PPG signal acquisition and analysis on *in vitro* tooth model for dental pulp vitality assessment

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Investigations into different methods of low-noise signal detection in photoplethysmography (PPG) intended for pulp vitality assessment have shown that the resulting signals must be amplified and filtered prior to digital signal processing. The purpose of this research is the development of a portable *in vitro* device with integrated computer for the recording, investigation and historical comparison of PPG signals. An accompanying digital filter program, capable of being operated by non-technical personnel has been developed using LabVIEW-software. The complete measurement system has been tested on an existing dental model.

The new low-noise measurement system utilizing an OPT101 sensor yields signal amplitudes up to 35 times higher than that of previous measurement systems. Furthermore, the versatility of the software allows changes and customization to appropriate applications.

***Index Terms*— PPG, pulp vitality, signal processing, tooth vitality**

I. Introduction

Knowledge concerning pulp vitality is very important in choosing the correct treatment for traumatized teeth. Traditional methods (sensibility response) are painful, subjective and generally unreliable. Recently, more specific methods of pulp vitality assessment such as pulse oximetry, laser Doppler flowmetry (LDF) and photoplethysmography (PPG) have been proposed [1]-[11]. These methods are based on the optical detection of pulpal circulation, which serves as evidence for pulp vitality. However, hitherto no clinical instruments based on this technique have been available.

A. Basics

The vitality of a human tooth can be determined according to pulpal blood flow (FIG. 1). The detection of pulpal blood circulation is difficult because the tooth crown is not totally transparent. Nevertheless, investigations of the optical characteristics of extracted human teeth [13]-[14] show that dentine has a high transmission factor at certain light wavelengths. Hirmer et. al [13] discovered recently that the spectral range between $\lambda = 0.65$ and $1.4\ \mu m$ represents a "transmission window" suitable for the detection of pulp vitality in teeth. Blood cells (erythrocyte) absorb light and the heart frequency pulse modulates light transmission. Consequently, when a light source placed at one side of the tooth and a photodiode at the other, a pulse signal can be acquired. This photoplethysmographic signal consists of two parts (FIG. 2). A large DC (direct current) signal, which represents constant transmission (e.g. through tissue, bone etc.) and a low level AC (alternating current) signal modulated by the heart frequency. For evaluation of the AC signal it must be separated from the DC part and subsequently amplified [15].

Pulse oximetry functions in similar way to PPG, but measurement is done at two different wavelengths: one with a high absorption factor for oxy-hemoglobin (HbO_2) and the other for deoxyhemoglobin (Hb). The oxygen saturation is calculated from the difference of the absorbed signals based on the Beer-Lambert law. The oxygen saturation is an indication of (in this case pulp) vitality.

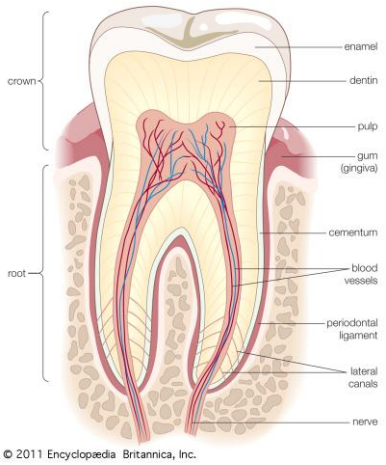

FIG. 1: Tooth: cross section of an adult human molar [12]

