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PAPERS

Non-destructive testing of human teeth using microwaves: a state-of-the-art review

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Tooth diseases including dental caries, periodontitis and cracks have been public health problems globally. How to detect them at the early stage and perform thorough diagnosis are critical for the treatment. The diseases can be viewed as defects from the perspective of non-destructive testing. Such a defect can affect the material properties (e.g., optical, chemical, mechanical, acoustic, density and dielectric properties). A non-destructive testing method is commonly developed to sense the change of one particular property. Microwave testing is one that is focused on the dielectric properties. In recent years, this technique has received increased attention in dentistry. Here, the dielectric properties of human teeth are presented first, and the measurement methods are addressed. Then, the research progress on the detection of teeth over the last decade is reviewed, identifying achievements and challenges. Finally, the research trends are outlined, including electromagnetic simulation, radio frequency identification and heating-based techniques.

Keywords: coaxial probe, human teeth, microscopy, microwave energy, non-destructive testing, permittivity

1 Introduction

Dental caries (also called cavities or tooth decay), periodontitis (also called gum disease) and cracks are the primary reasons for tooth loss, and they have become major public health problems worldwide. Dental caries and periodontal diseases have been considered the most important global oral health burdens. Caries is a permanently damaged area in the enamel that can develop into small openings or holes. It is the most common disease with increasing prevalence in many low- and middle-income countries [1]. Periodontitis is a serious gum infection and can destroy the bone that supports the tooth. It may start with plaque, which forms on the teeth when starches and sugars in food interact with bacteria in the mouth. The bacteria causing periodontitis can enter the bloodstream through the gum tissue. Cracks can be caused by teeth grinding, ageing, chewing/biting hard foods and large fillings. Cracks may appear as craze lines, fractured cusp, split tooth or vertical root fracture. At the early stages, a crack may not be visible or produce any symptoms until it extends to the dentine or the pulp cavity. Severe pain, swollen gums, sensitivity to cold and heat, pulp infection and tooth abscess can be caused if remained untreated. Tooth diseases can compromise the quality of life, cause irreversible tooth loss and pose a high economic burden due to the cost of the dental treatment related. Hence, timely detection and assessment of tooth diseases are vital for clinical intervention.

The diagnosis using conventional methods like staining with a blue dye, examination with a magnifying glass, probing and cold stimulation strongly depends on the experience of the endodontists. Several non-destructive testing (NDT) methods have also been employed, such as ultrasonics [2], oral X-ray, computed tomography (CT), cone-beam computed tomographic (CBCT) imaging [3], micro-CT, magnetic resonance imaging (MRI) [4] and terahertz imaging [5], [6]. Each method has advantages, limitations and field of application. The propagation of ultrasound in dentin and enamel is not fully revealed, posing some difficulties in the analysis of the ultrasonic images. X rays-based methods are ionising and can cause biological damage to human tissues. Oral X-ray imaging has low efficiency, and anatomic superimposition commonly occurs. Artefacts could be present in the images produced by CT and CBCT. Micro-CT cannot be readily applied in vivo [7]. MRI can offer excellent image quality, whereas the relatively large equipment limits its use for laboratory research. The equipment of terahertz imaging is intricate and relatively expensive. Hence, non-invasive, safe and convenient detection methods are still in urgent demand.

Recently, microwave testing as an alternative NDT approach has attracted increased attention. Microwaves are electromagnetic waves with frequencies ranging from 300 MHz to 300 GHz (the corresponding wavelength from 1 m to 1 mm). Microwaves are best known for their use in telecommunications, navigation and food processing, whereas they have also been used for NDT. Material abnormalities, termed as defects in NDT, can cause changes in the dielectric properties (also called permittivity), which can be reflected in the variations of the signals reflected or transmitted. Microwave testing has

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several distinct attributes, such as no need for couplants or transducers bonded onto the surface, good penetration in dielectrics and no ionising hazards [8]. Microwave testing has been applied in varied fields, like aerospace engineering [9], mechanical engineering, food engineering [10], [11], petroleum engineering, chemical engineering [12], civil engineering, forestry and medical science. Taking the last type as an example, research has been conducted on the detection of skin cancer [13], breast cancer [14], neck diseases [15], blood glucose [16] and colonoscopy [17].

