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Abstract. Since 1960 the technological evolution in dentistry have contributed to a greater demand for dental care. The success of dental implantology depends from several factors, one of which is the health of the gingiva microcirculation status. Due to the dental implant location, direct monitoring of the health of the gingiva is a complex task requiring specialized tools. In this paper we report an overview of the state of the art of implant health monitoring techniques and present our work on development of novel device for non-invasive direct gingiva health monitoring. Our technology is based on the pulse oximetry principle and allowing assessment into the microcirculation level of gums. This work is being supported by cooperation with the specialists as an advanced innovative device for routine clinical purposes.

Keywords: pulse oximeter, dental implant, gingiva perfusion, microcirculation.

1 Introduction

Dental problems like cavities, gingiva diseases and periodontitis are prevalent and almost every person experiences it throughout life. In dentistry, diagnosis may be defined as the process of combining data obtained from several different sources to try to identify dental related deviations from normal, such as: patient history, observation, examination and exploratory testing [1]. The tooth is composed by several parts: enamel is the hardest tissue of the tooth, cementum also is a hard substance that covers the tooth roots, dentin is a softer tissue and then the pulp is the heart of the tooth full of blood vessels and nerves, is responsible to maintain the tooth alive, by receiving the nutrients through the complex network of micro vessels. The oral dental tissues are well vascularized and well innervated. The high vascularity explains the profuse bleeding that occurs with wounds/trauma to the mouth but also in part the remarkable potential for healing. The main arteries to the teeth and jaws are derived from the maxillary artery, a terminal branch of the external carotid. The alveolar arteries follow essentially the same course as the alveolar nerves. The blood supply for the mandibular teeth comes from the inferior alveolar artery, the buccal gingiva is supplied by buccal artery, labial gingiva is supplied by mental artery and same branches of incisive artery, also the lingual gingiva is supplied by inferior alveolar artery and by lingual artery. The maxillary teeth and periodontium the blood supply is through the posterior superior alveolar artery that is a derived from buccal artery, that also gives branches to adjacent buccal gingiva, maxillary sinus and cheek. The palatal gingiva around the maxillary teeth is supplied primarily by branches of the greater palatine artery [2]. The pulp receives its blood supply through thin-walled arterioles entering through the apical and accessory foramina. These arterioles run longitudinally through the center of the pulp, branching out to its periphery where they form a capillary network in the sub odontoblastic area. These capillaries do not enter the dentin; they drain into the venules that run alongside the arterioles and pass out through the same apical foramen [3], [4]. For diagnosis of the dental pulp health status is should be use the results of several different tests and not the outcome of any specific one. The testing of the tooth vitality is an important marker for the diagnosis of pulp disease, if the result of these tests leads to the conclusion that the pulp is severely compromised endodontic treatment, or extraction may be necessary [5]. Ideally, any test should provide a simple, standardized, non-invasive, painless, reproducible, accurate and inexpensive way of testing [6]. The determination of the pulp's condition is determined by the vascular supply health and not the sensory fibers. Pulp sensibility tests are subjective and thus dependent on subjective factors such as the sensibility of both patient and dentist. As most of these methods are invasive (i.e. direct stimulation of the tooth), discomfort or pain for the patient might be possible. Therefore, work has been done in developing noninvasive methods that can provide measurements for dental pulp blood flow, such as spectrophotometry, laser doppler flowmetry and determination of the oxygen saturation (SpO_2) [1].One of the most accurate method is laser doppler flowmetry but comparing to pulse oximetry, despite of its high accuracy, it has a higher cost and is also sensitive to radiation angle [6], [7], [8]. The modern endodontics is becoming influenced by novel biological, genetic and metabolic approaches toward new strategies for regeneration of dental pulp were the knowledge of perfusion status of tissue is very important. Keeping this in mind, the technology of pulse oximetry can be adapted for the objective evaluation of the progress of regeneration, which could be a leap into the future of endodontics [9], [10]. The potential of pulse oximetry as a tool in accessing the dental pulp condition comes from fact that is noninvasive method which evaluates a significative marker of the pulp's condition. This paper describes a prototype based on low cost, simple and accurate PPG technology as a potential device for assessment of gingiva microcirculation around the dental implant as well as teeth pulp. For this prototype we have modified the pulse oximeter technology to be used in dentistry according to the specific position of the mouth and the location of the teeth. It should be noted that, despite ongoing research in this field, there is not any similar device in the market yet.

