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Microwave Radiometer for Detecting Internal Temperature of Biological Tissue

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Abstract. Microwave radiometers are gaining increasing attention for their ability to measure the temperature inside biological tissues, a capability that is of great significance in medical applications such as cancer treatment and burn therapy. However, there is still a research gap in their precise application in these areas. This study aims to explore the feasibility of using microwave radiometers to detect subcutaneous tissue temperature by analyzing low-frequency microwave signals. A miniature radiometric sensor was systematically experimented with in the study to evaluate its sensitivity, stability, and accuracy in real-time temperature monitoring. The results showed that the radiometer was able to accurately track subcutaneous temperature changes within a small error range, confirming its applicability in non-invasive medical applications. In particular, this study highlighted the effectiveness of the radiometer in microwave ablation therapy and biomedical thermoacoustic imaging, demonstrating its potential to improve diagnostic accuracy and therapeutic efficacy. Microwave radiometers have shown significant results in cancer treatment through microwave ablation therapy, image-guided precision therapy, and minimally invasive treatment. In addition, its application in biomedical microwave thermoacoustic imaging shows great potential to provide high-resolution and high-contrast images for cancer diagnosis and brain imaging. The research of microwave radiometers in the biomedical field has important practical significance and broad development prospects, which will have a positive impact on human health and medical care.

Keywords: Microwave Radiometer; Internal Tissue Temperature; Radiation Thermometry; Microwave Ablation Therapy.

1. Introduction

Microwave radiometers have a key function in measuring the internal temperature of biological tissues. This research on the application of microwave radiometers in the temperature measurement of biological tissues is of significant importance, especially in the field of medical treatment such as therapy place and burn treatment. Currently, advancing intelligent systems leveraging artificial intelligence techniques is a highly pressing endeavor. These technologies have the potential to markedly enhance the standard of living across numerous sectors. Take the medical field, for instance, where intelligent systems are capable of discerning critical and nuanced information within diagnostic data, thereby enhancing the accuracy of diagnoses and lowering the expertise needed by professionals conducting the analyses. Particularly intriguing are intelligent advisory systems that not only employ machine learning techniques and algorithms but also incorporate features that provide explanations for the solutions they suggest. Crafting these systems necessitates the utilization of mathematical modeling, data analytics, and machine learning approaches. Microwave radiometry stands out as a promising diagnostic technique, relying on the measurement of the natural electromagnetic emissions from human tissue in the microwave and infrared spectrum. This method is non-invasive, safe, and capable of detecting temperature irregularities several centimeters beneath the surface, making it applicable in diverse medical areas such as the early detection of breast cancer and the diagnosis of vascular conditions. Its advantages lie in its non-invasive nature, high precision, and the ability to monitor temperature changes in real time.

The beginning of the microwave radiometer is sourced from the early 20th century. In 1946, Dick developed the first device for measuring microwave radiation. A microwave radiometer consists of an antenna, a receiver, and recording and display equipment. As the time going, microwave radiometers have become applicable in various fields. In addition to accounting for the internal temperature of biological tissues mentioned in this paper, they have also played a significant role in meteorological observations [1]. Introduction to the RPG HATPRO Microwave Radiometer (hereinafter referred to as "microwave radiometer") is a weather monitoring device utilizing atmospheric microwave remote sensing technology. It can monitor and warn of mesoscale severe weather systems, atmospheric stratification, and cloud physical characteristics. It guides scientific research and operational activities related to weather modification, as well as monitoring the boundary layer atmospheric environmental quality during smog and haze weather conditions. The microwave radiometer selects appropriate frequencies within the typical atmospheric oxygen microwave V-band window (5.1~5.9 GHz) and the atmospheric water vapor microwave K-band window (22~31 GHz) for remote sensing measurements of atmospheric microwave radiation. It can also use the 183 GHz water vapor window for inversion in cold and arid conditions of low water vapor density. By doing so, it retrieves information such as tropospheric profiles of atmospheric temperature and humidity, integrated column humidity content and integrated column cloud water content.

The microwave radiometer itself does not emit signals and has the advantages of low power consumption, long life high reliability, unattended operation, and the ability to work continuously under all weather conditions. It can monitor the structural parameters of the atmosphere and their evolutionary processes in real time. Compared with the previous methods of predicting cloud water content or related parameters using empirical models, the use of a microwave radiometer can improve the timeliness and accuracy of detection and forecasting.

The study of the radiometer circuit indicates that the recorded temperature is influenced by the temperature at the radiometer's front end, which is attributed to dissipative losses occurring at this stage [2]. A 20 °C fluctuation in the temperature of the input section corresponds to a 2 °C variation in the measured temperature. Implementing a thermal compensation algorithm allows for the reduction of the measurement error to just 0.2 °C. It is widely recognized that microwave radiometers have a minimal error margin, offering significant support for accurate real-time temperature measurements.