Preliminary research has been carried out in the field of dentistry. However, to the best knowledge of the authors, no comprehensive review of these work is available for better promotion to achieve wider applications. In this review paper, the definition of permittivity, the measurement methods and the typical values of teeth are discussed first. The existing microwave detection methods can be categorised into reflection, transmission and planar circuit methods. The detection principle and applications of each type are addressed in detail. Then, some viewpoints on the research trends that could further explore the potential of the microwave technique are presented.

2 Electromagnetic characterisation of human teeth

2.1 The permittivity

The permittivity ε, one of the intrinsic physical properties, describes the interaction between the material and the incident electric field. The value of ε is small, and the relative permittivity ε_r,, the ratio of ε to the permittivity of free space $\varepsilon_0 = 8.8542 \times 10{-}12\,\mathrm{F/m}$), is more used. This is generally a complex number and can be expressed as

$$\varepsilon_{\mathrm{r}} = \varepsilon_{\mathrm{r}}' - j\varepsilon_{\mathrm{r}}'', \tag{1}$$

where the real part $\varepsilon_{\mathrm{r}}'$ represents the capability of energy storage, and the imaginary part $\varepsilon_{\mathrm{r}}''$ is associated with the energy loss in the material in the form of heat. The loss tangent $\tan\delta = \varepsilon_{\mathrm{r}}''/\varepsilon_{\mathrm{r}}'$ can also be used for the description of the loss. The permittivity (ε_{r}) is a function of frequency and temperature.

2.2 Permittivity measurement

Common permittivity measurement methods include the open-ended waveguide/coaxial probe, transmission line, resonant and free-space methods [18]. For teeth, the open-ended coaxial probe approach is widely used. There are some off-the-shelf coaxial probes, like a Keysight "Performance" dielectric probe which can be operated from 200 MHz to 50 GHz. In the calibration, the default standards are air, a short circuit (a shorting block) and water (deionised water at 25 °C). The material under test is assumed infinite in size, and the probe is not recommended for accurate estimation of low-loss materials ($\tan\delta < 0.5$) with $\varepsilon_{\mathrm{r}}' > 5$. A probe can be constructed with a low-cost semi-rigid coaxial cable (*eg* RG405), one end of which is machined flat and polished with fine sandpaper and the other end is terminated with a connector (*eg* female-type SMA (SubMiniature version A) plug connector). A typical experimental set-up is illustrated in Fig. 1, where the fringe electromagnetic fields at the probe tip interact with the tooth. The probe is connected to a vector network analyser (VNA) by a coaxial cable. A programme with Standard Commands for Programmable Instrumentation (SCPI) from a personal computer (PC) can be sent to the analyser for data collection. As a one-port measurement, the reflection coefficient S_{11} is extracted over a given frequency range.

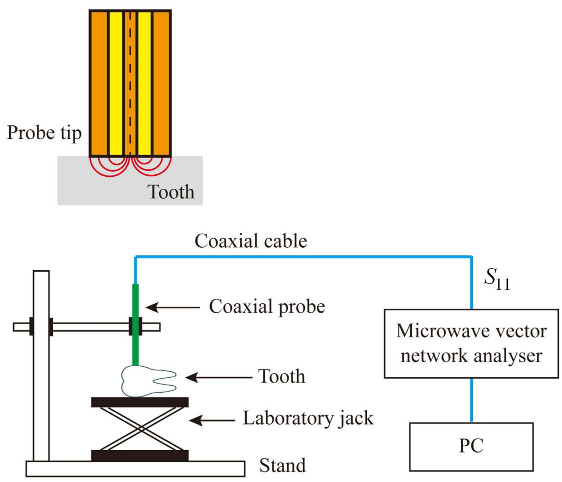

Fig. 1. Schematic diagram of the set-up for permittivity measurement of a tooth using a coaxial probe

The sample needs to be thick enough so that all the fields in the vicinity of the probe are located inside the material. As recommended, the material thickness should be four times the aperture diameter. This method is more suited to liquids or semi-solids, so that the probe can be immersed in the materials. For solids, good contact between the probe tip and the surface is required, *ie.* the surface should be as flat as possible. However, for the uneven surface of a real tooth, the measured permittivity would be considerably low if a large air gap (the value of ε_{r} is close to one) exists, *ie.* an intermediate value between the real value and one. In addition, the repeatability of the measurements cannot be guaranteed.