2 Contribution to Life Improvement

Periodontitis is the most common oral disease worldwide, with an age-standardized prevalence of 11.2%. It is a multifactorial disease, with risk factors such as diabetes mellitus (DM), smoking and, most commonly, inadequate oral hygiene (OH). The accumulation of dental plaque and calculus is usually caused by improper toothbrushing techniques, failure to carry out interdental cleaning and irregular dental visits. This accumulation predictably results in gingival inflammation. Persistent gingivitis is a key risk predictor for the breakdown of periodontal attachment. The device under development in this project can be used for both natural teeth and dental implants, since it can measure small amount of blood flow in natural dental pulp or microcirculation of gingiva around the dental implant. The most complicated problem with implants is peri-implant pathology that is defined as “the term for inflammatory reactions with loss of supporting bone tissue surrounding the implant in function”. This, after osseointegration, represents the leading cause of late dental implant failure. Risk factors associated with this pathology can come from different sources namely, the patient's health condition, the morphology of the implant placement location, the implant itself, the restoration procedure, clinical parameters, and patient compliance with good oral care [11]. Currently clinical investigation of dental condition as well as dental implant status normally is by indirect methods like thermal (heat or cold) and electric stimuli testing and radiographic is the most commons. Usually the result of these tests has been considering determining the actual status of natural of implantable dental [12]. However, these tests can have false-negative or false positive results and is not usable for traumatic dental which lose their sensitivity temporary or permanently. According to importance of dental implants in human health improving, optimal maintenance and post-installation care will be important due to the high installation cost and long healing time process. Necessity of devices that can monitor dental implant status in gingiva seems to be essential, one of the best ways should be developing existing approaches to address the specific conditions that this project is intended to address. Pulse Oximeter as a simple, low-cost, non-invasive, non-radioactive and accurate device can be a good choice for dentists on periodic visits or in case happening problem for the patient with implant to test the implant in the gum with a simple and painless test. This technique has the potential to become a device for routine dentistry practice to help life improve living by reducing periodontal disease.

3 State of the Art

Pulse oximetry is based in measuring oxygen saturation (SaO_2) in the blood (i.e. measuring the amount of oxygen diluted in the blood). Typically, this is achieved by the combination of two light-emitting diodes (LED) working at different wavelengths, one of the LED works in the visible red spectrum, close to the 660nm the other is set for the infrared (IR) spectrum, close to 940 nm. The tissue-reflected light form those LED is captured by a photodiode and its response is then used to calculate SaO_2 levels. In the arterial blood oxygenated hemoglobin (oxyhemoglobin, HbO_2) is found; its analogous, deoxygenated hemoglobin (Hb), circulates in the venous blood, both absorb different amounts of red and infrared light, with HbO_2 absorbing more infrared light than Hb [1], [13]. Figure 1 shows the spectral response of HbO_2, Hb and the skin-tissue model that is commonly used for pulse oximetry. The continuous component (DC), of the photodiode response represents the light absorbed by the tissue, the non-pulsatile arterial blood and the venous blood quantities. The variable component (AC) represents the pulsatile arterial blood component. The ratio of absorption at the two wavelengths is used as a basis for pulse oximetry and can be calculate by equations (1) or (2).

$$R_{abs} = \frac{AC_{\lambda_1}/DC_{\lambda_1}}{AC_{\lambda_2}/DC_{\lambda_2}} \quad (1)$$

$$R_{abs} = \frac{\log_{10}\left(I_{AC_{\lambda_1}}\right)}{\log_{10}\left(I_{AC_{\lambda_2}}\right)} \quad (2)$$

