Non-invasive Continuous Monitoring of Cerebral Edema Using Portable Microwave Based System

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Abstract. A portable non-invasive head detecting system based on microwave technology was developed for evaluation of cerebral edema change inside human brain. Real-time monitoring of cerebral edema in the brain helps the clinician to assess medical condition and treatment. In this work, a microwave signal was transmitted and coupled into an open-end circular waveguide sensor, incident on a 3D printed head phantom, and reflected back to receiver. Theoretically, the operation of this instrument depends on the conductivity contrast between cerebral edema and healthy brain tissues. The efficacy of the proposed detecting system is verified using 3D printed anatomically and dielectrically realistic human head phantoms with simulated cerebral edema targets with different size. Changes in the amplitude of time domain result were shown to be induced by the expansion or decrease of the edema volume. The eventual goal of this proposed head evaluating system is use in the hospital as an effective real-time monitoring tool.

1. Introduction
Cerebral edema is responsible for a huge number death and disabled around the world. For the reason that cerebral edema growth is a determinant of mortality and poor outcomes, and detecting edema expansion is an important prognostic indicator for treatment [1]. Continuous accurate detection of cerebral edema is the vital of timely adequate medication.
Because the general recommended imaging techniques, MRI or CT scan, are impossible to be monitoring tools, diagnosing the change of edema and evaluating the therapeutic effects only depend on the clinician’s experience in the rest of time. Thus, it is obviously that there is a clinical demand for a non-invasive, easy-to-operation, portable instrument, which is used for bed-side monitoring to observe the change of edema.
Microwave based detection has attracted much attention from the researchers as a non-invasive portable complementary diagnostic tool, due to its non-ionizing radiation, low power and low cost features [2-7]. Moreover, when brain edema occurs, there is accumulation of fluid and a change in the water composition of the tissue, which is bound to change the conductivity of edema region [8]. In this work, a novel microwave based head detection system for continuous assessment of edema is proposed. Moreover, the proposed method is verified in experiments using 3D printed anatomically and dielectrically realistic human phantom.
2. Methods and material

2.1. Head detection system
The prototype system is consist of a circular waveguide which is employed as detecting sensor, a coaxial cable to transmit and receive microwave signals, and a Vector Network Analyzer which acts like a data storing and processing unit. The inner cable should be long enough to produce strong signals in the circular waveguide, and the circular waveguide used in this study has the internal radius $a$ of 90.0 mm and the length $d$ of 115.0 mm as shown in figure 2-1. A soft plastic bag filled with matching medium is placed between head and sensor. The use of the matching medium ensures a good electromagnetic coupling between the sensor and the head tissue.

![Figure 2-1. The schematic diagram of the head detecting system](image)

2.2. Head mimicking phantom
In this work, an anatomically and dielectrically realistic head phantom is manufactured using the stereo-lithographic machine (Eden250, Stratasys Inc.). The basic design of the 3D voxel phantom is derived from MRI scan data of head. And the head model is divided into skin, skull, gray matter, white matter and cerebral edema portions. The model has separate compartments, so that the internal cavities can be filled with corresponding tissue equivalent materials, which are composed of gelatin, water, flour, sodium chloride with different recipes [9,10]. Figure 2-2 illustrates the 3D geometry of the brain phantom. In addition, the cerebral edema was simulated using mimicking material with conductivity of 0.67 S/m and the volumes (0, 5, 10, 15, 20 ml) of edema had been tested in this study.
3. Theory and calculation

Because the microwave propagates in waveguide incident from the dielectric to the air at the termination interfaces of waveguide sensor give rise to high coefficient reflection, interior reflections are produced and most of energy is confined in the head and medium. In this work, loss due to conductivity \( \sigma \) should be taken into account, so the complex permittivity \( \varepsilon \) can be written as

\[
\varepsilon = \varepsilon_0 \left(\varepsilon_r - j \frac{\sigma}{\omega \varepsilon_0}\right)
\]

(1)

Where \( \omega \), \( \varepsilon_0 \), \( \varepsilon_r \) denote angular frequency, permittivity of free space, dielectric constant, respectively.