Berezhanska *et al* [19,20] introduced the concept of coupling liquids in ultrasonics to alleviate the negative effect of the air gap. It is noted that the meaning of coupling is different in each method: in ultrasonics the liquid is used to reduce the great energy loss of the ultrasonic signal in the air; here it is used to offer a reference permittivity. As shown in Fig. 2, two cases are compared: one with the coupling liquid only (a mixture of glycerine and water, case A) and the other one with the liquid between the probe and the tooth (case B). Glycerine was chosen,

Table 1. Permittivity data of human teeth reported in the literature

	Frequency range	Vector network analyser	ε_r
Enamel and dentin [24]	0.04-40 GHz	Wiltron 360B	5 GHz: 7.26-j0.39 (enamel) 7.18-j0.91 (dentin) 10 GHz: 7.00-j0.29 (enamel) 6.65-j0.74 (dentin)
Enamel [25]	0.1-8.5 GHz	Not available	2.4-4.6 with an average of 4.0
Enamel [26]	1-20 GHz	FieldFox N9951A	5.38-j0.67 (average)
Teeth [20]	0.5-18 GHz	Keysight E5063A	10-11 (crown) 8.0-9.5 (root)

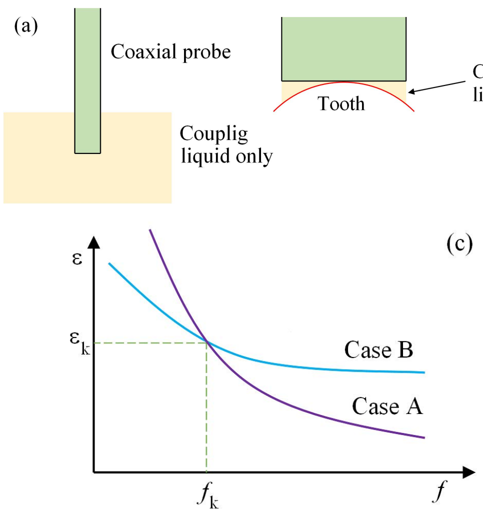

Fig. 2. Permittivity measurement of a tooth using a coupling liquid: (a) – case A with the coupling liquid only, (b) – case B with the gap between the tooth surface and the probe tip filled with the liquid; (c) permittivity spectra of both cases

as the mixture of glycerine and water did not evaporate at room temperature. The intersection point of the two permittivity spectra indicates a more accurate permittivity value of the tooth at a specific frequency, *ie*. f_k in Fig. 2 (c), in which the permittivity of the liquid was the same as that of the tooth. By changing the mixing ratio of water, the permittivity of the coupling liquid can be changed as required, so that permittivity values of the tooth at multiple frequencies can be obtained. It is noted that only when the intersection occurs can a valid permittivity value be generated. In other words, if no intersection occurs, the mixing ratio of water should be changed accordingly. They used this approach to conduct ex-vivo measurements of healthy human teeth at room temperature $(20.7 \pm 0.2\ °C)$, two molars and two premolars. As illustrated in Fig. 3 (a), for good positioning of the tooth under the probe surface during the measurements, the tooth was placed into plasticine holders coated with a cling film. The probe was first immersed into a holder filled with the coupling liquid, and a drop of the liquid was kept attached to the probe tip. The results showed that the variation of the measured relative permittivity was reduced when the coupling medium was used. An example of the permittivity results is given in Fig. 3 (b). The measurements performed on the molar and premolar are represented by red- and blue-shaded bands, respectively. The upper and lower limit of the recorded relative permittivity range is shown by dashed lines.