If using equation (1) the SpO_2 rate is calculated trough the utilization of a stored conversion table with empirical formulas based on healthy patients' measurements, so it can vary with the implementation. As a reference, a ratio of R_{abs}= 0.5 would correspond to a SpO_2 of 100%; R_{abs}= 1 would correspond to SpO_2 of 82% and R_{abs}= 2.5 would correspond to a SpO_2 of 0%. Equation (2) uses only the AC component for SpO_2 calculations, here I_{AC} is the intensity of the light measured at 660 nm and 940 nm, 1 and 2 respectively.

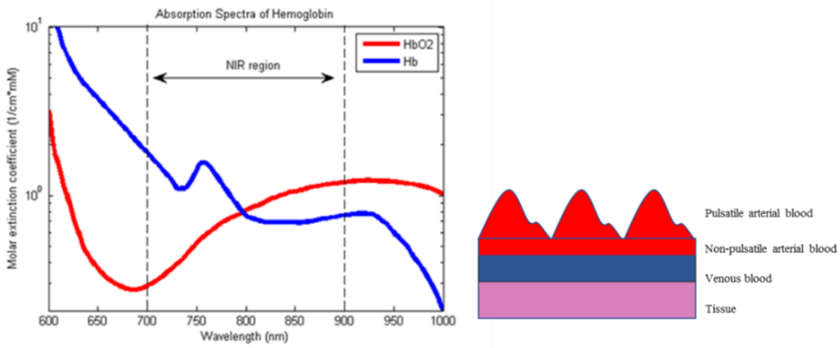

Fig. 1. The rate of absorption of HbO2 and Hb at different wavelengths, (CCBYSA 3.0), (right), skin tissue model for signal considerations, (not to scale) .

The potential of pulse oximetry as a complementary resource tool for utilization in the evaluation of dental pulp condition has been the subject of research for some time. In normal conditions, a healthy dental pulp will have a measurably high percentage of oxygen in its contents, as the dental pulp progress from a healthy condition to an inflammatory condition the oxygen levels start to decrease, note that this decrease in oxygen levels has not been verified in all inflammatory conditions. Several studies have tackled the issue of determining the reference oxygen saturation levels for healthy dental pulps in different clinical scenarios. From those studies it was obtained that: for maxillary central incisors the oxygen saturation varied from 79.31% to 94%; for maxillary lateral incisors 78.51% to 87.47%; canine 79.85% to 91%; premolars 86.2%. Also, premolars and molars were evaluated as a single group whose mean oxygen saturation values was recorded as 92.2% [1].

The utilization of pulse oximetry as a noninvasive tool for human health monitoring is a relatively recent advance. The technology is basing its working principles in the modification of Beer's law and the reflectance, (absorption), response of hemoglobin when exposed light. In pulse oximeter, Red and IR wavelengths are used to trans-illuminate a tissue bed, the reflected portion of the signal is detected and processed. The processed signal is used to calculate pulse rate and oxygen saturation, as it varies with used wavelength and the characteristics of pulsatile blood circulation. Due to these characteristics, (detection of pulsatile blood absorbance), the technology appears to be suited for the detection of pulpal blood circulation, provided that is, that a sensor/ sensor head that can be used in the tooth structure can be engineered [14], [15].

