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Research Article

Assessment of the Efficacy of Thermography for the Detection of Artificially Induced Fractures in Teeth- An *In Vitro* Study

Shimpi Manasi Rajendra* and Chaudhary Shweta

Department of Paediatric Dentistry, Bharati Vidyapeeth Dental College and Hospital, Pune, India

***Corresponding Author**: Shimpi Manasi Rajendra, Department of Paediatric Dentistry, Bharati Vidyapeeth Dental College and Hospital, Bharati Vidyapeeth Deemed to be University, Pune, Maharashtra, India.

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Abstract

Introduction: Most clinicians find it difficult to diagnose vertical teeth fractures due to the complicated and diverse symptoms that vary according to the position and extent of the fracture. Current methods such as radiography, transillumination, use of dyes, and operative microscopic examination have limitations, and the use of dental radiography or microtomography are controversial. Among the newer technologies, data on Thermal imaging can be considered as a viable option for detecting Vertical Fractures.

Aim: This study aims to assess the thermal changes associated with dehydration for the detection of artificially induced fractures in teeth using infrared imaging.

Materials and Method: 49 extracted teeth, of which artificial fractures were induced in 31 teeth and 18 intact (without any fracture) control teeth were used in the study, keeping them hydrated at all times. A FlukeTi400 infrared camera was used to capture a video of 60 seconds for each tooth, i.e. 10s to capture baseline temperature, 40s drying period where compressed air at 30psi was released onto the occlusal surfaces, producing a thermodynamic transient on the tooth surface, and a final 10s period for temperature stabilisation.

Results: The maximum drop in temperature from baseline was 1.32°F, 1.47°F, and 1.37°F for the incisor, premolar and molar control groups whereas, it was 4.8°F, 7.99°F, and 6.2°F for the fractured groups respectively. This comparison showed a p value of 0.015 for incisors and < 0.001 for the premolar and molar group.

Conclusion: Thermal Imaging can be a very promising method of diagnosis of tooth fractures due to its Non-invasive and Radiation-free Mechanism.

Keywords: *Infrared Thermography; Thermal Imaging; Vertical Fractures; Diagnosis; Cracked Tooth Syndrome*

Abbreviations

VRF: Vertical Root Fractures; IRT: Infrared Thermography; IR: Infrared; K: Kelvin; CT: Computed Tomography; CBCT: Cone Beam Computed Tomography; TI: Thermographic Imaging

Introduction

A root fracture poses considerable threat to the life of a tooth and it often necessitates extraction. One of the major reasons for extraction of endodontically treated teeth is the occurrence of vertical root fractures (VRF) [1].

The literature suggests that conventional diagnostic methods to detect dentoalveolar fractures exhibit low diagnostic efficacy. The inability of conventional imaging modalities to adequately visualize VRF indicates the need for the development and study of alternative diagnostic imaging systems that carry the potential of improving the detection of VRF [2].

For relatively non-displaced fractures, superimposition of overlying and adjacent anatomical structures and a beam direction that is not parallel to the fracture line impede the radiographic detection of VRF. Clinical and radiographic indicators of VRF are used to arrive at a diagnosis in most instances [3].

Frequently a combination of signs and symptoms may imply the presence of a vertical root fracture. A fracture can originate coronally, apically, or in any intermediate part of the root. The clinical and radiographic findings depend on the location and the extent of the fracture. The diagnosis of a root fracture usually results in eventual extraction. In cases involving multirooted teeth, hemi-section of the tooth may be done. Many causes of vertical root fractures have been reported. These include the wedging effect of endodontic posts (1), the expansion of posts from corrosion (2), and the use of excessive force during root canal filling procedures (3). Several authors have implicated the increased loss of dentin during root canal shaping and post preparation as possible causes (4). Others have suggested that dehydration of root structures following endodontic treatment may be responsible [4].

Vertical root fractures invite various irritating agents like bacteria and their metabolites, necrotic pulpal tissue, sealer components and food debris, which are forced into the fracture site during mastication. The source of bacteria into the fracture site may be due to communication from the gingival sulcus or from the canal itself. This results in periodontal breakdown and deep probing defects usually associated with the VRFs. Overtime, there is an ingrowth of granulation tissue into the fracture space which causes further widening of the fracture space leading to progressive ingress of bacteria and their metabolites and fluid [5].

The poor prognosis of the condition coupled with clinical and financial consequences for the patient necessitates early detection using clinical and/or radiographic means [3].