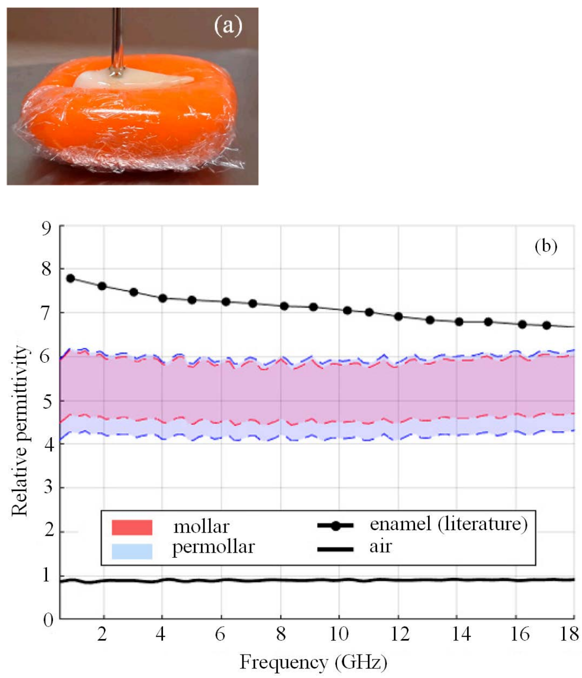

Fig. 3. Experimental results of the permittivity of a tooth using a coupling liquid [20]: (a) – photograph showing the contact between the probe and the tooth, (b) – permittivity of dental crowns

2.3 Typical permittivity data and signal penetration

Permittivity data of human teeth recently reported are listed in Tab. 1. Measurement of the pulp has not been reported. As the pulp has a higher water content than dentin, higher permittivity values can be expected for the high permittivity of water (ε_r' generally around 80 and ε_r'') around 20 at room temperature [21]).

To evaluate the penetration capability of microwaves in a material, the penetration depth d_p is commonly used. For a plane wave incident on a half space of a medium,