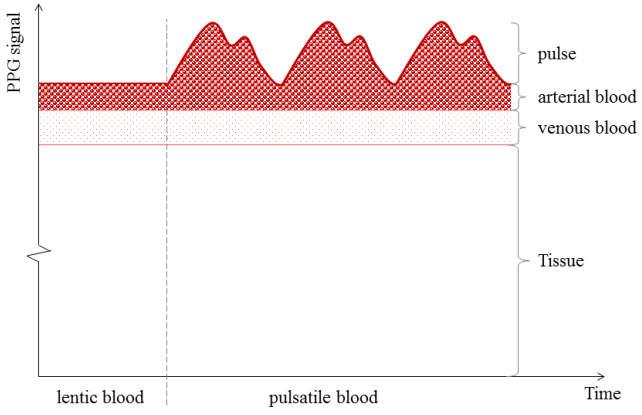

FIG. 2: PPG signal of lentic and pulsatile blood

B. Previous research

Much work has already been carried out in the field of pulp vitality assessment using pulse oximetry [16]-[19]. Some researchers have used commercially available, and some self-made, pulse oximeters. Tested on an *in vitro* tooth models or *in vivo* on incisors, successful determination of pulp vitality has been achieved. However, in both cases blood circulation within the gingiva (gum) was not taken into account. Gingiva is also supplied with blood and the quantity predominates in comparison to pulpal blood circulation. Consequently, it is a moot point whether the measured *in vivo* signals are actually from tooth or potentially from gingiva. As a result, it is essential to also investigate the influence of gingiva circulation on the pulp signal.

C. Goal of the study

Because of the optically diffuse dental constitution, the transmitted PPG signals are very small and prone to noise. Consequently, any signal processing system must possess a large SNR (signal-to-noise ratio).

The goal of this study was to create a PPG instrument specially designed for pulp blood flow measurements and having advantages over the general purpose systems hitherto used. Here, data from an *in vitro* tooth-gum model measured with two different systems are presented. One uses existing analogue signal processing from previous investigations [20] and the other employs more elaborate analogue-digital signal processing using LabVIEW software for filtering and evaluation of the PPG signal combined with an integrated photodiode sensor and transimpedance amplifier. This system yields signal amplitudes up to *35* times higher than those of previous measurement systems. Furthermore, an *in vitro* model, including a tooth and gingiva blood circulation, has demonstrated that gingiva blood flow strongly influences the tooth blood circulation signal making dental pulp vitality assessment considerably more difficult.

II. Materials and Methods

A. Experimental configuration

To realistically simulate blood flow in the tooth, an *in-vitro* tooth-gingiva testing model was established (FIG. 3).

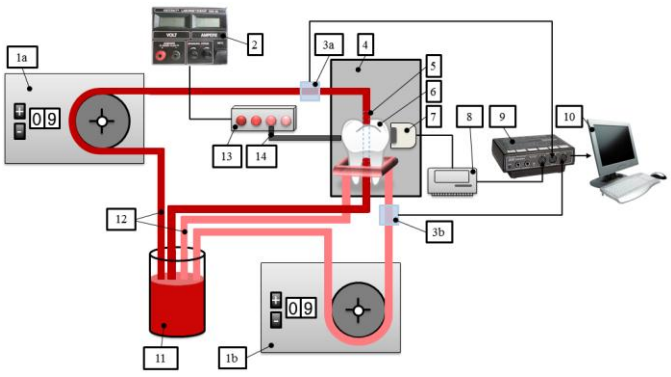

FIG. 3: In-vitro tooth-gingiva model for signal simulation

Blood (*11*) is pumped through a silicone tube (*12*) in closed cycles by two separate controllable peristaltic pumps, one for tooth (*1a*) and one for gingiva (*1b*) circulation. For pressure control, pressure sensors (*3a/b*), are fitted in both circuits. A perforated human tooth (*6*) with glass tube (*5*) for simulating the numb pulp is clamped in retaining brackets (4). Gingiva is imitated by blood circulation around the root. Light (*13*), adjustable by supply current (*2*), is carried from a fibre-optic cable (*14*) to the tooth surface. On the opposite side of the tooth, at the height of the light source, a photo detector (*7*) is firmly mounted in a retaining bracket. By these means, only the pulp is directly illuminated and the transmitted signals acquired. Initially, the PPG signal is filtered by the signal processing system (*8*). Then, together with the pressure signals, it is digitalized by an analogue-digital (A/D) converter (*9*) before being transferred to a computer program (*10*) for later evaluation.

B. Existing (initial) signal acquisition system

At the beginning of this project a simulation model [20] was available. It included a light source system, a photo detector (PD) *SFH229*, a signal processing system and an A/D converter (FIG. 4). Transmitted light modulated the photodiode current, which was initially converted to a voltage. This voltage was then filtered though R-C networks (passive low pass, LP) during which the DC voltage was eliminated by capacitive coupling. Finally, the AC voltage was amplified and then digitized by a 12-bit A/D converter.