4 Research Contribution and Innovation

Pulse oximetry is an application of Photoplethysmography (PPG), an optical noninvasive measurement technique used for the assessment and measuring blood volume changes in the microvascular bed in tissues [16]. This technology is based on emitting light to tissues through LED and measure small variations in light intensity associated with changes in blood volume. As referred in the previous chapter, the photodiode response signal is composed of an AC and DC component, this for the RED and IR wavelengths. Note that, the signals are not simultaneous, the LEDs are switched at convenient frequency as to allow for the correct photodiode response. The DC component of PPG changes with volume of the non-pulsatile arterial and venous blood, the depth of the vessels and the general constitution of the skin and muscle tissue; also, its noteworthy to referee that due to normal motion brought by respiration the DC signal is not constant but has slight variations over time. The AC is the variable component and varies with the heart rate. PPG relies on two working modes: transmission and reflectance. In the transmission mode the LEDs are placed in opposite side to the photodiode, so the signal output being proportional to the part of the light that crosses the tissue. In the reflectance mode the photodiode response is proportional to the part of the light the is backscattered by the tissue with blood vessels. Figure 2 presents the differences with both, the transmission and reflectance techniques, where it uses on gum with dent or with an implant is exemplified. As tissue/bone diameter increases, or more dense materials are used (as prosthetics) this technique becomes more difficult to use. So, reflectance mode of operation becomes more adequate.

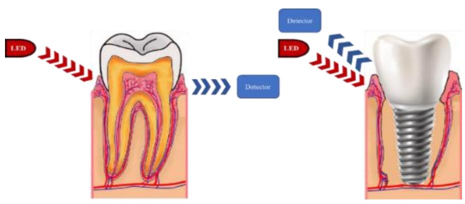

Fig. 2. Pulse Oximetry work modes across the dental tissue and tooth, transmission and mode reflectance modes, (right and left, resp.). Implant model used as a reference.

The utilization of reflectance mode pulse oximetry in the mouth cavity has advantages but also some drawbacks. As both, the LEDs and the photodiode can be packed close together, this configuration allows for a compact system, so the probe is easier to use in the dental environment, additionally one of the sources of interference with PPG signals, the ambient light is also diminished as the mouth skin attenuates some wavelengths of the ambient light that reaches the sensor. A drawback of this mode of operation comes from fact that, as the probe is typically difficult to stabilize for any

significant amount of time in any location in the mouth cavity, the reflected signal can be affected by motion artifacts, so additional signal processing may be necessary to try and reduce these effects. Motion artifacts are mainly characterized by low-frequency random noise, induced by slight movements and probe pressure changes [17]. Their reduction can be done at firmware or software level by using filtering techniques; complementary to the filters, at controller level the utilization of accelerometer transducer coupled to the probes head, in the vicinity of the photodiode, can provide multi-axis signals which can be used to compensate for the motions. At this stage in the prototype development those have been considered but have not been implemented.
The prototype under development is composed of 3 main components, as shown in figure 3. A front detachable probe housing, where the LEDs, photodiode and signal condition circuit are placed; a middle connecting arm with a degree of flexibility for maneuvering the probe on the mouth cavity; and a final rear part where power signal acquisition, control and communications with the central software is located. The system is being built as an open architecture concept, thus allowing for modification on the probe's head sensors, or other hardware changes to be incorporated with minimal system redesign. Currently, the probe head sensor unit consists of red and infrared light sources and a photodiode which are mounted side by side, figure 3. The photodiode outputs the signal from the reflected Red/IR light from the gingiva during the cardiac cycle.

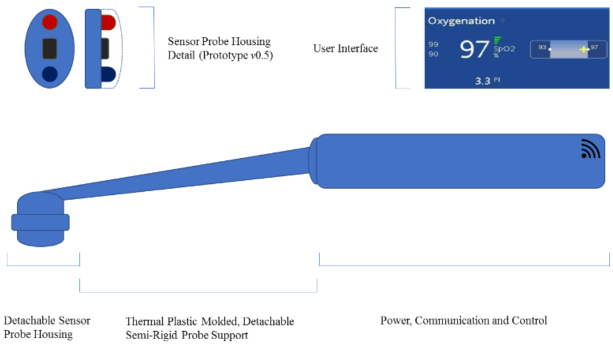

Fig. 3. Conceptual design of the probe prototype under development and the user interface.