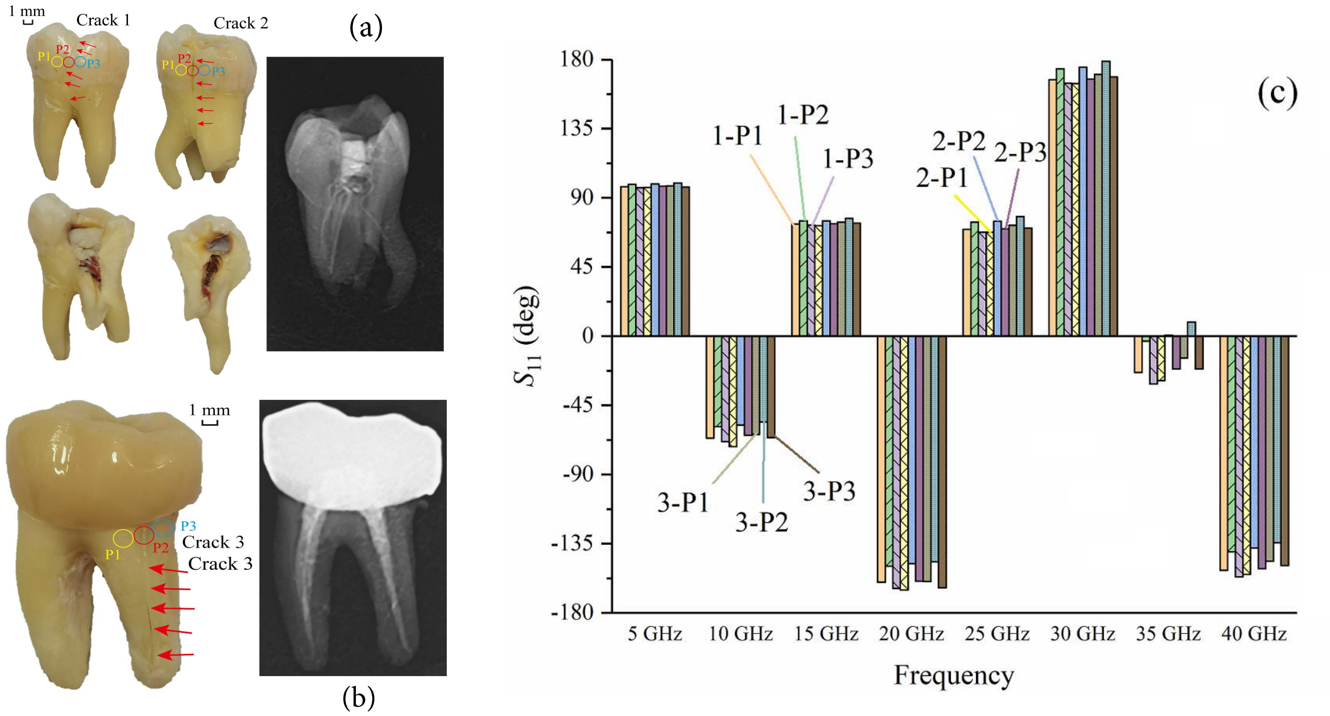

Fig. 4. Detection of cracks in a tooth using an open-ended coaxial line probe [26]: (a) – photograph and X-ray image of the first tooth with cracks 1 and 2, (b) – photograph and X-ray image of the second tooth with crack 3, and (c) – phase responses of the three cracks at eight frequencies

d_p is the depth where the magnitude of the electric field is reduced to 1/e (about 37 %) and can be calculated by [22], [23]:

$$d_p = \frac{c}{\pi f \sqrt{2}\left\{\varepsilon_r\left[\sqrt{1+\left(\frac{\varepsilon_r''}{\varepsilon_r'}\right)^2}-1\right]\right\}^{1/2}}, \qquad (2)$$

where c is the speed of light in free space, and f is the operating frequency. In a real detection scenario, the criterion of plane waves may not be satisfied, whereas the metric can be used for the comparison between different materials. By substituting the value of $\epsilon_r = 7.00 - j0.29$ at 10 GHz into (2), d_p is approximately 87.08 mm

3 Existing microwave detection methods for human teeth

3.1 Reflection method

Other than permittivity measurement, the coaxial probe can also be applied for detection purposes. From the changes in S_{11}, the presence of defects can be revealed. To obtain a high spatial resolution, the diameter of the probe should be as small as possible. At a higher frequency, the penetration is weaker, corresponding to a smaller sensing region around the tip.

Li *et al* [26] used an open coaxial line probe to detect cracks in two teeth over 1-40 GHz. One tooth was extracted due to splitting, and two cracks were barely visible when the two split parts were held together. The other tooth was extracted due to gum infection. Its crown was covered by an artificial dental crown, and a crack extended from the crown to the root. As seen in Fig. 4, all the three cracks cannot be identified in the X-ray images. The cross-sectional area of the probe was approximately 1.11 mm^2. Compared with the magnitude, as shown in Fig. 4(c), better performance (signal difference between the regions with and without a crack) was achieved using the phase at 35 GHz. From the analytical modelling, the signal penetration was found limited within the depth close to the probe aperture size, enabling localised inspection. There was also a close correlation between the extent of the crack and the phase value, suggesting the possibility of quantitative analysis.

3.2 Transmission method

Hoshi *et al* [27] analysed the signal transmission through tooth samples over 33-110 GHz using three waveguides. As illustrated in Fig. 5, a tooth sample was placed between two rectangular waveguides. With the presence of caries, the magnitude of the transmission coefficient (S_{21}) was lower than that of a healthy tooth. They also measured the complex permittivity of dental caries using a coaxial probe [24]. The caries with a higher moisture content had a higher permittivity value. It should be pointed out that this set-up is more appropriate for laboratory study. For in-vivo measurement, the positioning of the waveguides on the same side can be considered.