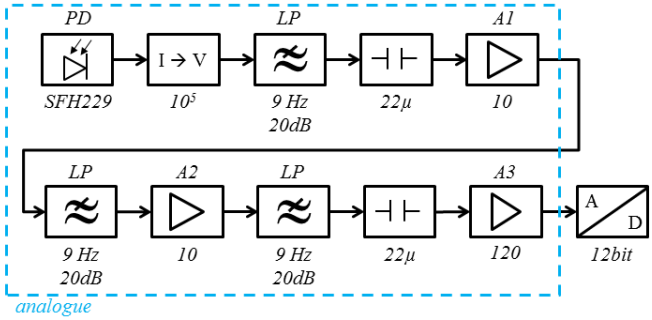

FIG. 4: Block diagram of *initial system*

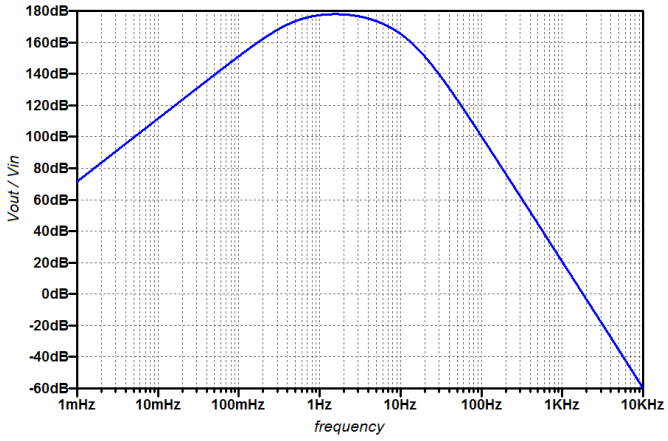

FIG. 5: Response characteristic of *initial system*

The frequency response curve (FIG. 5) shows the characteristics of the resulting band pass system. Here, the signal is attenuated at low frequencies. The output increases at a slope of *+40dB/Decade* until the frequency reaches the

lower cut-off frequency $f_L = 0.6\ Hz$. After the higher cut-off frequency $f_H = 4\ Hz$, the output decreases at a rate of *-80dB/Decade* attenuating any high frequency signals. The maximum gain is $10^9 \approx 180\ dB$ at *1.5 Hz*.

C. Developed (present) signal acquisition system

During this project, another signal acquisition system *(present system*) has been developed (FIG. 6) using an *OPT101* sensor. This is a single device with integrated photodiode and *I-to-V* converter; consequently, it provides a voltage output. In addition, a combination of analogue and digital signal processing systems has been built, which allows switchable selection of both *initial* and *present* sensors.
Filtering is achieved via a *2nd* order active filter. First a high pass filter with $f_C = 0.3\ Hz$ cut-off frequency for eliminating the DC offset voltage was incorporated. Then an amplifier with variable step gain (*1-5-10-20-50-100*) follows. The analogue low pass filter attenuates signal frequencies above $f_C = 6\ Hz$. If necessary, the signal may be further amplified by the second amplifier. By using a 14-bit A/D converter, even small signals can be acquired ($\Delta u = 1mV$) with good precision. The signals can be imported, filtered and evaluated using an algorithm written using LabVIEW or a similar system. Filter properties (cut-of frequency, order, characteristic) can be adjusted on demand.

