorded simultaneously with a single RF circuitry, as shown in Fig. 6.

Figure 7 shows a typical result of tomographic imaging based on the modulation scattering technique. In the imaging, a cylindrical water phantom is placed in a bolus tank which is filled with 0.225% saline solution. Simultaneous measurement is carried out at two modulation frequencies, 13 kHz and 17 kHz. The circular cross section is reconstructed correctly, although the SN ratio is degraded a little. This is a disadvantage of the method. Data acquisition time is approximately 3 minutes.

DISCUSSION

In the study, it has been demonstrated that high-speed imaging is possible even in a microwave computed tomography using a chirp pulse signal. The estimated time may not be quick enough for clinical application of the tomography. But,

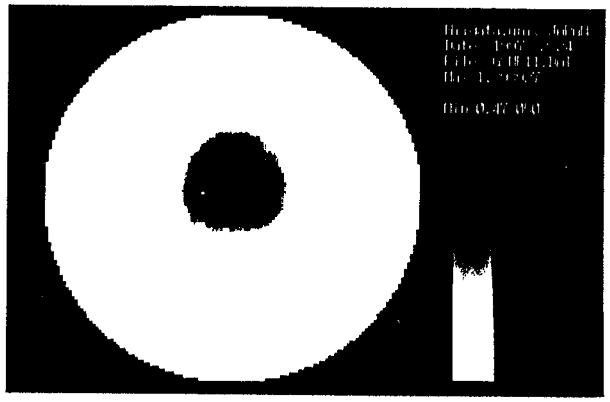

Fig. 7 CT image obtained by modulation scattering method

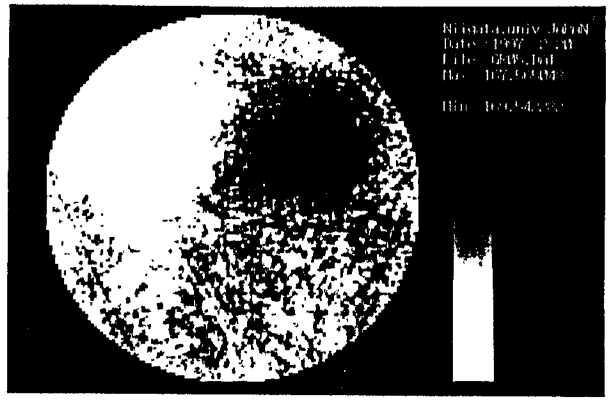

Fig. 8 CT image obtained for 0.5°C temperature change

at least, imaging of biological target, such as an animal, will be possible. To discuss the problem, data acquisition time for tomographic imaging has been estimated as shown in Table 1. Data acquisition time is calculated provided that an array antenna composed of 12 dipoles are used for signal receiving or signal modulation. But, “12 dipoles” came from the number of poles of a RF switch which happened to be available. Thus, Table 1 gives just rough estimates for data acquisition time of the chirp radar-type microwave computed tomography that could be developed even at a research laboratory. Data acquisition time Td is given by the following equation,

$$Td=\{120xA0+(12xA1+A2)x10\}x50+A3x49,$$

where attenuation data are supposed to be collected at 120x50 points. Even when the modulated signal was measured only at two points at the same time, data acquisition time is estimated to be 1.2 minutes in modulation scattering method. This would be a fairly short data acquisition. On the contrary, dipole array based scanner requires 4.3 minutes for tomographic imaging.. Since parameters used for the estimation are almost the same as actual ones, it shows a good coincidence with the actual data acquisition time, 4.5 minutes. The biggest advantage of the method is a fairly good quality of images. By developing a new scanner, such as the third generation X-ray CT scanner (R-R scanner), the better results may be obtained.

Lastly, a temperature image which is obtained by the high-speed imaging is given to show usefulness of the new microwave computed tomography. Figure 8 is a tomogram showing 0.5°C temperature change. Experimental procedure is the same as one for Fig. 1. Differences between them are temperature and data acquisition time. Slight difference in

Table 1 Estimated data acquisition time

Antenna type	Dipole array (12 dipoles)	single aperture horn + DMS array (12 dipoles)*	
Sweep time	20 ms	20 ms	A0
Switching time	20 ms	1 μs	A1
Mechanical scan (Translation)	30 ms	30 ms	A2
Mechanical scan (Rotation)	50 mS	50 ms	A3
Simultaneous measing points	1	2	n
Data acquisition time	4.3 min.	1.2 min.	Td

*: DMS: Diode-loaded dipoles for modulation scattering

image quality comes from originally small difference in attenuation.

For practical application of the chirp radar-type microwave computed tomography, high speed imaging are needed. The estimated, or actually realized data acquisition time is not necessarily short enough for imaging of a real human body. But experimental results are very important as the first step toward practical use of the new thermometry system.

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