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View online: https://doi.org/10.1016/j.jnlest.2021.100082

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Diagnosis of Dental Caries Using Terahertz Technology

Nagendra Parasad Yadav* | Guo-Zhen Hu | Zheng-Peng Yao | Ashish Kumar

Abstract—Recently, the diagnoses of dental caries and other dental issues are in a queue as only X-ray-based techniques are available in most hospitals around the world. Terahertz (THz) parametric imaging (TPI) is the latest technology that can be applied for medical applications, especially dental caries. This technology is harmless and thus suitable for biological samples owing to the low energy of THz emission. In this paper, a developed TPI system is used to investigate the two-dimensional (2D) and three-dimensional (3D) images of different samples from human teeth. After analyzing the measured images of human teeth, the results suggest that the THz parametric technology is capable of investigating the inner side structure of the teeth. This technique can be useful in detecting the defects in all types of human and animal teeth. The measurement and analytical calculations have been performed by using the TPI system and MATLAB, respectively, and both are in good agreement. The characteristics of THz waves and their interactions with the tooth samples are summarized. And the available THz-based technologies, such as TPI, and their potential applications of diagnoses are also presented.

Index Terms—Dental caries, early diagnosis, medical application, terahertz (THz) parametric imaging (TPI), three-dimensional (3D) imaging.

1. Introduction

The term “terahertz (THz) radiation”, which is also recognized as THz waves or THz light (1 THz corresponding to $10^{12}$ Hz in frequency, 33.3 cm$^{-1}$ in wavenumber, 4.14 meV in photo energy, and 300 µm in wavelength), is located between the high-frequency microwave region and the long-wavelength far-infrared region of the electromagnetic spectrum. This spectral range provides properties from radio waves, which can penetrate through plastics, textiles, paper, and cardboard. This is a wide specific absorption property from the infrared region for proteins, explosives, narcotics, and biomolecules at frequencies between 0.1 THz and 5.0 THz. Penetration through opaque materials is important, while absorption refinement is useful for chemical
differentiation. Currently, the diagnostic techniques in dentistry primarily rely on X-rays to monitor dental caries\(^1\). However, due to its ionizing radiation, X-rays cause harmful effects to human health, when used frequently\(^2\),\(^3\). Furthermore, the X-ray investigation of a tooth may cause a negative impact on the nearby healthy teeth, leading to another kind of damage to those not infected. Unfortunately, there are very few alternative techniques to X-rays currently available. Moreover, there is no technology that can detect the presence of caries in the tooth structure with a high probability\(^4\). Some schemes have already been proposed to evaluate the efficiency of different diagnostic modalities for the early diagnosis of dental caries in children\(^5\)-\(^8\). The above reasons create a need for a new method of inspection in which the maximum internal and external defects in the human tooth can be detected.

THz parametric imaging (TPI) has great potential for medical applications as it is a non-destructive imaging method. It does not cause any ionization hazards on biological samples due to the low energy of THz radiation. Recent investigations suggest that the TPI based methods can be used for the early identification of dental diseases and imperfections in the tooth structure and simultaneously overcome the harmfulness induced by X-rays\(^9\). Thus, the THz imaging (TI) system has been developed for dental diagnoses due to its essential advantages in medical studies, such as non-ionizing, biologically innocuous, and differing absorption indexes, making it helpful when interacting with biological samples\(^10\). The TI dental diagnosis has considerable demands in hospitals, especially in highly populous countries. Recently, by using the THz time-domain spectroscopy (THz-TDS) based methods to analyze the changes in absorption and refractive indexes, significant differences were found between permanent and primary teeth\(^11\). The refractive index values for permanent and primary teeth, which have been used in this work, were found to be 2.53 and 2.54, respectively, while the absorption coefficient values were 26.29 and 29.67, respectively. The size of the sample was 10 mm. Three-dimensional (3D) TI has been implemented in \(^12\) and \textit{in vivo} studies have been performed in \(^13\). This technique has also shown promise in measuring the effects of mineralization and demineralization\(^14\). Furthermore, recent advances of continuous-wave (CW) THz systems with a wide dynamic range have been developed for medical applications. Such systems are being developed toward imaging applications in defense\(^15\), and show high potential for medical uses. This TPI system enables us to analyze the properties of various types of teeth in two-dimensional (2D) and 3D space. It is capable of early detection of caries and the lower tooth density, which cannot be detected in other imaging systems. With different types of 2D analysis, the accuracy of the infected position inside the tooth can be seen and 3D plotting can be applied to obtain the depth of the contaminated area.

