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SpO2 Sensor Embedded in a Finger Ring: design and implementation

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***Abstract*— A novel concept of Oxygen Saturation (SpO2) sensor embedded in a finger ring is presented in this paper. Due to the mechanical conception of the probe, the sensor fits any finger topology and assures a constant force applied to the phalanx. Ambient light artifacts are rejected at the analog electronics level. Finally, an innovative distribution of light sources and detectors and a dedicated signal processing procedure resolve the anatomical heterogeneity of different phalanx topologies, compensate low perfusion indexes due to the phalanx anatomy and estimates equivalent pulse oximetry SpO2 indexes. First in-vivo validation results of the novel sensor are discussed at the end of the paper.**

I. INTRODUCTION

Because of its clinical relevance, Oxygen Saturation (SpO2) is one of the key physiological parameters recorded in poly-somnography: repeated arterial de-saturation derived from obstructive sleep apnea has been associated to ventricular bigeminy [1] and several cerebrovascular accidents [2]. Although fingertip probes are accepted as the gold standard method in such clinical practices, disturbances due to its long term usage have been repeatedly reported by sleep laboratories. The development of a less-obtrusive SpO2 probe that would improve patients' comfort is, therefore, justified.

For most patients, a finger ring is a jewel that is comfortable to wear during very long periods, if not forever. Some attempts have already been done to developed a ring-like SpO2 probe: since the 90s, in the MIT Home Automation and Health-care Consortium, Asada et al. develop a miniaturized ring sensor based on the state-of-the-art technology of pulse oximetry [3]. Interesting improvements in the low power consumption and wireless conception of the sensor have been achieved [4]. On the other hand, several works have been recently published regarding the low perfusion problematic [5]. However, none of these groups has proposed a concept based neither on the ergonomics of the probe nor the signal-processing problems derived from the anatomic differences between phalanxes.

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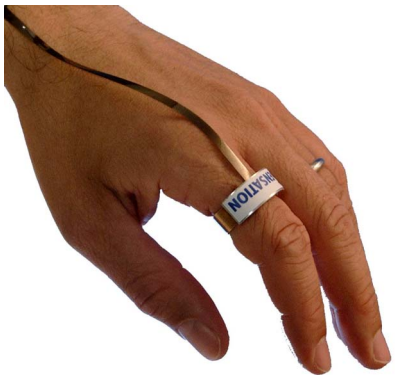

Fig. 1. The SpO2 sensor integrated in a finger ring. The current prototype weights less than 5g and has demonstrated to be more comfortable than standard fingertip probes.

In the framework of the European Integrated Project SENSATION [6] (Advanced Sensor Development for Attention, Stress, Vigilance and Sleep/Wakefulness Monitoring) CSEM and HEIG-VD are developing a Finger Ring intended for long-term monitoring of arterial desaturation. Being aware of the foreseen clinical applications, only ambient light artifacts and spontaneous motion artifacts have been contemplated and therefore, rejected. However, special care has been taken on the optic and mechanic adaptability of the probe to the patient's phalanx.

This paper presents the general conception of the ring probe. After an overview of the standard pulse oximetry technique, the novel concepts of mechanical fixation of the probe, multi-light-sources distribution and dedicated signal processing are provided. While waiting for definitive clinical validation tests, some preliminary in-vivo results are compared to commercial finger-tip oximeters.

II. THE BASICS OF PULSE OXIMETRY

Since the early works of T. Aoyagi [7] the principles of pulse oximetry have been untouched. Two contrasting wavelength lights are injected in a tissue and a reflected or transmitted part of the photons are further recuperated at the skin surface. Such photons having traveled through the arterial tree will be easily recognized because of its pulsating characteristics: at each cardiac systole, a general increase of diameter of capillary bed modifies the absorption of the light beam in a quantity described by the Beer-Lambert law:

$$I = I_0 e^{-\alpha_\lambda d} \quad (1)$$

where I denotes the intensity of light recuperated at the skin surface, I_0 denotes the baseline intensity of light and $e^{-\alpha_\lambda d}$ models the arterial absorption which depends on the absorption index α_λ at the wavelength λ and the arterial pulsating displacement d.

The arterial oxygen saturation (S_aO_2) is defined as the relative concentration of oxygen-saturated hemoglobin (HbO_2) and oxygen-free hemoglobin (Hb). By using two different wavelengths (typically $\lambda_1 = 660\,\text{nm}$ and $\lambda_2 = 940\,\text{nm}$) the relative concentration of such two absorbers can be distinguish due to their contrasting absorbing characteristics at such wavelengths (see Figure 2).

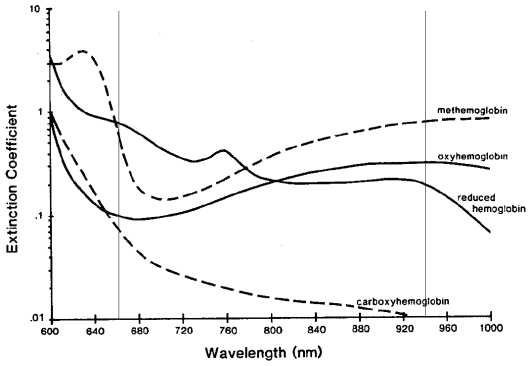

Fig. 2. Absorption spectra of oxygen-saturated hemoglobin (oxyhemoglobin) and oxygen-free hemoglobin (reduced hemoglobin). Image extracted from [8]