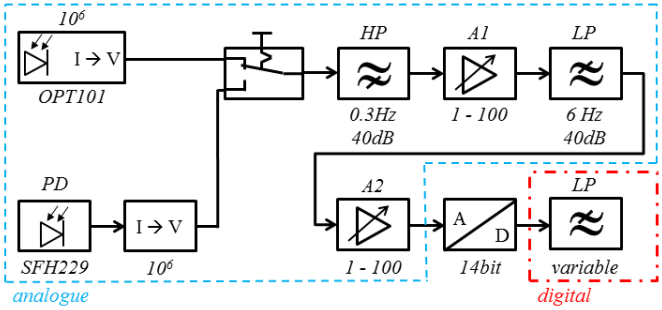

FIG. 6: Block diagram of *present system*

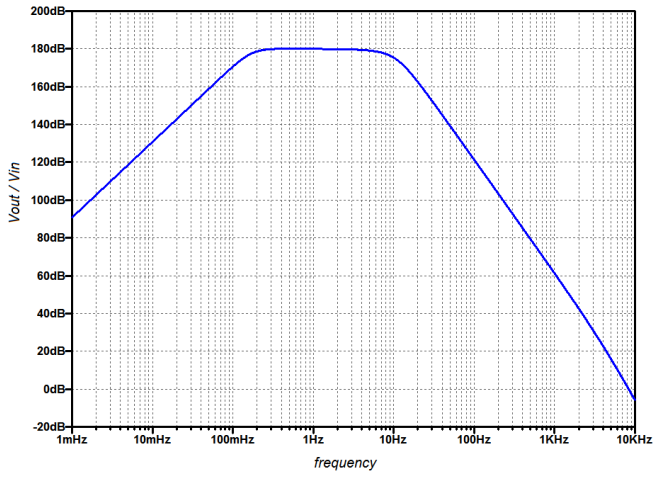

FIG. 7: Response characteristic of *present system*

The resulting frequency response of the analogue section of the *present* system is shown above (FIG. 7). Simulation using a gain of *A1=100, A2=10, I-V=10⁶* provides a maximum gain of about 10^9 *(180 dB)*. The lower cut-off frequency is $f_L = 160\ mHz$ and the higher cut-off frequency $f_H = 8.4\ Hz$.

D. Computer program

The measuring program can be operated via the control panel (FIG. 8). It runs for a pre-set duration, stops and saves measurement data automatically. Measured pressure signals are converted from *Volts* into *mmHg* and are plotted in a graph. The PPG signal is filtered using a Butterworth filter with selected settings and is also displayed in a further graph. For better clarity, the unfiltered signal can be displayed if desired. The displayed signal durations can be set via a slider during the measurement process. Signal peaks are detected and plotted in the signal diagram. Measurement settings including sample rate and number of samples to be read can be changed if necessary.

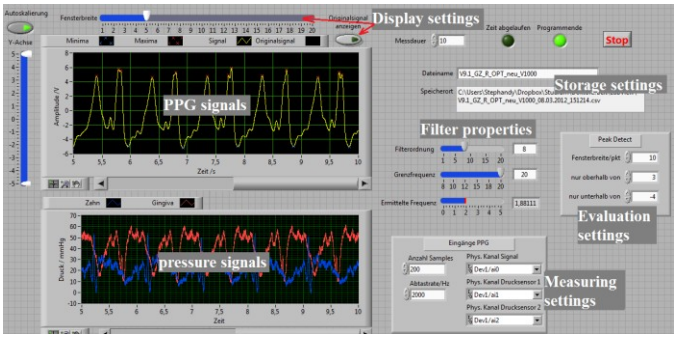

FIG. 8: Control panel of PPG signal acquisition program

E. Experimentation

Different combinations of *initial* and *present* systems were tested:

1. *Initial* system, *initial* sensor SFH229
2. *Present* system, *initial* sensor SFH229
3. *Present* system, *present* sensor OPT101

All experiments were conducted with red ($\lambda = 625\ nm$) and infrared ($\lambda = 940\ nm$) light. Furthermore, different circulation combinations were tested:

- Tooth circulation only
- Gingiva circulation only
- Tooth and gingiva circulation

In all cases, light sources and photo detectors were mounted at the upper end of the pulp thus minimizing effects of gingiva circulation (q.v. FIG. 3: In-vitro tooth-gingiva model for signal simulation.
The LEDs (light emitting diode, Golden Dragon / SFH 4231) were supplied with a current of *500 mA*. It should be noted, that while measuring with *present system* and *OPT101* with infrared light the supply current was reduced to *40%* (*=200 mA*) because of the control range.
For measuring with the *present system*, the gain of the first amplifier was set to *50* and that of the second to *20*, providing a total gain of *1000* multiplied by 10^6 (*I-to-V* coefficient).
The cut-off frequency of the programmed filter was set to *20Hz* using a filter order of *8*.

III. Results

In table 1, peak-to-peak voltages of the PPG signals are

given. Data is classified by three parameters: measurement system, blood circulation and light source.