The importance of early detection of caries is emphasized by the fact that an incipient lesion, amenable to remineralization, can be arrested, reversed, or restored with minimal invasion\(^16\). This new technique making use of THz waves for applications in dentistry is growing more rapidly with the development of new instrumentation. The experimental results show that there are slight differences between various tooth groups, such as low-density and high-density teeth and carious and healthy teeth\(^17\). Similar studies have been demonstrated in \(^18\) to \(^22\), but they usually suffer from the disadvantages of low speed or complicated operation. The main principle of this report suggests that dental structures, such as dentine, enamel, or even carious portions, must be analyzed with higher resolution. Detailed discussion about the experimental setup and its optical function, results, and conclusions are given in Sections 2, 3, and 4, respectively.

2. Experimental Setup and Its Basic Principle

The experimental setup and its demonstration are shown in Fig. 1. Lens-free made by the semiconductor Terasense sensor is a modern imaging technique, in which the sample is placed directly into or very close to the Terasense sensor and illuminated by a partial THz source located far above it. Such a system enables the
experiment to be operated in a very easy way. With a polarizer, metalens, hyperlens, and THz antenna applied, higher resolution imaging can be realized. The details of the optical THz setup with step by step separation between each instrument are schematically shown in Fig. 1 (a), where the TTL modulation indicates the transistor-transistor logic modulation. The THz depth imaging system consists of an impact-ionization-avalanche transit-time (IMPATT) diode generator, two HRFZ-SI-H lenses, a POL-HDPE-OD polarizer, and a detector. The IMPATT diode has a frequency of 100 GHz and output power of 80 mW/180 mW/400 mW, which is supported by the TI cameras. The detector used is a Terasense camera, having a wide spectral range of 50 GHz to 0.7 THz and an array of 1024 pixels with each pixel being 1.5 mm. The HRFZ-SI-H lens has a diameter of 50.8 mm and a focal length of 40 mm while the POL-HDPE-OD polarizer has a diameter of 50 mm and a frequency range of 0.01 THz to 30 THz.

IMPATT is a high-power semiconductor diode, which can be used in high-frequency microwave fields. When a voltage gradient is applied, the IMPATT diode results in a high current rather than a breakdown as these standard diodes have been known to experience. The measurement time is very quick, and data can be obtained rapidly. The transmitted THz waves are projected on an array of bolometer detectors. The signal is separated from the noise with a lock-in amplifier synchronized with an IMPATT generator. In this condition, the polarizer controls the power spectrum to analyze a sample with different ranges. The noise equivalent power records the images, whose row vector represents each pixel image taken at an individual frequency. A matrix of measured frequencies defines the structure of the defect of the teeth, where the main limiting factors include the distance from the sensor to the sample, spatial and temporal coherence of illumination, the finite size of equally spaced sensor pixels, and finite extent of the image sub-field of view (sub-FOV) used for reconstruction.

3. Results and Discussion

The THz technology is a breakthrough in medical applications, especially for the diagnosis of many
diseases in the human body, because THz radiation is non-ionizing and can be used in the inner imaging of samples. Such attributes make it an ideal technique to investigate its feasibility for dental applications. To perform imaging in this frequency range, there is no need to slice the teeth as the inner structure can be probed, even though in the research presented here, each tooth was thinly sliced by a diamond saw to effectively measure the refractive index and absorption coefficient. The tooth samples were prepared by thinly slicing the primary and adult teeth and were measured in the wet and dry states. It was observed that the wet samples have higher absorption and lower refractive indexes compared with the dry samples. Therefore, these results show that there is a clear difference between the dentine and enamel sections of each sliced tooth.

