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Terahertz technology: A Review on dental perspective

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Abstract:
Significant act of spontaneities of existing methods and new explorations are going on in the improvement of fresher imaging modalities that could change the study of dental radiology. Imaging dental tissues has been a challenge due to its different physical and chemical properties. To overcome this, terahertz radiation (THz) came into use for imaging purpose. THz imaging is very encouraging in scientific and biomedical applications. Terahertz imaging doesn't cause any ionization peril on organic samples because of low energy of THz radiation. Despite the fact that it is firmly absorbed by water, which displays extremely interesting physical and chemical properties that add to solid interaction with THz radiation and teeth can still be viewed in 3-dimension. Terahertz pulsed imaging (TPI) can be utilized in the early detection of dental caries and defects in the tooth structure without using x-rays. With the development of coherent sources, terahertz technology is used widespread from biomedicine to telecommunications. In this paper we present a short review of terahertz radiation from the point of dental imaging. We discussed the development of terahertz radiation from its initial state till its recent advancement; viable terahertz sources; described its modern applications in dentistry and various fields.

Keywords: 3- dimension, dental caries, terahertz pulsed imaging (TPI), terahertz radiation (THz), terahertz sources.

INTRODUCTION:

Many recent innovations in medical imaging appear to be straight out of a sci-fi film. But there are many clinical problems which require precise 3-dimensional images, specifically tooth structure. Though many fortunate imaging techniques have originated, they all had their own shortcomings. There had always been a difficulty in imaging tooth structure due to its structural properties [1]. At present X-rays are used as primary diagnosing technique in dentistry to monitor dental caries, though it is an ionizing radiation with possible damaging effect on tissue structure. Other methods such as tactile method, caries detector dyes, gel with papain and laser fluorescent devices are also present [2]. What if the caries is diagnosed at an earlier stage? The tooth structure gets remineralized, lesion size can be contained, thereby preserving natural tooth structure. Various techniques for detection of early caries exist, which mostly rely on destructive sample preparations or high dose of ionizing radiation, but do not estimate the degree of demineralization [3]. For this reason, there is a call for advanced technologies to illustrate the tooth structure without detrimental effects on human health.

Terahertz radiation (THz) also called terahertz waves, terahertz light or T-rays. It is an electromagnetic radiation of frequency between 0.1 and 10THz [1]. Terahertz radiation lies in the region between microwaves and infrared light waves known as the “terahertz gap”, where this region remained hidden due to absence of its sources and good detectors [4]. Unlike X-rays, THz is nonionizing radiation with an energy level of 4.14meV, which does not pose any ionization hazard [1]. Since, it has low energy level it can penetrate through materials such as plastics, paper and ceramics. Terahertz waves are strongly absorbed by water due to which they provide better contrast for soft tissues [4]. Due to its non-ionizing or non-destructive property it can be used for security screening, inspecting semiconductors, food, and pharmaceutics, agricultural products, 2D and 3D imaging, high speed computing and medical diagnosis like tumors and skin cancers [5,6]. Terahertz radiation can be used in dentistry as they are capable of demarcating different layers in the tooth. Terahertz imaging has the potential to identify dental caries in early stages and imperfections in tooth structure without posing an ionization hazard as in X-rays [7]. Since, the THz rays do not produce any detrimental effect, they are considered biologically innocuous and will be the future of diagnosis in dental and medical fields.

HISTORY OF TERAHERTZ RADIATION:

1897	H. Rubens and E.F. Nichols noted a gap between optical and electronic radiation in the electromagnetic spectrum [8].
1960	First image was produced using terahertz radiation [9].
1970s	With the progress in receivers and high-altitude outboard platform observatories, Terahertz and sub terahertz frequencies were used in astronomy. The operational principles of quantum cascade laser were also presented [8].
1983	D. Auston and P. Smith presented coherent detection of short burst of terahertz radiation using the picosecond photoconductors in the form of dielectric resonators [8].
1988	Terahertz was first tested as a tool for dendrochronology (scientific method for dating tree rings) [10].
1990s	The terahertz applications in imaging expanded widely with the emergence of mode locked Ti: sapphire femtosecond lasers [8].