Conventional radiography is routinely used if VRF is suspected, but several reports have shown that periapical radiography is not accurate for ascertaining diagnoses of VRF. Needle Inspection, Periodontal probing, Fracture staining, Operative Microscopic examination, radiography and computed tomography scanning are the most commonly used diagnostic Tools. However, human eyes can only detect 2 points that are 200 μm apart, and the resolutions of micro-computed tomography scanning and radiography are about 80 μm. It is difficult to detect microcracks smaller than 80 μm with these methods [6].

Among the newer technologies, data on Thermal imaging shows promising results for it to be a viable option for detecting Vertical Fractures. Thermal Images are characterised by their spatial resolution i.e. the separation between two nearby spots, (the temperatures of which can be assessed distinctively) and by their thermal resolution i.e. the minimum temperature difference that can be measured at two distinct spots on an image [7].

Infrared thermography (IRT) is a science dedicated to the acquisition and processing of thermal information from non-contact measurement devices [8].

It is based on infrared radiation (below red), a form of electromagnetic radiation with longer wavelengths than those of visible light. Any object at a temperature above absolute zero (i.e., $T > 0$ K) emits infrared radiation [9].

The human eye cannot see this type of radiation. Thus, infrared measuring devices are required to acquire and process this information.

IRT has many advantages over other technologies [10]. In general, the main advantages of IRT are the following:

- IRT is a non-contact technology: the devices used are not in contact with the source of heat, i.e., they are non-contact thermometers. In this way, the temperature of extremely hot objects or dangerous products, such as acids, can be measured safely, keeping the user out of danger.
- IRT provides two-dimensional thermal images, which make a comparison between areas of the target possible.
- IRT is in real time, which enables not only high-speed scanning of stationary targets, but also acquisition from fast-moving targets and from fast-changing thermal patterns.
- IRT has none of the harmful radiation effects of technologies, such as X-ray imaging. Thus, it is suitable for prolonged and repeated use.
- IRT is a non-invasive technique. Thus, it does not intrude upon or affect the target in any way [11].

Infrared thermography is a simple, harmless, non-invasive and non-ionising technique. The method highlights abnormal temperature pattern measurements, and the images that are produced can be digitally stored and analysed to provide insight into the thermal pattern. The method has already been used in several medical fields, including following up haemangiomas, vascular malformations, rapid diagnosis of thrombosis in the extremities, inflammation, abscesses, wound infections and obesity control [12].

Thermography is a process by which temperature differences can be mapped in a two-dimensional image. The process detects electromagnetic radiation emitted by a body or liquids that are at a higher temperature and takes advantage of Stefan-Boltzmann's law, which states that the thermal radiation emitted by a body is proportional to the fourth power of the body's thermodynamic temperature. This makes thermography a powerful tool to detect even the smallest differences in temperature [13].

Characteristics of a thermal image

There are clinical applications which call for information about the distribution of temperature over a large area of the body's surface. This information is generally displayed as a thermal image which informs the clinician about the temperature of every spot over the area of interest at a certain instance in time. The characteristics include:

1. **Spatial resolution:** The distance between two spots which are close by, whose temperatures can be determined individually, and due to their thermal resolution. Thermal resolution is the least difference in temperature, which can be determined at two individual spots on the image.
2. **Temporal resolution:** The lag in time between a temperature difference at a definite spot on the observed area and the resultant change on the thermal image.
3. **Time responses:** In addition, like temperature measurement at a single location, different thermal imaging devices have their characteristic time responses, i.e. the time taken to obtain a reliable thermal image of a monitored area [14].

The principle of thermography is as follows: since any object which is higher than the absolute temperature -273K emits infrared rays in proportion due to vibrations and rotations of the atoms or molecules which constitute the object, it is possible to measure the temperature of the object by measuring the infrared output. Thermography is not invasive to the human body, as opposed to x-rays or gamma rays [15].

Thermal Imaging has proved to be a viable option for the detection of caries. In a study done by Zakian., *et al*. (2010), 25 human teeth were subjected to air drying for the detection of early carious lesions. The principle behind the use of Thermal Imaging is that the continuous evaporation of water accumulated inside the pores produces a thermodynamic transient on the tooth surface that will last until a new thermal equilibrium is reached when the tooth dries. The temporal profile of the temperature will depend on the amount of water stored inside the lesion as well as the shape of the lesion and can therefore contain information related to the degree of porosity and severity [7].

A similar principle could be employed to diagnose fractures present in tooth surfaces by the use of dehydration of the tooth surface to evaluate the change in temperature of the tooth surfaces.

This study aims to assess the thermal changes associated with dehydration for the detection and quantification of artificially induced fractures in teeth using infrared imaging.

Materials and Methods

The design of this study and the consent forms were reviewed and approved by the ethical committee of Bharati Vidyapeeth Dental College and Hospital, Pune, India. A written consent was obtained from the individuals whose teeth were indicated for extraction and who were willing to participate in the study.