This study is based on the functional use of the microwave radiometer, relying on low-frequency microwave signals to attempt to detect the warm microwave radiation signals from subcutaneous tissue, thus obtaining temperature data of the human internal tissue. First, the functions of the microwave radiometer are analyzed, and then, through blackbody radiation, the measurement of the internal temperature of biological tissue by the microwave radiometer is completed.

2. The Microwave Radiometer

2.1. The Principle of the Microwave Radiometer

The function of a microwave radiometer is to measure the microwave radiation emitted by objects, which is electromagnetic radiation with wavelengths ranging from millimeters to meters. The brightness and power of blackbody warm radiation directly depend on its absolute temperature, and the microwave radiometer measures the brightness temperature of an object. A previous thermometer relies on the thermal expansion and contraction of mercury to measure the surface temperature of the human body after reaching thermal equilibrium. Similarly, electronic thermometers are also widely used in daily life. The basic principle of electronic thermometers usually depends on the effect of temperature on certain physical properties. The thermoelectric effect refers to the phenomenon where an electric current is produced in a closed loop when two different types of conductors or semiconductors are in contact and the two contact points are at different temperatures. The microwave radiometer can rip into the human skin with low-frequency microwave signals, theoretically allowing it to detect the thermal microwave radiation signals from subcutaneous tissue, and thereby obtain temperature data of the subcutaneous tissue.

2.2. Composition

A microwave radiometer is a highly sensitive receiver that can receive microwave thermal radiation signals emitted by a target [3]. Low-frequency microwave signals can penetrate the human epidermis, theoretically enabling the microwave radiometer to detect the thermal microwave radiation signals from subcutaneous tissue and obtain temperature data of the subcutaneous tissue [4]. These findings indicate that passive microwave radiometry is ready to become a precise and cost-effective non-invasive thermometry method for both short-term and long-term monitoring of subsurface tissue temperatures. [5]. As previously mentioned, a radiometer consists solely of a highly sensitive receiver. There are two main differences between the receiver in a radiometer and those in traditional radar and communication systems. First, the input signals received and processed by traditional receivers are generally nearly monochromatic and correlated, whereas the electromagnetic waves emitted by natural substances are uncorrelated and can span a wide electromagnetic spectrum. In other words, these waves are similar to white noise and closely resemble the noise generated internally by the receiver. The second difference concerns the signal-to-noise ratio (S/N) at the receiver's output. In traditional receivers, S/N must be greater than 1 to reliably extract information from the received signal. However, for radiometers, the power of the received radiant signal is usually much less than the noise power of the receiver. Therefore, to accurately measure the brightness temperature (TB), a highly sensitive receiver that can average the signal over time and frequency is necessary. Moreover, since there is no absolute microwave reference in nature, a periodic, stable, and precise calibration process is indispensable. A microwave radiometer is primarily composed of the following key parts: antenna system, receiver, detection and processing unit, and control system. These components work together to enable the radiometer to accurately measure the microwave radiation of the target object and convert it into temperature information. Different applications and design requirements may lead to variations in the specific composition of microwave radiometers, but the components listed above are the basic parts.

2.3. Experimental Operation

Radiation thermometry is a convenient and non-invasive method for measuring body temperature [3]. This study conducted multiple measurements of human skin at different temperature states to verify the feasibility of microwave thermometry, especially on the cheeks where subcutaneous temperature can be easily altered. Before internal body temperature measurements, experiments were conducted by contacting the antenna with a table, air, and a palm, revealing that the antenna had a deeper resonant characteristic only when in contact with the human body, allowing for the measurement of the microwave thermal radiation power of body tissues. The specific experimental steps involved observing a significant increase in the output voltage on the oscilloscope, indicating that the system was functioning normally and ready for body temperature measurements. After verifying that each module was correctly assembled and tested, the final feasibility test for measuring subcutaneous body temperature was conducted. Measurements were taken using air and four states of human skin as samples. The experimental results showed a high degree of agreement between the measurements taken with an independent thermocouple in the mouth and the method used in this study, indicating that the L-band microwave radiometer can measure temperature changes in subcutaneous tissue, thus proving the radiometer temperature measurement system is suitable for various applications requiring monitoring of body temperature. The principle of detecting radiant signals to obtain temperature is based on the law of blackbody radiation. A blackbody is a theoretical construct that completely absorbs all incoming radiant energy, without reflecting or transmitting any of it. The power of blackbody radiation is dependent on its temperature, and this relationship is encapsulated by Wien's displacement law, which defines how the peak wavelength of blackbody radiation varies with temperature. According to this law, the peak wavelength λmax of the emitted radiation from a blackbody is inversely proportional to its absolute temperature T, such that the product $\lambda maxT$ is a constant: $\lambda maxT= b$, where b is approximately equal to 0.29 meters times Kelvin. In real-world scenarios, the temperature of an object can be ascertained by examining the radiation it emits and correlating this with the characteristics of blackbody radiation. Since the radiation emitted by the human body falls within the microwave frequency range, a microwave radiometer is an appropriate tool for measuring it.