3.3 Planar circuit method

The near-field microwave microscopy method has been developed. An open planar resonator sensor with a sharp

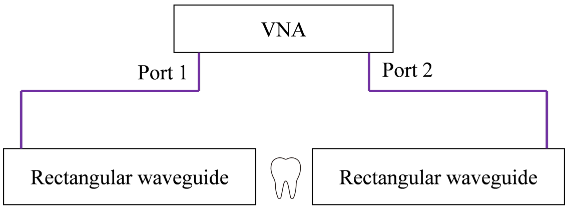

Fig. 5. Schematic diagram of the set-up for the transmission analysis of a tooth sample using two rectangular waveguides (adapted from [27])

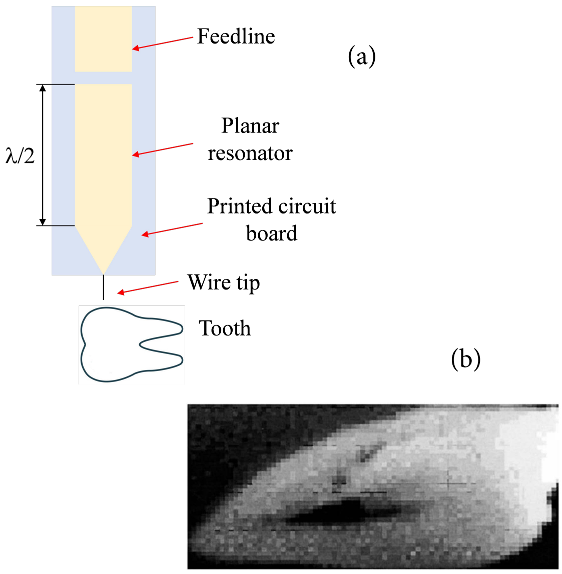

Fig. 6. Microwave planar resonator for near-field imaging of teeth [28]: (a) – diagram of the microstrip line resonator, (b) – evanescent microwave image of a tooth sample

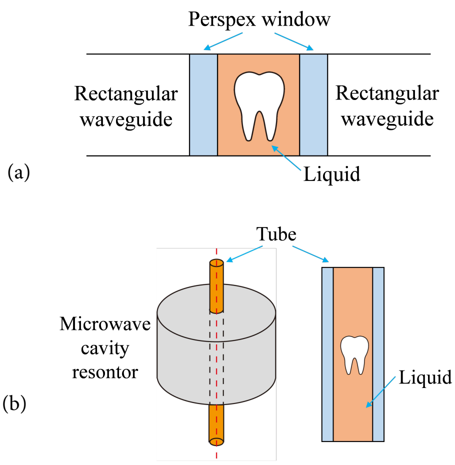

Fig. 7. New permittivity measurement methods of teeth: (a) – transmission line method, (b) – TM_{010}-mode cylindrical cavity resonator

probe tip is used. With the presence of the sample in the evanescent field, both the resonance frequency and the quality factor of the resonator are changed, and the amount of change mainly depends on the permittivity of the sample and the distance between the tip and the sample. During the scan of the sample, if the distance is kept constant, only the variation of the permittivity of the sample is related to the change of the resonance parameters.

Tabib-Azar *et al* [28] developed a half-wavelength ($\lambda/2$) microstrip line resonator sensorm shown in Fig. 6 (a), to image a tooth. The resonator was fabricated on a 0.68 mm-thick Duroid printed circuit board (PCB) using photolithography. To improve the spatial resolution, a wire with a pointed etched tip was attached to the tapered portion of the resonator. Its spatial resolution was around 0.4 μm at 1 GHz. From the image obtained, Fig. 6 (b), the dark portion of the tooth was successfully identified.

4 Future trends

New permittivity measurement methods

Adopting the idea of using a coupling liquid, the in-waveguide transmission line and resonant methods can be employed to evaluate the effective permittivity of the whole tooth. For example, for the transmission line method, a three-layer set-up, shown in Fig. 7(a) within a rectangular waveguide [29] can be used, where the tooth and the liquid are placed between two Perspex windows to avoid leakage. Using the Tischer model [30] or Nicolson-Ross-Weir (NRW) algorithm [31], the permittivity can be calculated from S_{11} and S_{21}.