Sample preparation

49 Freshly extracted Human Permanent Incisors, Premolars and Molars (Figure 1) were collected from patients reporting to Bharati Vidyapeeth Dental College and Hospital, Pune. Soft tissues were removed from the collected teeth and the teeth were thoroughly cleaned before placing them in a solution of distilled water and 0.5% thymol to keep them hydrated and free from bacteria. Of these, 6 intact permanent Incisors, 6 Premolars and 6 Molars (without any fracture) were used as the control groups.

Figure 1: *49 Freshly extracted human permanent teeth.*

Procedure

Figure 2 illustrates the Armamentarium used in the study. This includes a Fluke Ti400 Infrared Camera, an air jet compressor, a chisel and a mallet.

Figure 2: *Armamentarium used in the study.*

Fracture induction

A cuboidal hollow mould made of Stainless Steel was used in which Putty was placed till the brim. Each tooth was mounted within the mould upto the Cemento-Enamel Junction embedded within the putty. Access cavity preparations were made for each tooth and the root canals were prepared using K files to a final size of 40, .02 taper.

Following this, each tooth was removed from the putty mould, placed within a wax mould and using a tapered chisel and a mallet, artificial fractures were introduced within the root using gentle tapping (Figure 3). The tapered chisel was placed in the Palatal canals in case of the maxillary multi-rooted pre-molars and molars, the distal canal in case of mandibular molars, in order to artificially induce fractures. The teeth were then placed within the putty mould and back into Distilled Water.

Figure 3: *Method of induction of fractures.*

Method of obtaining images

An infrared (IR) camera Fluke Ti400 with an infrared spectral response range from 7.5 mm to 13mm and thermal sensitivity of ≤ 0.05°C at 30°C target temp (50 mK) was used for the purpose of this study. The camera is fitted with an in-built 5MP lens with a spatial resolution of 1.31 mRad (Figure 3). The samples were kept at room temperature 27°C (approximately 300 K) before taking the measurements. Each tooth within its mould, after removing it from distilled water, was attached to a platform. A graded template was attached to one side of the mould such that the occlusal surfaces of all the teeth mounted in the mould was kept constant and standardised at a fixed distance of 20cm from the lens of the camera (Figure 4).

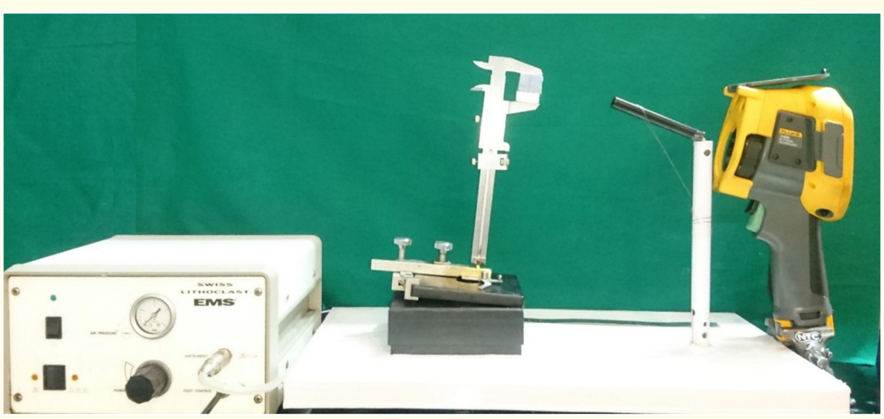

Figure 4: *Set-up of the apparatus.*

The air jet nozzle was positioned below the camera at a fixed distance of 15 cm from the occlusal surface of the tooth. Compressed air at a standardised pressure of 30psi was released onto the occlusal surfaces of the teeth to subject them to air drying. The thermal camera was used to measure the ambient temperature and the air-jet temperature coming from the nozzle. Changes in the gas temperature (e.g. due to expansion) were therefore accounted for. Every tooth was measured under the same humidity conditions; all measurements were taken within 2 hours.

The measurement of each tooth was made immediately after taking it from its bottle container where it was kept to remain hydrated. Each measurement consisted of capturing a video of 60 seconds. A drying period was included in this time. The recorded sequence to be organised was as follows: (a) initial 10s to capture reference temperature or baseline, (b) followed by a 40s drying period where the air compressor was switched on, and (c), a final 10s waiting period to allow temperature stabilisation and to record the final temperature.

The Fluke Smart View 4.3 software (Figure 5) was used to analyse the temperature of each tooth every 10s till the end of one minute, by marking the mid-point of the occlusal surface of the tooth. The readings of each tooth consisted of the analysing the temperature at the midpoint of the tooth at 0s, 10s, 20s, 30, 40s, 50s and 60s.