1995	The terahertz time domain spectroscopy was used to create terahertz image, which provoked greater level of interest and a swift in terahertz technology [9].
2002	The first passive terahertz technology was developed at Rutherfold Appleton laboratory [9].
2004	For the purpose of security screening, the first compact terahertz camera was introduced, which effectively imaged guns and explosives under clothing [9].
2007	Scientists invented a compact device as a source of T-rays / THz radiation, which is portable and battery operated [9]. The terahertz spectroscopy can differentiate pigments, binders and mixtures of various medieval manuscripts to enhance the readability of the text [11].
2008	Engineers at Harvard University, illustrated that at room temperature a few hundred nanowatts of THz radiation could be emitted using a semiconductor source. Previously, cryogenic cooling was essential which held back their use in daily application [11].
2009	Researchers presented that while unpeeling an adhesive tape T-waves were produced and this spectrum exhibited a peak at 2THz and a wider peak at 18THz [9].
2011	Using terahertz radiation, researchers developed a chip which can transmit 1.5 Gbit /second [9].
2013	Researchers invented a method to produce a graphene antenna viz., constructed as graphene strips positioned as 10-100 nanometers wide and 1 μm length. This could broadcast in THz frequency [9].
2014	The researchers started working on a security screening system using THz technologies. They can also be used to detect explosives and identify any chemical composition [12].
2016	Researchers proposed the application of terahertz radiation in urban and anti-terrorist action i.e., scanning behind the walls or inside compounds [12].
2017	China North Industries group corporation successfully assessed the capacity of THz instruments to detect stealth aircraft [12].
2019	Food industries started using terahertz technologies to evaluate food quality and verify food safety, since THz is a noninvasive and rapid technology [13].

TERAHERTZ SOURCES:

Naturally, THz radiation is emitted from anything with a temperature more than 2 kelvins as a part of the black body radiation. Extra terrestrially, the cosmic background radiation and the sun are a thermal source of THz waves [14]. As of now, there are many viable sources of terahertz radiations.

1. Thermal sources:

Under thermal sources, globar was used commonly in laboratories. It is a carborundum (SiC) rod which is electrically heated, whose emissivity range is 0.5-0.8 at 1650 K [14]. It has a very weak output power and emits a wide spectral region. Mercury arc lamp also comes under thermal source of terahertz radiation, which is more powerful than a globar source and can generate broadband continuous terahertz radiation [15].

2.Vaccum electronic sources:

As a part of vacuum electronic sources, the backward wave oscillator, travelling wave tubes, gyrotrons, klystrons, free electron lasers and synchrotrons are present [14]. The backward wave oscillator (BWO) is a slow wave device but top rated, as they can operate in the terahertz region at moderate power levels i.e., 1-100 Mw. It has a corrugated structure through which the electrons spiralize in a magnetic field interconnecting with the first spatial harmonic of the BW. BWOs function with a step-up potential of 1-10 kV and magnetic field of 1T [16]. Whereas, the gyrotrons are fast wave devices and provide high power radiation in both pulsed and continuous waves (CW). Gyrotrons are capable of modulating the output power and frequency, moreover it can also focus the generated wave beam by quasi optical elements [17].