Due to the electromagnetic wave couples to the circular waveguide and then transmits along longitudinal direction, the complex propagating constant \( \gamma \) in circular waveguide is shown as

\[
\gamma = \alpha + j \beta = \left( k_c^2 - \omega^2 \mu_0 \varepsilon_0 \varepsilon_r + j \omega \mu_0 \varepsilon_r \sigma \right)^{1/2}
\]

(2)

Where \( \alpha \) and \( \beta \) denote attenuation constant due to conductivity loss and propagating constant, respectively. Then and can be expressed as respectively

\[
\alpha = \frac{1}{2} \left( k'^2 - k_c^2 \right)^{1/2} - \frac{1}{2} \left( k'^2 - k_c^2 \right)^{1/2}
\]

(3)

\[
\beta = \frac{1}{2} \left( k'^2 - k_c^2 \right)^{1/2} + \frac{1}{2} \left( k'^2 - k_c^2 \right)^{1/2}
\]

(4)

Where \( k' = \omega \left( \mu_0 \varepsilon_0 \varepsilon_r \right)^{1/2} \), \( k'' = \omega \left( \mu_0 \varepsilon_r \sigma \right)^{1/2} \), \( \varepsilon'' \) and denotes the imaginary part of \( \varepsilon \). As a result, the change of edema volume can be evaluated in light of the relationship between attenuation constant \( \alpha \) and the conductivity \( \sigma \) in the waveguide.

4. Results

As mentioned in section 2, head phantoms with different volume of cerebral edema (0, 5, 10, 15, 20 ml) had been detected in this work. In addition, when a range of frequencies are swept in the
frequency domain, the wave package is consist of such multiple frequencies. In this work, the experimental frequency range of wave group is from 150 to 450 MHz. The time domain experimental results of various cerebral edema models are shown in figure 4-1. These results are obtained from frequency domain results by Inverse Fast Fourier transform. While the zero time reference should be set as the end point of the VNA cable, the first significant peak relates to the connecting point between coaxial cable and waveguide sensor, and the second significant peak corresponds to the waveguide open-ended end reflection. Moreover, the amplitude difference between these two significant peaks corresponds to the power attenuation due to conductivity loss. Although there is little difference in conductivity in these cerebral edema models, the amplitude still can be clearly observed if enlarge the results, i.e., enlarged the second significant peak of the results over time range of 2.5 to 6 ns as shown in figure 4-2. Seen from figure 4-1, it is interesting to see that the magnitude shifts in different cerebral edema models, indicating that the amplitude vary with change in the conductivity of the head phantom. To illustrate this, the conductivity of edema tissue is greater than other tissues, edema growth will give rise to overall conductivity of brain increasing. In this experiment, the volume of cerebral edema expand from 0 to 20 ml, the amplitude have decreased 0.858 dB.

![Figure 4-1. Time domain experimental results of various edema models](image1)

![Figure 4-2. Enlarged the second significant peak of the experimental results shown in figure 4-1.](image2)

5. Discussion and conclusion
The experimental time domain performance shows that the power of microwave signal clearly decreased due to conductivity loss. Moreover, for the reason that the microwave instrument has the advantage of extremely high detecting resolution, this proposed method has a quite high resolving power for evaluating the conductivity of brain.
Since the left significant peak relates to the connecting point between the coaxial cable and the waveguide sensor, and the right significant peak corresponds to the waveguide open-ended end reflection, the wave group velocity can be calculated by $V_g = 2L/t$, where $L$ denotes the length of wave group propagated, and $t$ denotes the time of flight. The proposed system is capable of not only measuring the conductivity of brain but also evaluating the relative permittivity of brain theoretically. In summary, this work demonstrated that a non-invasive system for the continuous monitoring of cerebral edema and verified it using a realistic 3-dimensional head phantom to illustrate the performance in term of sensitivity and accuracy. By using the proposed system to measure the magnitude of microwave signal, the conductivity of brain can be evaluated. As a result, there is a very satisfactory accordance between the measured values and the nominal ones, which shows that this proposed system has the potential to real-time monitor the rate and size of edema expansion in clinical environment.

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