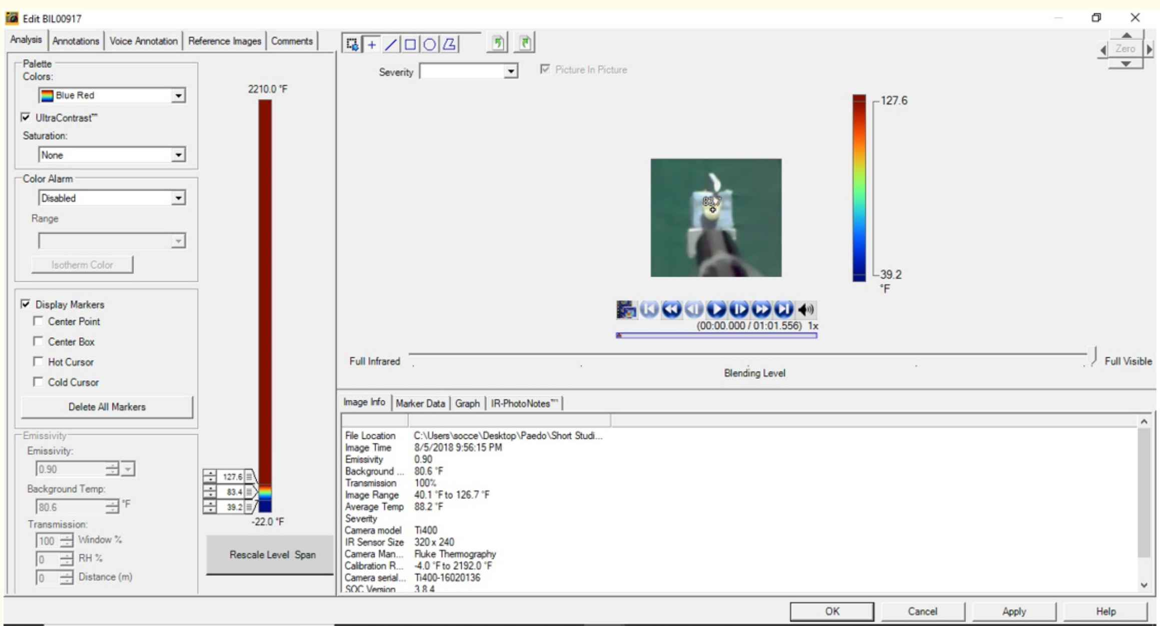

Figure 5: *Fluke smart view 4.3 software.*

Results and Discussion

Results

A comparison of temperature at different time intervals amongst cases and controls using unpaired t test showed that there was a steady fall, followed by a rise in temperature amongst the three groups- i.e. Incisors, Premolars and Molars. The fall in temperature seen in the cases with the presence of a vertical root fracture was much higher when compared to that of the controls in the incisor group (Figure 6), Premolar group (Figure 7) and the Molar Group (Figure 8).