No.	measurement system	sensor	blood circulation					
			tooth	gingiva	tooth + gingiva	tooth	gingiva	tooth + gingiva
1	initial	SFH229	0,409	0,031	0,421	1,545	0,828	2,070
2	present	SFH229	0,471	0,038	0,498	1,805	1,185	2,355
3	present	OPT101	12,206	1,083	10,819	4,839	2,641	5,550
PPG signal in V_{pp}			red (625 nm)			infrared (940 nm)		
			light source					

Table 1: Measured data: PPG signal in Vpp

The data obtained are depicted in the bar graph of Figure 9. Signals from experiments with a red light source and the *initial* sensor *SFH229* were too small for the graphical scale of figure 9, so they have been shown multiplied by *10*.

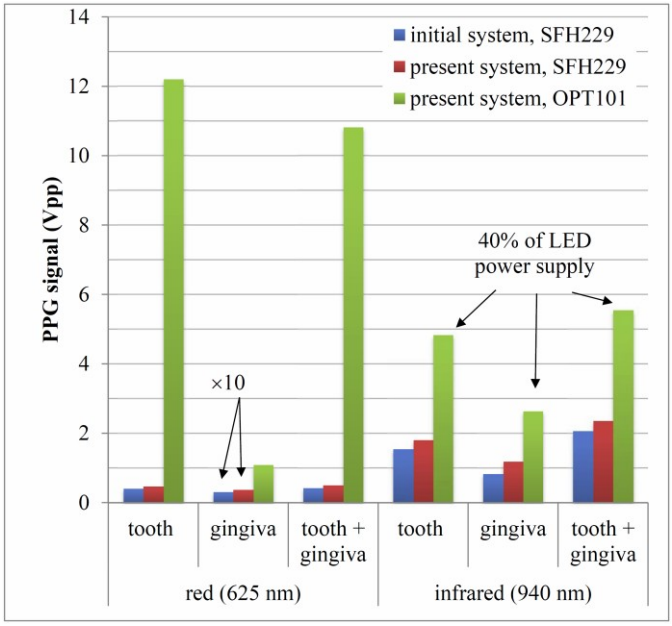

FIG. 9: PPG signal in Vpp

IV. Discussion

These results have shown that a PPG signal is acquirable even when no blood flows through a tooth. When using infrared light, this signal constitutes approximately half of the tooth signal. With a red light source it is reduced to about one tenth. Consequently, it appears that the influence of blood flow in the gingiva on the tooth signal is dependent on the illumination wavelength. This suggests that there should be a wavelength where the gingiva signal is evanescent.

Furthermore, measured signal amplitudes with the *present system* are larger than those from the *initial system*. Signal processing alone yields an improvement of about *10%*, but the *present* sensor *OPT101* produces up to *25-35* times higher signal amplitudes when using red light. In addition, measurement data using IR light with only 40% current supply yield amplitudes *3* times higher than with *initial system*.

Improvements result from increased detector surface area on the one hand and on the integrated *I-to-V* converter on the other. The OPT101 has a planar window whereas the SFH229 a convex window. Therefore, light beam impact is upright and signal level is higher. Due to the direct conversion of current to voltage within the sensor module, the signal to be transmitted is larger and more noise resistant.

The results show that the current supply and consequent heat losses can be reduced without any deterioration in signal levels while using the *present* sensor.

V. Summary

In this paper, a signal processing system for PPG signal acquisition for dental pulp vitality assessment was developed and tested. In particular, the sensor used (*OPT101*) has resulted in great improvements and even small signals are detectable. This is very important for later *in vivo* applications, where smaller signals are expected, because *in vitro* tests emulate an ideal situation.

The possibility of optical detection of dental pulp vitality has been verified, but the results show that the gingiva signal influences the tooth signal. The influence at red light (*625 nm*) was smaller than at infrared (*940 nm*) wavelengths. For in vivo tests to unambiguously distinguish between healthy teeth and dental necrosis, the influence of the gingiva must be eliminated. Consequently, further tests using different light sources should be carried out in order to ascertain wavelengths where the gingiva signal may be neglected.

Acknowledgment

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