3. Laser sources:

THz lasers are built from semiconductors, germanium and silicon. The terahertz laser sources include gas, semiconductors, diodes, dual-mode, multi-mode and quantum cascades [14]. Among them, the quantum cascade laser (QCL) drew more attention compared to others. It is a compact terahertz source; the main advantage is the high optical output power in both pulsed and continuous wave modes [15]. The quantum cascade lasers are based on the classic semiconductor lasers, i.e., only one type of charge carriers, electrons are used with the help of intersubband transitions. QCLs do not use semiconductors as a bulk in their optically active region, instead they use periodic thin layers of varying material composition to form a superlattice, which causes the electric potential to change across the length of the device, thereby splitting the energies (band splitting) into discrete electronic sub-bands. This will cascade the electrons down a series of identical energy steps, and emit a photon at every step. This makes the quantum efficiency of QCL greater than unity and leads to their high output power. The energy level is determined mainly by the thickness of the layers rather than the material [18].

4. Transient currents:

On changing a dipole, terahertz waves can be emitted. Due to drift currents (carrier drift) or diffusion currents, transient current may arise on its own. Diffusion current arises when opposite charge carriers diffuse at various rates i.e., a dipole is formed which is named as Dember effect / Photodember effect. Mostly, diffusion is perpendicular to the surface, if parallel it is called a lateral effect. This direction is more favorable for coupling out. Whereas drift currents are strongly determined by local surface field and dominate for high electric fields. Due to this fact, drift current emissions are known as surface-field emission [14].

5. Mechanical excitation:

Terahertz radiation can be generated from surfaces without any photoexcitation. The peeling of adhesive tape from its roll or from any other surface, has certainly shown to radiate at terahertz frequencies (range of 2-3cm s^{-1}). It is stated that a double-sided tape shows heating effect with no charge separation whereas the common single sided tape shows separation of charges while winding it. The emission does not depend on the speed while unwinding the tape and the intensity is small accounting to a mere increase in blackbody radiation at room temperature. The radiation is emitted at a broad range of THz frequencies (1-20 THz) [14].

TERAHERTZ APPLICATIONS:

The sources produce adequate intensity of terahertz radiation for research, analysis, security, medicine, pharmacy, art and many other applications. Terahertz spectroscopy has been implemented majorly in industries.

1.Gassensing:

Terahertz can distinctly identify toxic gases from a mixture of different other gases. In a situation of burning plastics, carbon monoxide, hydrochloric acid and hydrogen cyanide is often produced. THz spectroscopy not only identifies these toxic gases, also they quantify their concentrations through black smoke (nontransparent to visible light) from a safe distance. It can be used for material analysis in plastic industries like quality control and to determine the additive content as the polymers are transparent to terahertz radiation [19].

2.Pharmaceutics:

Terahertz radiation has the ability to resolve the spectral and structural information of components which has added interest in pharmaceutical industries. It can also be used for identifying and quantifying polymorphs [4], to study the mechanism of polymorphic phase transition [20] and distinguishing behaviors of hydrated and anhydrous forms of crystalline pharmaceutical materials. Terahertz pulsed spectroscopy is also used for the study of dehydration mechanisms and investigating the solid-state properties of materials in pharmaceutics [21].

3.Food industries:

Terahertz technology is applied for maintaining food safety and quality as well as detecting food processing. In the interest of preventing diseases in animals, veterinary drugs are ingested while feeding the animals, causing drug residues in beef, pork and mutton. Terahertz spectroscopy as a non-invasive technique is used for antibiotic residue detection in animal origin products. Terahertz spectroscopy has confronted contamination by aluminum sheets when enrolled over sausages. THz technology is used for evaluating the quality of chocolate bars, as it is more susceptible for contamination while manufacturing like stones or glass splinters (stones arise from the ingredients like nuts, raisins, etc. and glass may arise from light bulbs). THz can be used for the problems of melting and reshaping of chocolates by locating the melted part without opening the package. The extra virgin olive oil (EVOO) samples from different geographic zones can be classified accurately using THz spectroscopy, as EVOOs from different areas possess different fatty acid contents. This can be used to avoid fraud or mislabeling its geometric origin. Mixture food matrices such as milk powder, cereal powder, hamburgers, meatballs, patties are encountered to adulteration due to monetary profits. These can be revealed with non-invasive terahertz spectroscopy. Apart from adulteration, overuse of antibiotics to control livestock diseases leads to unsafe residue levels in milk or meat products were assessed using terahertz time domain spectroscopy [13].