Additionally, the defect tends to significantly change the refractive index and absorption spectra, which suggests that THz techniques can be an invaluable tool in dentistry. The tooth sample contains many parts, such as the root, crown, and neck. Each part shown in Fig. 2 (a) can be observed in the TI result (Fig. 2 (d)) of the tooth sample in Fig. 2 (b). Correspondingly, the density profile is shown in Fig. 2 (c), which was plotted by contour plotting methods whose procedure is depicted in Fig. 3. The MATLAB data were taken from the Terasense camera.

Fig. 2. Experimental tooth sample and its THz imaging: (a) structure of the human tooth, (b) picture of the tooth sample, (c) density profile obtained by MATLAB, which represents the 3D imaging of the tooth, and (d) THz image clearly showing each part of the tooth.

Fig. 3. Procedure of contour plotting.
We also imaged these tooth samples (dental caries with a length of 10 mm at different positions) using the polarizer. As depicted in Fig. 4, the imaged results taken by the Terasense camera are obvious. It is clearly observed that the TPI images with dissimilar positions of dental caries are different. This demonstrates that TPI can be useful for early diagnoses. Notably, instrument resolution is about 1 mm. Understanding how to break the diffraction limit and improve the resolution of TI always plays a vital role in future research. Fig. 5 shows the real structure and TI of the tooth sample with a low density, from which the difference between the healthy and weak roots can be easily distinguished. Fig. 5 (d) indicates that the root of the low-density sample is not healthy. For the high-density sample, the results are shown in Fig. 6. One can easily determine that when the tooth sample is high-density, the root will be healthy, which is confirmed in Fig. 6 (d). Based on Figs. 5 and 6, it is clear that one can obtain a quick diagnosis using the proposed technology at an early stage, especially for young people and older adults, based on the high- and low-density characteristics. Currently, the TPI technology is not comparable to X-ray or magnetic resonance imaging (MRI) technologies, because X-ray imaging and MRI are already mature techniques. Therefore, the applications of TI have initially focused on specific areas where THz pulses have unique capabilities.

Fig. 4. THz images of human teeth with 10-mm dental caries at different positions.

Fig. 5. THz imaging of the low-density tooth sample: (a) picture, (b) structure of the human tooth, (c) THz image of the low-density tooth, and (d) contour plot obtained from data of (c).

The THz images of the high-density tooth show the root is healthy at the higher-density region, which can be seen from Fig. 6. The 2D images were generated by acquiring the intensity of the THz radiation at each pixel. After measurement analysis, the results indicate that THz radiation is sensitive to the variations in the structure of the samples. This certifies that this method can be useful in detecting tooth defects. The high
average power utilized in the CW TI system allowed for the detection of the structural changes below the surface of the bone/tooth structure even though the images were obtained only in 2D. Evidence of structural changes induced by the implant locations was clearly observed in the THz images obtained at a frequency of 370 GHz.

Fig. 6. THz imaging of the high-density tooth sample: (a) picture, (b) structure of human tooth, (c) THz image of the high-density tooth, and (d) contour plot obtained from data of (c).

4. Conclusion

The THz-based technology is a promising and innovative tool for medical diagnoses. In this work, we investigated the human teeth of different dental caries by using the Terasense technology. The Terasense camera can perfectly capture the image at the resolution of about 1 mm. To investigate various tooth samples in 2D and based on the density distribution in the samples, we constructed a TPI system, which is a CW TI system. All measurement processes were easy to handle. These are the first reported results regarding TI, which shows that the Terasense technology may have a big demand in medical industries, especially for highly populous countries. The sliced teeth sections were investigated using 2D THz images obtained by measuring the reflected THz peak amplitude across the sample. All measurement processes were taken with a spot size of about 10 mm, which limited the resolution in TI. However, taking into account the fact that THz procedures and devices are not yet fully developed and continually under research and expansion, and THz is being integrated into smaller medical devices, a possible assumption is provided that these obstacles will be controlled for several years. Future applications of this technology are not only in medical but also in security, food inspection, pharmaceutical and medical investigation, and nanotechnology. TPI has the potential to be used in assessing dental structures and diagnosing dental problems. The preliminary measurement shows that TI methods are highly sensitive to structural changes in teeth and have the potential to diagnose such changes, which is an important factor in detecting and monitoring dental caries.
Disclosures

The authors declare no conflicts of interest.

References


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