As illustrated in Fig. 7(b), a TM_{010} -mode cylindrical cavity resonator can be used. A tooth can be put in a liquid-filled quartz tube, and then the tube is placed along the axis. When the tooth is at different places and the changes in the resonance frequency of the cavity are insignificant, the permittivity values of the liquid and the tooth become close. From the resonance frequency and quality factor, the permittivity can be computed using the material perturbation theory [32].

Waveguide-based inspection

Similar to an open-ended coaxial probe, a rectangular/circular waveguide can also be used in the reflection mode. As illustrated in Fig. 8, a waveguide is a metallic pipe that guides and transports microwave signals. In the test, a waveguide with a flange or flangeless waveguide can be used and placed close to the tooth in a contact or non-contact way. The waveguide works like an antenna, and the sample is in the near-field region. Compared with the open-ended coaxial probe, better penetration can be achieved. Different sizes of waveguides correspond to varied frequency ranges. The smaller the waveguide, the higher the operating frequency would be. The inner dimensions of some rectangular waveguides recommended are listed in Tab. 2. For a better spatial resolution, a smaller waveguide is desired.

Table 2. Recommended rectangular waveguides for potential detection of teeth

Waveguide band	Recommended frequency range (GHz)	Inner dimensions ($a \times b$, unit: mm)
Q	33-50	5.7×2.8
V	50-75	3.8×1.9
W	75-110	2.54×1.27

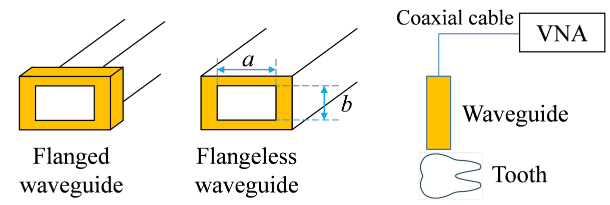

Fig. 8. Evaluation of teeth using an open-ended rectangular waveguide

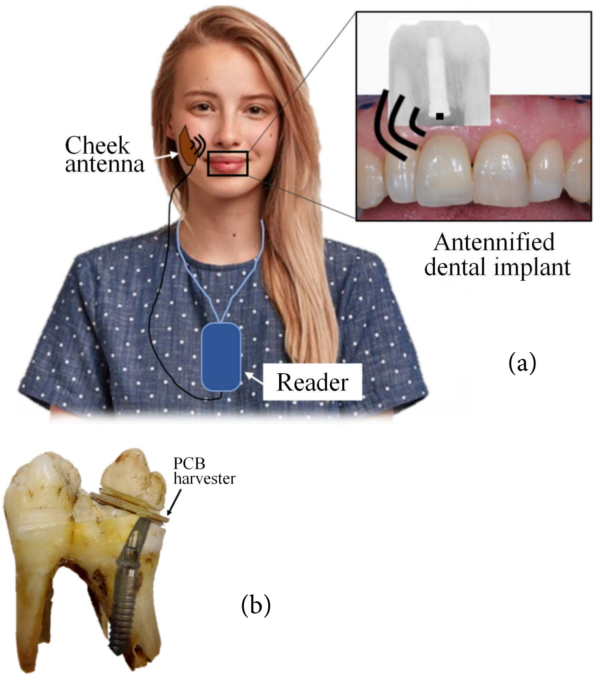

Fig. 9. Temperature monitoring of teeth using the RFID technique [35]: (a) – illustration of the concept, (b) – photograph of the prototype

Radio-frequency identification identification (RFID)-based inspection-

RFID is a new modality for internet-of-things (IoT) applications [33]. In conventional RFID, a tag collects radio frequency energy from an interrogator (*eg* , a reader antenna), activates a chip inside and transmits an ID code back to the interrogator. The ID code is a fixed number used as a unique identifier of a "thing". Tags can work over several frequency bands, such as low frequency (LF) (*eg* , 125-134 kHz), high frequency (HF) (*eg* , 13.56 MHz), ultra high frequency (UHF) (*eg* , 433, and 860-960 MHz) and super high frequency (SHF) within the microwave range (*eg* , 2.45 and 5.8 GHz), [34]. When chips with sensing capability are integrated into the tag, wireless and real-time monitoring of the teeth could be possible, and precision medicine can be enabled. For example, the metallic screw of an implant can work as an antenna for energy harvesting and an RFID chip can be placed inside a non-metallic crown. To avoid complete electromagnetic shielding, the chip should not be fully surrounded by metals. Panunzio *et al* [35] designed a prototype for temperature monitoring. As shown in Fig. 9, a microchip transponder and a tuning inductor were soldered on a 0.6 mm-thick PCB, and the PCB disk was positioned above a dental implant. The sensor worked in the UHF range. A preliminary study indicated a good backscattering link using an on-check antenna.