4.Archeology:

Terahertz spectroscopy and imaging can be used for recognizing texts in parchments (used as manuscripts in ancient eras made of calf, goat or sheep skin) and can readily differentiate the text from its stains [22]. THz transmission spectroscopy can distinguish and identify mixtures of different pigments and binders used in medieval manuscripts. It can also disclose hidden drawings of multilayer mural paintings and differentiate from the unknown outer layers [23].

5.Medicine:

Terahertz imaging has a promising application in the medical field too. In patients with burns like second degree or partial thickness burns, terahertz imaging provides clear information on formation and development of edema in the burn area. It is widely used in skin cancer imaging. Larger tumors or infiltrative tumors often reach a greater extent than the portion visible to the naked eye so the surgeons would remove a considerable portion in order to achieve complete resection. With terahertz imaging the skin cancer margins can be detected and preserve possible normal surrounding tissues. Generally, cancerous tissues are less dense compared to normal tissues which show different amplitudes, wavelength, low refractive index and absorbance of terahertz waves. Terahertz is used in early detection of breast cancer, due to the presence of high adipose tissue in breast [24].

6.Dentistry:

Terahertz imaging can play a major role in dentistry. Enamel erosion is a spiking public health problem that requires a non-destructive technology to measure the enamel thickness of the tooth to quantify the problem [25]. Terahertz imaging can provide 3D images without any detrimental effects. It can also detect mineral changes in the tooth structure and measure the lesion depth, which helps in treatment planning [26]. Dental caries manifestation is a complex procedure provoked by genetic, behavioral, microbial and environmental factors [27]. This THz imaging aids to detect dental caries with greater specificity in earlier stage and other imperfections, thus preventing unnecessary loss of tooth structure. Few studies have proved that, in a sample tooth different absorption rates of terahertz are recorded which can differentiate healthy tooth structures from dental caries. In detection of oral cancer, terahertz imaging is far more precise compared to histological examination [28].

Studies were done regarding terahertz radiation to correct dental peri-implant conditions due to tobacco intoxication. In this study, terahertz frequency (THF) of 129GHz were used. 36 rabbits were divided into three experimental groups and one control group. Tobacco intoxication is stimulated for six weeks in the experimental groups, and implantation is proceeded. The tobacco intoxication was prolonged throughout the experiment. For the first experimental group no physiotherapy was performed meanwhile, the second and third experimental groups had numerous schemas of terahertz therapy. Histological methods were used to evaluate the results. Results showed an active regeneration process in the control group whereas, in the second and third groups which received terahertz therapy showed remarkable changes compared to the first group. Within a period of one month the thickness of the connective tissue was significantly lowered when compared to the first group. Osteogenesis took place with less cartilage formation in second and third groups than in the first group and proved the efficacy of terahertz for the treatment of dental implants in conditions of tobacco intoxication [29].

Experimental studies were conducted for diagnosing dental caries using terahertz radiation. For this study, samples of extracted teeth after placing in 0.9% aqueous NaCl for six days were selected. In this, one sample had no caries and the second had moderate caries on the vestibular surface. On the surface of the sample, THz radiation was angled normally. As a result, temporal shaped terahertz pulses returned from the sample. By step-by-step scanning of immobile samples of dental tissue with an interval of 0.5mm, the images were obtained. It showed greater absorption of terahertz radiation by caries affected dental tissue and comparatively lesser absorption of terahertz radiation by healthy tooth structure. And also, from this study it is known that caries affected enamel and dentine reflect lower intensity terahertz radiation compared to the healthy tissues [30].