In the field of radiometry, brightness is characterized as the radiant power flux per unit area and per unit solid angle. Radiant intensity, on the other hand, denotes the radiant flux per unit solid angle in a particular direction. Consequently, by measuring the radiant intensity, one can determine the brightness of biological tissue. To showcase the sensitivity and long-term stability of the microradiometer sensor, it experimented with using a phantom that was identical in size to a human head. In this setup, the temperatures of the scalp and brain phantoms were regulated independently. Throughout the 4.5-hour experiment, the radiometer reliably monitored the temperature fluctuations of the brain phantom with an accuracy within ±0.4°C. Despite the scalp temperature being maintained at a constant 32°C, the radiometer's measurements exhibited a strong correlation with the temperature variations in the brain phantom. [5]. This is because the software algorithm calculates the corresponding brain temperature changes based on the ratio of the radiant power of the tissue inside the skull to the total radiation signal collected by the sensor. The experiment showed that the calculated brain radiation temperature was within ±0.4°C of the brain temperature measured by the fiber optic sensor. Although microwave radiometers have small errors under general conditions, they may be interfered with by electromagnetic signals (such as microwave communications and mobile communications), affecting the accuracy of experimental results. In addition, current microwave radiometer systems are mostly used in satellite payloads and are relatively expensive; and the energy of spontaneous microwave signals emitted by the human body in the low-frequency band is weak and difficult to detect.

2.4. Experimental Steps

1. Placement of Samples: Place the biological tissue sample at the focus of the radiometer's antenna or an appropriate position.

2. Initial Measurement: Conduct a measurement without the biological sample to record the radiation.

3. Conduct Measurement: Turn on the microwave radiometer and measure the microwave radiation of the biological tissue sample.

4. Multiple Measurements: If measuring temperatures at different depths, it may be necessary [6]. Hence, there is significant promise in integrating the concepts of multichannel and multi-frequency operation with a compact design into a unified radiometer system. This integration serves to enhance its functional capabilities while reducing its physical footprint. Such a development enables the radiometer to be employed not only for measuring the intrinsic microwave radiation emitted by the human body through the skin but also for assessing radio brightness temperatures across natural cavities. Additionally, it opens up the possibility of utilizing monolithic integrated circuit technologies as minimally invasive biosensors. The creation of affordable and easy-to-use devices for the early detection of a wide range of diseases will furnish a strong boost to the advancement of personalized medicine.

3. Application

Microwave radiometers can be employed in microwave ablation therapy for cancer treatment. This medical approach uses microwave radiation to generate heat, precisely controlling microwave energy to induce high temperatures at the tumor site, thereby killing tumor cells. The benefits of this treatment include minimal invasiveness, high efficiency, and fewer complications. Microwave ablation therapy is typically guided by imaging technologies such as ultrasound, CT, or MRI, allowing for precise targeting of the tumor's location and size, focusing the treatment on the tumor area while protecting surrounding normal tissue. Microwave radiometers are also used in biomedical microwave thermoacoustic imaging, a non-invasive imaging technique that provides high spatial resolution and high-contrast images, useful for cancer diagnosis, joint evaluation, brain imaging, and more. Overall, the application of microwave radiometers in cancer treatment demonstrates unique technological advantages, particularly in microwave ablation therapy, image-guided precision treatment, and minimally invasive treatment.

Currently, microwave sensors are in the stage of research and development, moving towards practical applications, and microwave remote sensing technology is gaining increasing importance in various fields of geology. In the future, systematic research and development of microwave radiometer systems will be a key focus to adapt to the expanding application fields and the growing market demand. Microwave radiometers offer a non-invasive method for monitoring temperature changes in biological tissues. In the context of cancer thermotherapy, precise control of tissue temperature is crucial. This represents a significant advantage over conventional thermometers. Microwave radiometers can assist doctors in monitoring the temperature of tumors and surrounding healthy tissue to ensure effective treatment and reduce the need for surgery, thereby minimizing patient discomfort and risk. The advancement of microwave radiometers in the biomedical field has the potential to greatly improve patient care and reduce the risks associated with treatment.

4. Conclusion

The study systematically explores the application of microwave radiometers in the biomedical field, particularly in cancer treatment, revealing their important role in measuring the internal temperatures of biological tissues. The experimental results confirm that microwave radiometers have the advantages of being non-invasive, highly accurate, and capable of real-time monitoring of temperature changes, providing strong technical support for cancer treatment. Through microwave ablation therapy, image-guided precision treatment, and minimally invasive treatment, microwave radiometers have shown significant effectiveness in cancer treatment. Additionally, their application in biomedical microwave thermoacoustic imaging demonstrates great potential, offering high-resolution and high-contrast images for cancer diagnosis and brain imaging. Looking ahead, the continuous research and development of microwave radiometer technology will further expand its applications in the biomedical field, contributing to improved medical standards, reduced patient suffering, and lower treatment risks. Therefore, the study of microwave radiometers in the biomedical field holds important practical significance and broad prospects for development, which will have a positive impact on human health and medical care.

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