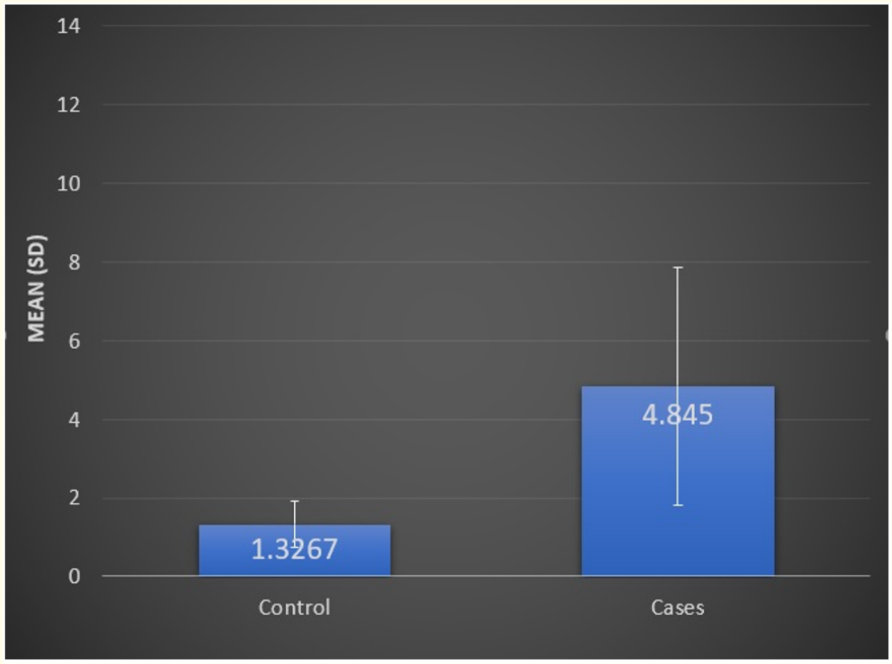

Figure 6: *Maximum drop from starting temperature for incisor group.*

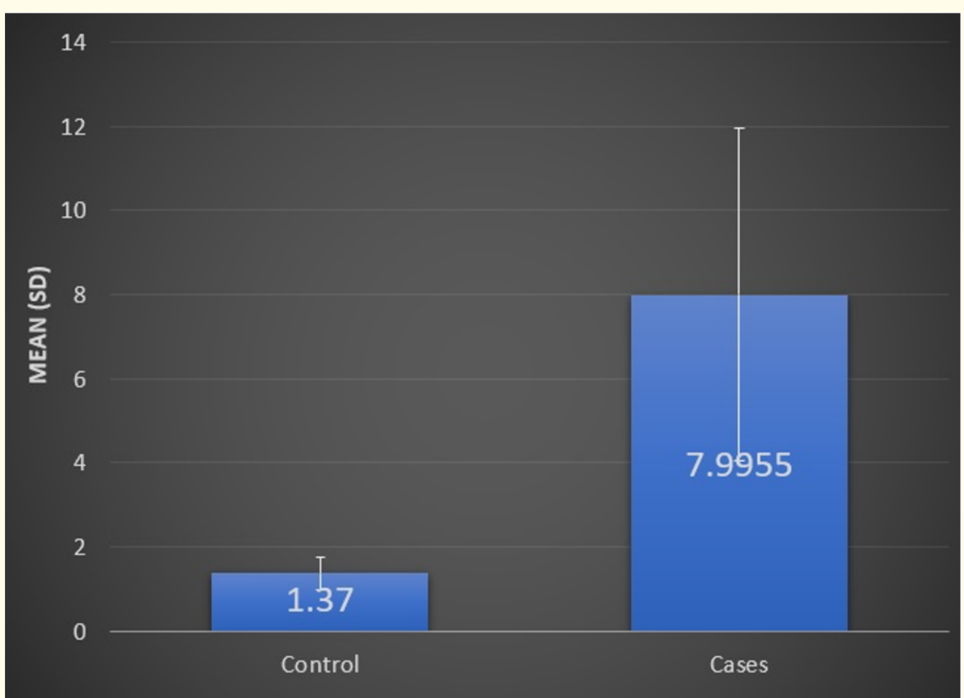

Figure 7: *Maximum drop from starting temperature for premolar group.*

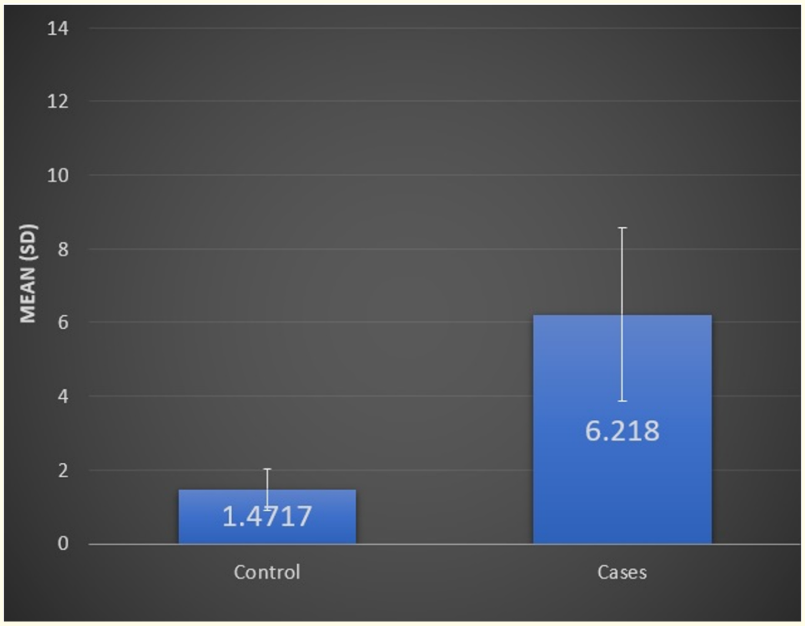

Figure 8: *Maximum drop from starting temperature for molar group.*

Table 1 shows the temperature changes seen in the incisor group, table 2 the premolar group and table 3, the Molar Group. It can be seen that a maximum drop in temperature is noted after 40s after the initial time, i.e. 30 seconds after the air- compressor has been switched on. This corresponds to the maximum drop in temperature from the temperature at baseline after a period of 40s after recording the baseline temperature. This corresponds to the time where almost all the water from within the entire tooth has evaporated leading to fall in temperature.