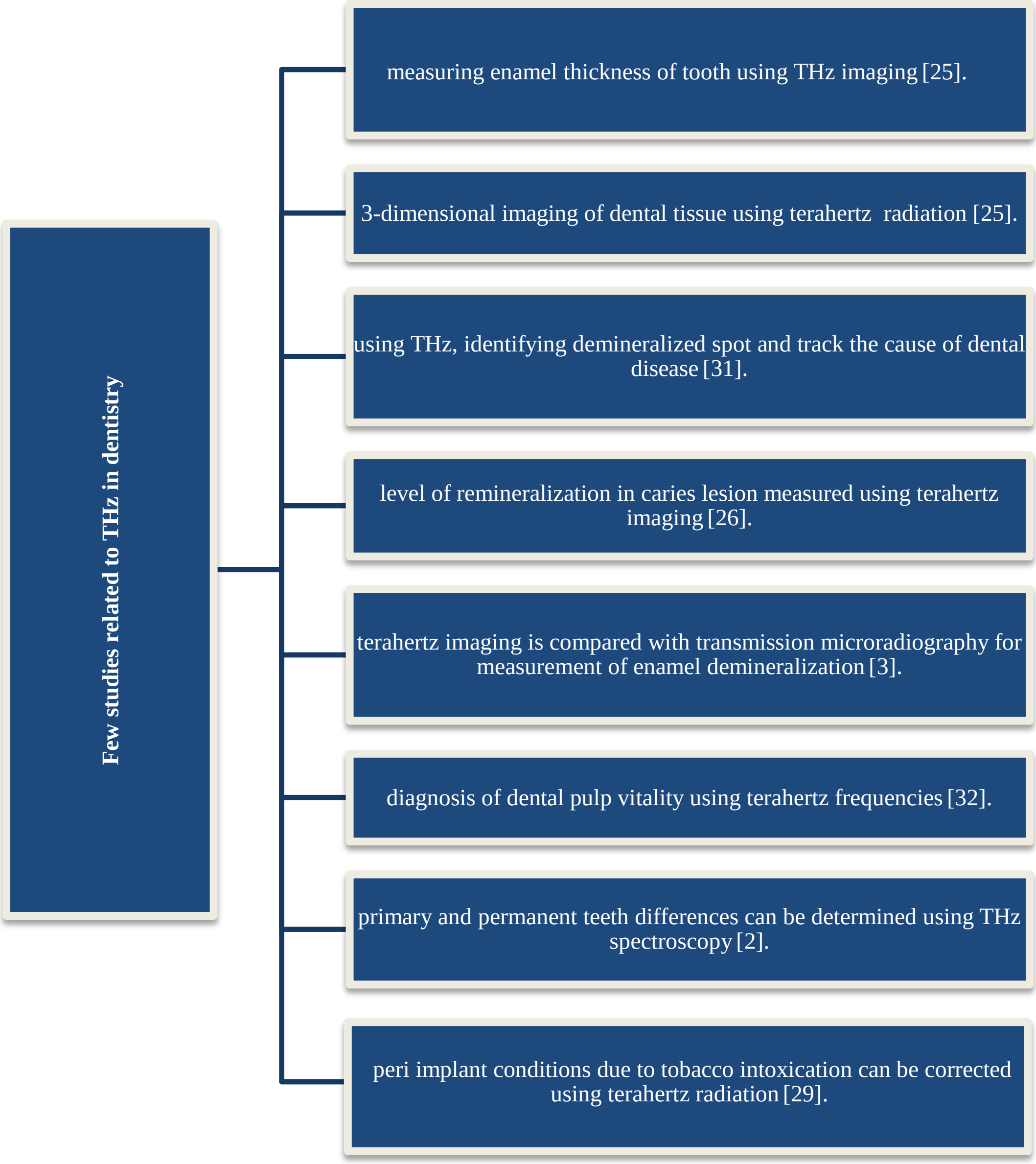
Differences between primary and permanent teeth were studied. Using THz time domain spectroscopy 25 teeth samples of which 9 primary teeth and 16 permanent teeth were analyzed. The refractive index of teeth sections and its absorptive effects were figured for transmission measurements. The study showed differences in absorption coefficient values of primary and permanent teeth, which is due to higher tubular liquid concentration and larger diameter of dentinal tubules of primary teeth than the permanent [2].