The assessment of a healthy gingiva oxygen saturation is done in levels ranging between 90% to 99%. For test proposes a small user interface was used, this presents the measured oxygenation levels, top right corner of figure 3. Currently there are no international or other, established guidelines of median oxygen saturation levels that can be used to access whether a gingiva or dental pulp can be considered healthy, inflamed, or necrotic. This lack of standard indicates that further research in this area needed. The current prototype head is still quite cumbersome, so, miniaturization and ergonomics studies with dentists are being envisaged to be performed concurrently. Initial tests have shown acceptable signal quality for this stage of development, although it can already be foreseen that daily use of the system will require additional signal processing, even more if the PPG waveform is to be added to the interface. For user interface, the display unit will be expanded to include a PPG pulse-wave signal to complement the numerical information currently being shown, oxygen saturation (SpO2).

5 Discussion and Future Work

Preliminary results of the prototype head probe were satisfactory, showing a good potential to playing as an alternative device for daily routine procedures in dental clinics. One of the biggest problems in using the prototype other than the effective factors which cause deoxygenating of hemoglobin and changes in the blood oxygen saturation, should be movements of the probe which can complicate readings. For this it will be needed the utilization to some type of signal processing. According with the current development options for the prototypes' hardware, Fourier Analysis can be discarded as the signals are not truly periodic, so additional manipulation would be required to adapt the signals to allow for a cycle-by-cycle analysis, for quasi-periodic signals in PPG, as proposed in [18], this option would also require the adoption of advanced 16 or 32 bit microcontrollers with Digital Signal Processing capabilities (DSP), thus increasing the parts costs of the device. Moving Average Filter (MAV), have been used previously in PPG signals and with interesting results [19]. A third option being considered for the attenuation of motion artifacts on the signal is a Passive Motion Cancelation algorithm (PMC), where the motion interference on the photodiode is obtained by sampling its signal when both the Red and IR LEDs are disconnected, from here the step frequency of the motion artifacts is obtained. Later when the LEDs are connected the resulting signals are processed with a filter that extracts the frequencies corresponding to the motion artifacts, typical < 0.3 Hz [20]. Any of the later 2 after-mentioned filters can be implemented at hardware/firmware level with similar degree of complexity. The propose model for the probe has the layout of an electric toothbrush, (figure 3), a shape select as its ergonomics are extensively tested by years of user's experience, their general dimensions can accommodate the new, in development models for the probe's head sensor and the motor/battery pack enclosure can provided enough space for the prototypes' electronics and power supply. Additionally, the materials that compose the shell of the probe are already approved for human utilization, so allergic skin contact reactions should be minimal. The next development steps will firstly go in testing the new head probe in a skeleton toothbrush shell, after the successful completion of those, the electronics will be adapted for custom printed circuit board (PCB), design to the specifications of the toothbrush shell. This PCB will accommodate the necessary IC's for signal acquisition and control, the power unit and a low-power wireless communication transceiver. According to a good acceptance of dental implants over the past few decades and the growing trend for their utilization worldwide, it is necessary to promote a simple, cost effective and non-invasive device that can help the dentists in the diagnosis, optimization and extending the life of the dental implants, which in turn will play an important role in global health improvement, decreasing costs of dental repairs due to late detection of problems. This project by using current techniques and technologies for developing a new, cost effective device to meet the specific limitations of the mouth cavity will contribute to this life improvement.

Acknowledgments. The authors would like to thank the Fundação para a Ciência e Tecnologia (FCT, Portugal) and NMT, S.A. for co-financing the PhD grant (PD/BDE/130083/2017) of the Doctoral NOVA I4H Program.