	Group	N	Mean	Std. Deviation	t value	P value
0s	Control	6	79.0750	1.72763	1.702	0.111
	Cases	10	81.7820	3.61854		
10s	Control	6	78.0683	1.87395	2.412	0.030*
	Cases	10	83.0710	4.81002		
20s	Control	6	78.2833	1.08964	1.817	0.091
	Cases	10	82.3300	5.31712		
30s	Control	6	78.0350	1.78845	2.167	0.048*
	Cases	10	81.8160	3.99796		
40s	Control	6	77.8267	1.86203	0.574	0.575
	Cases	10	78.9670	4.58882		
50s	Control	6	77.7633	2.03668	3.155	0.007*
	Cases	10	82.1700	3.01197		
60s	Control	6	79.1850	1.24019	4.710	< 0.001**
	Cases	10	84.6400	2.63981		

Table 1: *Comparison of temperature values in terms of {Mean (SD)} at different time intervals among cases and controls using unpaired t test for Incisor Group.*

$p < 0.05$ - Significant, $p < 0.001$ - Highly significant**.*

	Group	N	Mean	Std. Deviation	t value	P value
0s	Control	6	81.2033	1.86344	2.101	0.05*
	Cases	11	83.8727	2.76807		
10s	Control	6	81.3633	1.98935	1.820	0.089
	Cases	11	84.1509	3.41794		
20s	Control	6	80.7000	2.03085	0.505	0.621
	Cases	11	79.8145	3.97962		
30s	Control	6	80.0883	2.00762	0.719	0.483
	Cases	11	78.9936	3.39045		
40s	Control	6	79.9450	1.74033	1.429	0.174
	Cases	11	77.3127	4.27274		
50s	Control	6	80.6700	1.65012	0.634	0.535
	Cases	11	81.3636	2.36624		
60s	Control	6	81.3067	1.73391	1.980	0.066
	Cases	11	83.3255	2.13264		

Table 2: *Comparison of temperature values in terms of {Mean (SD)} at different time intervals among cases and controls using unpaired t test for Premolar Group.*

$p < 0.05$ - Significant; $p < 0.001$ - Highly significant**.*

	Group	N	Mean	Std. Deviation	t value	P value
0s	Control	6	81.5767	3.71000	2.014	0.064
	Cases	10	84.2740	1.67864		
10s	Control	6	81.2250	3.66925	1.574	0.138
	Cases	10	83.8280	2.90995		
20s	Control	6	80.7767	3.57232	0.495	0.629
	Cases	10	81.4790	2.16138		
30s	Control	6	80.5917	2.73343	1.083	0.297
	Cases	10	79.2110	2.30778		
40s	Control	6	80.4083	2.68769	0.988	0.340
	Cases	10	79.1820	2.22823		
50s	Control	6	81.0300	2.97500	1.236	0.237
	Cases	10	82.5000	1.82638		
60s	Control	6	81.2750	3.53808	2.142	0.05*
	Cases	10	84.4130	2.35920		

Table 3: *Comparison of temperature values in terms of {Mean (SD)} at different time intervals among cases and controls using unpaired t test for Molar Group*

$p < 0.05$ - Significant; $p < 0.001$ - Highly significant**.*

After this period, a steady rise in temperature has been noted in the samples until the tooth reaches a thermal equilibrium with the surrounding.

Table 4 shows the maximum drop in temperature from the baseline temperature. It can be seen that the premolars and molars show a highly significant drop in temperature as compared to the controls (p value < 0.001) while the incisor group also shows a significant drop in temperature with a p value 0.015.

	Group	N	Mean	Std. Deviation	t value	P value
Incisors Maximum Drop from starting temperature	Control	6	1.3267	0.59106	2.775	0.015*
	Cases	10	4.8450	3.03046		
Maximum Drop from starting temperature	Control	6	1.3700	0.38997	4.022	< 0.001**
	Cases	11	7.9955	3.96615		
Molars Maximum Drop from starting temperature	Control	6	1.4717	0.56880	4.776	< 0.001**
	Cases	10	6.2180	2.36255		

Table 4: *Maximum Drop from starting temperature in terms of {Mean (SD)} at different time intervals among cases and controls using unpaired t test.*
p < 0.05 - Significant; p < 0.001 - Highly significant**.*

Discussion

VRFs exhibit almost no or minimal symptoms in the early stages. With time, dull pain on mastication may develop as a result of the separation of the fractured root segments.