Using terahertz radiation, studies were done to obtain 3-dimensional information of dental tissues. Incisors were used for the study because they are easy to access, less curved and have thin enamel layers. To measure enamel thickness pilot incisor was hemisected for comparing terahertz and visible image. For confirmation of accurate results, the labial enamel thickness of an incisor had been altered by acid etching and each step was made to have 100μm deeper than the next. In terahertz images, the curvature of the tooth surfaces was exaggerated because tooth structures have a higher refractive index compared to air. The enamel dentine junction was less noticeable than the enamel-air intersection due to smaller refractive change. Same way a set 12 incisors were imaged, whose enamel dentine junction was clearly evidenced as a dark line in a light background and enamel air intersection as a light line in a darkened background. Their enamel thickness ranged from 0.4 to 0.9mm. The tooth with artificially altered enamel also showed a difference in height between steps as 100μm [25].

To exhibit the distinctive properties of enamel and dentine using terahertz frequency, studies were done using extracted human molars sectioned to around 600μm and ground to required thickness. The teeth were demineralized in 6% hydroxyethyl cellulose gel with lactic acid at pH 4.5 for 7 days and nail varnish was used in the sections other than the area to be demineralized. Time domain using THz spectroscopic setup were used to process terahertz images and set of parabolic off-axis mirrors were used to focus the terahertz beam on the sample. The images obtained from demineralized samples shows inclination from surface to inner parts due to increase in carbonate towards the interior. The data obtained from terahertz imaging and spectroscopy showed an increase of terahertz transmission signal in demineralized spots compared to healthy tooth structure and also can be used to determine the progress of demineralization and trace the root of dental diseases [31].

Studies were done to compare terahertz pulsed imaging (TPI) and transmission microradiography (TMR) for figuring the depth of artificially demineralized enamel lesions. The transmission microradiography is referred to as the gold standard for measuring the lesion depth but that requires the teeth to be cut into thinner sections prior to microradiography. As terahertz is non-destructive and non-ionizing, the results were compared for accuracy. Two lesions were prepared such as acidified gel lesions and based on a polymer solution. In acidified gel method, the enamel was capped with 8% methyl cellulose left overnight at 4°C, pH at 4.6 with KOH and nurtured at 37°C. For the polymer method, the enamel blocks were immersed in 0.2% of Carbopol, 0.1M lactic acid, 50% saturated based on hydroxyapatite crystals, pH at 5 with KOH and then placed at 37°C for 14 days. When both the lesions were checked using TPI and subjected to TMR, the results showed that the mineral content from TMR is the same as the refractive index figured out by TPI. This study proved that TPI can quantitatively provide the extent of lesion and has the prospect do so in vivo too [3].

Diagnosis of pulp vitality currently relies on a patient's perception by elicited nerve response. Though many noninvasive techniques like laser doppler flowmetry, ultrasound, photoplethysmography have been proposed, these techniques are not used clinically. So, studies are being carried out to determine satisfactory transmission windows in the infrared and terahertz spectrum to detect the pulpal blood flow [32].



CONCLUSION:

An overview of some sources and applications of terahertz radiation is addressed in this review. We have described the unique properties of terahertz radiation in various fields. Terahertz is an attractive and reliable technique. The great advantage in using terahertz is that, it is non ionizing, harmless and is transparent to materials which block infrared and visible spectra. However, X-rays provide valuable information for diagnosis in dentistry, but it is an ionizing radiation and causes possible tissue damage. Some limitations like oversize equipment, image resolution, complicated data handling and primary investments are to be resolved.

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