References

1. C. Estrela, K. S. Oliveira, A. H. G. Alencar, F. B. Barletta, C. R. Estrela, and W. T. Felippe, “Oxygen Saturation in the Dental Pulp of Maxillary and Mandibular Molars - Part 2,” Braz. Dent. J., vol. 28, no. 6, pp. 704–709, 2017.
2. Berkovitz B.K.B., Holland G.R., M. B. J.: Oral Anatomy, Histology & Embryology (Fifth edit). ELSEVIER Ltd, (2018).
3. V. Gopikrishna, G. Pradeep, and N. Venkateshbabu, “Assessment of pulp vitality: A review,” Int. J. Paediatr. Dent., vol. 19, no. 1, pp. 3–15, 2009.
4. S. Kakino, S. Kushibiki, A. Yamada, Z. Miwa, Y. Takagi, and Y. Matsuura, “Optical Measurement of Blood Oxygen Saturation of Dental Pulp,” vol. 2013, 2013.
5. L. Commander, D. M. Kenee, C. S. B. Mcclanahan, and C. J. D. Johnson, “Clinical Update,” vol. 22, no. 8, pp. 17–18, 2000.
6. A. S. Review, “Methods of Diagnosis and Treatment in Endodontics,” Order A J. Theory Ordered Sets Its Appl., vol. 2012, no. June, 2012.
7. M. T. Workshop, “Advantages and limitations of laser Doppler flow meters.”
8. * Miguel de Araujo Nobre, Antonio Mano Azul, Evangelista Rocha, Paulo Malo, Risk factors of peri-implant pathology , Eur J Oral Sci, Eur J Oral Sci. 123(3):131-9, 2015
9. A. Abd-elmeguid, D. C. Yu, and C. FRCD, “Dental Pulp Neurophysiology” vol. 75, no. C, pp. 139–143, 2009.
10. S. D. Dutta and R. Maria, “Pulse Oximetry: A New Tool in Pulpal Vitality Testing,” People’s J. Sci. Res., vol. 6, no. 1, pp. 2011–2014, 2013.
11. S. Radhakrishnan, K. Munshi, and A. M. Hegde, “Pulse oximetry: a diagnostic instrument in pulpal vitality testing.,” J. Clin. Pediatr. Dent., vol. 26, no. 2, pp. 141–145, 2002.
12. R. Nivesh Krishna and S. Pradeep, “Recent diagnostic aids in endodontics - A review,” Int. J. Pharm. Clin. Res., vol. 8, no. 8, pp. 1159–1162, 2016.
13. K. P. Shetty, S. V. Satish, K. Kilaru, K. Chakravarthi Ponangi, A. M. Luke, and S. Neshangi, “An in vivo evaluation of the change in the pulpal oxygen saturation after administration of preoperative anxiolytics and local anesthesia,” J. Dent. Res. Dent. Clin. Dent. Prospects, vol. 10, no. 1, pp. 31–35, 2016.
14. A. Abd-Elmeguid and D. C. Yu, “Dental pulp neurophysiology: part 1. Clinical and diagnostic implications.,” J. Can. Dent. Assoc., vol. 75, no. 1, pp. 55–59, 2009.
15. A. B. Novaes, S. L. S. De Souza, M. Taba, M. F. D. M. Grisi, L. C. Suzigan, and R. S. Tunes, “Control of gingival inflammation in a teenager population using ultrasonic prophylaxis,” Braz. Dent. J., vol. 15, no. 1, pp. 41–45, 2004.
16. S. Kakino, Y. Takagi, and S. Takatani, “Absolute transmitted light plethysmography for assessment of dental pulp vitality through quantification of pulp chamber hematocrit by a three-layer model.,” J. Biomed. Opt., vol. 13, no. 5, p. 054023, 2011.
17. B. MATTHEWWS & N. VONHSAAN, “Advantages and Limitation of Laser Doppler flow meters.,” Department of Physiology, School of Medical Sciences, University of Bristol, Bristol, UK.
18. Reddy, K. A.; George, B.; Kumar, V. J. Use of Fourier series analyses for motion artifact reduction and data compression of photoplesmiographic signals. *IEE Trans. Instrum. Meas*. 2009, 58, 1706-1711.
19. Lee, J.; Jung, W.; Kang, I.T.; Kim, Y.; Lee, G. Design of filter to reject motion artifact of pulse oximetry. *Comp. Stand. Interfaces* 2004, 26, 241-249.
20. Wang, L.; Lo, B.; Yang, G. Z. Multichannel reflective PPG earpiece sensor with passive motion cancellation. *IEE Trans. Biomed. Circuits Syst*. 2007, I, 235-241.