Clinical diagnosis of VRFs is difficult because the symptoms are variable or non-specific; the clinical and radiographic findings are related to the extent and location of the fracture [2-6]. Until today, the most common modalities for diagnosing VRF in routine clinical practice have been conventional and digital intraoral radiography. Sometimes, diagnosis of VRF is a complicated problem for the clinician. If the initial radiographic examination did not show a radiolucent fracture line to provide a definite diagnosis, the proceeding can be difficult and an incorrect diagnosis more likely [16].

Youssefzadeh., *et al.* (1999) were the first to use computed tomography (CT) to detect VRF. In their study, patients with clinically suspected VRFs underwent dental radiography and medical CT, and the results were compared with intraoperative findings. These authors reported that although both methods were highly specific (100%), they differed in sensitivity (23% for conventional radiography and 70% for spiral CT). However, the use of spiral CT is not recommended for the detection of VRF due to its high radiation dose, limited availability and high cost [17].

A clinical study by Bernardes., *et al.* compared CBCT and intraoral images for the detection of root fractures and used clinical symptoms as indicators for the true presence of fracture. The CBCT images were significantly more accurate than the periapical radiography images [18,19].

However, despite its advantages, CBCT technology also presents some limitations, such as high radiation doses when compared to plain-film radiography.

Infrared imaging offers a non-ionising, non-invasive technology to detect fractures in teeth. Infrared imaging was introduced into medicine in the second half of the 20th century. Early studies using contact thermography (infrared imaging) and scanning thermography produced results that suggested there were applications of the technology in areas as diverse as detection of breast cancer and malfunctions of the nervous system. However, the early instrumentation was not sensitive enough to detect the subtle changes in temperature needed to accurately detect and monitor disease. The further development of focal plane staring array infrared sensors has allowed very high quality imaging as well as the export of digital temperature measurements amiable to computer-assisted image analysis and algorithm development.

Two different approaches are employed in Infrared Thermography: passive and active [20].

In passive IRT, the radiation coming from the target object is measured without any external heat stimulation. This information can be used for temperature measurement. On the other hand, in active IRT, the specimen is subjected to external thermal stimulation [21,22].

The heat propagation depends on the material's thermal properties, but also on subsurface anomalies, which result in temperature differences on the surface target. In this case, the measured radiation comes from the thermal response of the target to the external excitation. This study employs the use of Active Infrared Thermography, where an air current is used to produce a thermodynamic transient on the tooth surface, which is then recorded by the Infrared Camera.

A similar study was carried out by Fanibunda [23] (1986) who suggested that it would be possible to relate pulpal blood supply to the rate of return of surface tooth temperature to normal after the application of a thermal change (either hot or cold).

As a cold stimulus, Fanibunda wetted the tooth with saliva and measured the temperature whilst the tooth was subsequently exposed by opening of the mouth. The latent heat of evaporation of surface moisture caused a drop in temperature. The temperature fell sharply and then slowly recovered to an equilibrium temperature. It was suggested that the time taken to reach equilibrium depended on the pulp blood supply [24].

An *in vivo* study done by Pogrel., *et al.* to check for temperature differences between vital and non-vital teeth, where isolated teeth were cooled with a stream of cold air with symmetrical cooling to about 22°C. After cessation of cooling with the stream of air, the teeth rewarmed to their former temperatures. It was here that the main difference was noted, in that vital teeth rewarmed within 5 seconds, whereas nonvital teeth took up to 15 seconds to rewarm [25].

Thermographic imaging (TI) has also been used to measure tooth surface temperature [26-28].

Crandell and Hill evaluated an incisor with a periapical abscess of the facial surface with the mouth closed. They assumed thermography would become very important in diagnostics, for example in the determination of teeth vitality, although their attempt at an open-mouth thermogram was not successful. They were one of the first to publish their findings of infrared thermography and its application in dentistry. Since then, there has been interest in the application of thermographic methods to the study of oral lesions [29].

Thermal images depend on number of functions, not least of which is the ambient environment, in which the evaluated temperature is the relative temperature. Thermal images are thus affected by the atmosphere around the subject. Since infrared radiation behaves according to the inverse square law, moving the object toward the thermovision camera increases the intensity beyond the subject. In this study, the distance from the camera to the subject was a constant 0.20m. Thermography depicts the relative temperatures of different areas.

The system used here can detect temperature differences as little as 0.08°C. In the dental field, periodontal diseases such as gingivitis, periodontitis can cause a temperature rise in the tissue around the gingiva. Thermography is a potentially useful addition to the diagnostic technique which may be used for screening patients for endodontic diseases in the intraoral region. Manabu., *et al.* have also reported that thermography can also be useful in testing for pulp vitality [15].