Heating - based microwave methods

In the methods mentioned above, the power of the microwave signal is generally low (milliwatts). Alternatively, microwave energy can be used for a short period of heating, so that heating-based NDT methods can be adopted. It should be noted that the power and time of the microwave energy should be carefully controlled to avoid any permanent damage. The guideline issued by the international commission on non-ionizing radiation protection (ICNIRP) [36] shall be followed. The reference level for occupational exposure to electromagnetic fields is 50 W/m^2 over 2-300 GHz, which is equivalent to an electric field strength of approximately 137 V/m in free space. The applicator can be a coaxial probe, waveguide or antenna. For example, the coaxial applicator has been widely used in microwave ablation, in which microwave energy is used to heat and destroy diseased biological cells and tissue (*eg* , liver tumours [37]). Here, the principles of two methods are presented as an example, *ie*, microwave thermography and microwave-induced thermoacoustics.

In microwave thermography, a thermal camera can be used to capture the irregularity of the temperature distribution caused by tooth diseases. Compared with the traditional thermal excitation methods, such as thermal lamps, laser and ultrasonic, microwave heating has several advantages, such as improved volumetric heating, better heating efficiency and precise on-off control of heating [38]. In microwave thermoacoustics, absorbed microwave energy causes thermal expansion, which can produce thermoacoustic signals. The frequency of this kind of thermoacoustic signal is commonly in the ultrasound range. By acquiring the time-resolved signals using an ultrasonic transducer, images can be generated. This technique has been applied for the diagnosis of breast cancer [39][41].

Advanced signal processing

Currently, with the presence of known defects, the changes in the signals can be observed in the raw magnitude or phase data. However, due to the complexity of electromagnetic fields outside the open-ended probe and within the sample, a rigorous description is not available. Hence, the inverse problem is ill-posed. For future work, artificial intelligence-assisted signal processing methods can be employed for better quantification (classification and feature extraction) and automated diagnosis.

Electromagnetic simulation

The existing research is primarily based on experiments. To better study the wave propagation inside the teeth and optimise the settings of the experimental set-up, electromagnetic simulation software (*eg* CST and COMSOL) can be applied. With the known permittivity data of all the regions in a tooth (*ie* , enamel, dentin and pulp), an accurate simulation model can be created. If the volume of each region is not readily available, the whole body with an effective permittivity value can be built instead. With additional information about the thermal properties of the tooth, multi-physics modelling can be conducted for heating-related microwave methods.

Another application can be the study of signal penetration in teeth. As seen in (2), d_p is inversely proportional to f. Hence, a lower frequency is desired for the detection of defects deeper inside the material. However, for permittivity measurement, a considerably large penetration depth may not be appropriate in the open-ended coaxial probe case, as other regions that are not the region of interest may be sensed as well. In this case, the data at higher frequencies are more reliable. Hence, how to choose a proper frequency range to focus the sensing region for detection or obtain the accurate permittivity data of the region of interest for measurement is a problem worth further investigation. This is one of the areas in that electromagnetic simulation can fit.

5 Concluding remarks

A state-of-the-art review of microwave non-destructive testing for human teeth during the last decade has been presented, covering the measurement of dielectric properties and examination of caries and cracks. The advantages and limitations of the methods have been discussed for the reader's benefit. Though great progress has been made, the potential for wider applications is yet to be fully exploited. More work on permittivity measurement, waveguide-based inspection, electromagnetic simulation, radio frequency identification and heating-based techniques could be considered in the near future.

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