A study by Cummings., *et al.* (1999) used modern thermal imaging techniques to investigate the temperature rise induced at the pulpal well during thermal debonding of ceramic brackets using an electrothermal debonding unit. The average pulpal wall temperature increase for the teeth debonded at the end of a 3-second heating cycle was 16.8 degrees C, while at the end of a 6-second cooling cycle an average temperature increase of 45.6 degrees C was recorded [30].

The black body radiation theory states that every object above zero Kelvin will radiate infrared electromagnetic energy. which can be detected with an Infrared camera and temperature measurements can be performed. The thermodynamics of the drying process of porous media have been reported through models in the past.

The thermodynamic response to drying has been employed by for caries' detection in the past by Kaneko., *et al.* and Zakian., *et al.* Kaneko., *et al.* have reported a method to quantify the degree of mineral loss and lesion depth in flat surfaces of incisors with artificial lesions based on water evaporation from tooth surfaces. According to them, the area under the time-temperature curve was best correlated to the degree of porosity and therefore to mineral loss [31]. In the study by Zakian., *et al.* a drop in temperature was observed on air drying the occlusal surfaces of naturally demineralised teeth [7].

Tooth temperature will be influenced by a number of factors such as ambient and body temperature, breath and moisture. The amount of water stored inside the tooth will depend on the extent of the fracture within the tooth; it is therefore expected to find a temperature drop proportional to the severity of the fracture when air-drying the tooth.

The use of Infrared Cameras to detect Vertical Root Fractures has not been used in the past. This study employs the use of Thermal Imaging for detection of Vertical Root Fractures by using the same principal as was employed by Zakian., *et al* [7]. In our study, the severity of the fracture determines the amount of water within it, and thermodynamic changes are expected at these sites. Teeth with extensive fractures will have a larger amount of water within the fracture line and this water would experience difficulties in coming out to the surface on air drying, resulting in an extended evaporation time.

The thermodynamic changes in the teeth without fractures is expected to be lesser as those compared to the teeth with fractures due to the presence of additional crack lines in the teeth apart from the Root canals.

This was illustrated in our study, where it was seen that the mean drop in temperature from the temperature at baseline was 1.326 ± 0.59106 for the controls and 4.8450 ± 3.03046 for the cases in the incisor group, 1.3700 ± 0.38997 for the controls and 7.9955 ± 3.96615 for the cases in the premolar group and 1.4717 ± 0.56880 for the controls and 6.2180 ± 2.36255 for the cases in the molar group (Table 4). This shows that there is a significant change that occurs on air- drying a fractured tooth as compared to air drying a sound tooth with an access cavity.

A number of factors require some consideration in these measurements such as the initial room and tooth temperature as well as the air-jet temperature. Teeth were left for a period of 24 hours to equate to the room temperature and the air compressor used was also stored at room temperature. It was observed that high pressures would dry the tooth too quickly complicating the ability to discriminate between sound teeth and fractured teeth. Note that the difference in water content in a sound tooth with an access cavity and a fractured tooth might be small enough to cause false negatives. This is also partially overcome by the gentle removal of water excess on the surface before taking the measurements

Although in this study, the measurements were taken at room temperature, the results presented would still be valid for measurements taken at body temperature since they only rely on the temperature change, therefore only the relative tooth and air-jet temperatures are of importance.

Conclusion

Our investigations demonstrate that thermal imaging has the ability to detect vertical fractures in teeth. This could potentially be useful for *in vitro* measurements where other methods such as radiography may fail to detect a fracture due to superimposition of the tooth surfaces. However, the viability of taking *in vivo* measurements still requires further studies to assess the effect of intra oral environment conditions in the measurements such as humidity variations due to respiration, ambient and oral cavity temperatures and the presence and viscosity of saliva. Studies have been done *in vivo*, by keeping the teeth to be analysed isolated using a thick rubber dam sheet.

The author recommends that future studies may be made more accurate under the following circumstances:

- Carrying out the readings in an air conditioned room with a pre-set stabilised temperature
- Humidity conditions within the room should be measured and stabilised
- An isolated working area which includes isolation of the tooth to be examined using a thick rubber dam sheet for a minimum time period of 20 min to allow the temperature of the tooth to stabilise and not be under the influence of the temperature and humidity conditions associated with the oral cavity.
- Minimum personnel within the room
- Standarised air pressure and a stabilised temperature of the air though the air jet.

This technique is currently limited to visible surfaces; however further research is required to evaluate detection of inter-proximal surfaces and fractures below the presence of restorations or fissure sealants.

Conflict of Interest

The authors do not have any financial interest or any conflict of interest.

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