Historically, the concept of Perfusion index (PI) has been associated to the quality of placement of fingertip probes. Because of the crucial role that this measurement will play in the interpretation of our data, its physiological interpretation is here developed. As Masimo describes in [9], PI corresponds to the ratio of pulsating (AC) to non-pulsating (DC) components given a wavelength. It can be demonstrated that,

$$\frac{AC}{DC} \simeq \ln \frac{I_{\text{max}}}{I_{\text{min}}} = \ln \frac{I_0}{I_0 e^{-\alpha_\lambda d}} = -\alpha_\lambda d \qquad (2)$$

Therefore, PI is proportional to the arterial pulsating displacement d: at a given light-path, it reflects to the total increase of diameter of the capillary bed. High PI values depict well irrigated regions, while low PI values are related to regions where little capillarization exists. For commodity, PI is normally expressed in $\%$ and nominal values in transmittance probes are in the order of 1% to 5% [10]

III. PHYSIOLOGY OF THE PHALANX

Classical pulse oximetry on the finger tip relies on the rich capillary bed on this site: due to its homogeneous distribution of capillaries, big enough pulse strength is assured at any probe placement (i.e. average Perfusion Indexes are greater than 1%). Figure 3 illustrates a typical distribution of capillary bed at the finger tip. Similar characteristics are found at the forehead.

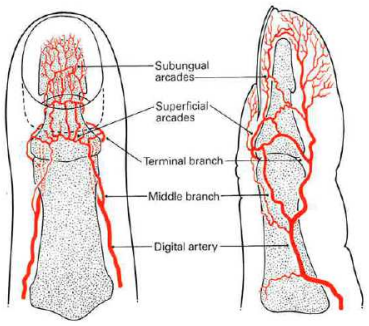

Fig. 3. Capillary bed in fingertips. Image extracted from [11]

However, as it is shown in Figure 4, the phalanx is conformed by an heterogeneous mixture of phalanx bone, arteries and secondary arterioles, veins and tendons. Due to this physiological mixture, Perfusion Indexes at this site are weaker than in the finger tip case.

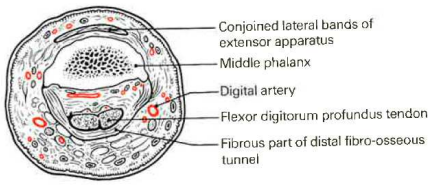

Fig. 4. Cross-section of finger at phalanx level. Image extracted from[11]

To better illustrate these facts, Figure 5 reproduces the probability distribution of Perfusion Indexes when measured at the phalanx and the finger tip. For each curve, 50 samples where obtained from the same subject by using in all cases, the same probe (e.g. same electronics and optical setup in both cases). As it can be observed, while the mean PI at the finger tip is around 0.8%, the mean PI at the phalanx is decreased to 0.3%: the phalanx contains less than half of the capilarisation of the finger tip.

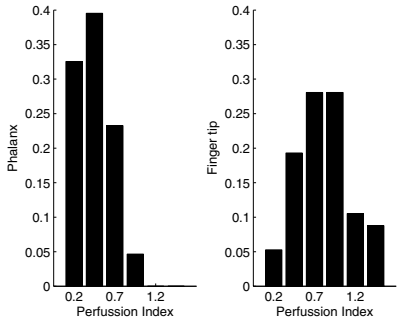

Fig. 5. Probability distribution of Infra-red Perfusion Indexes (PI) at phalanx and finger tip placements

IV. MECHANICAL ISSUES

During the mechanical conception and prototyping, three main aspects have been considered: the comfort for the user, the optical properties of the probe and specially the safety issues. The comfort for the user has been achieved by building a ring that can be opened during placement operations. Once placed, the user can lock it by pulling a flexible band, at this stage the finger ring adapts itself until reaching a final pressure that is defined by the ring. All these operations can be performed by the user himself without assistance. In Figure 6 the main elements involved in the self-adjustement mechanism are illustrated.

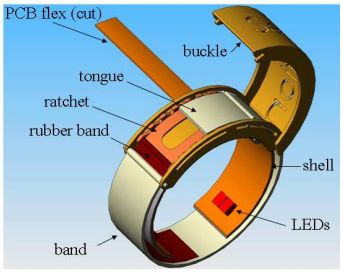

Fig. 6. Self-adjusting mechanism of the finger ring. The mechanical design follows the European directive concerning medical devices

The desired optical properties of the probe are centered around the novel distribution of LEDs and photo-diodes: the distribution has been facilitated by the use of a flex PCB to which the optical components are mounted. The current distribution of optical components is showed in Figure 7

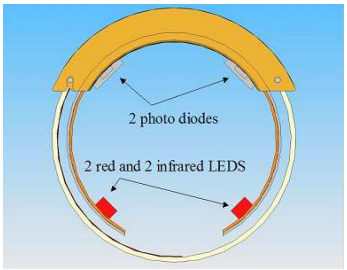

Fig. 7. Distribution of optical components over the flexible PCB: two photo-diodes and 4 LEDS are mounted.

For the safety assessment of the sensor, the European directive 93/42/EEC concerning medical devices has been foreseen. Special care has been taken with the chemical, physical and biological requirements of the materials in contact with the user and the requirements regarding the physical features (volume/pressure ratio to avoid finger choking).

V. ELECTRONIC ISSUES

Housed in a wrist case (Figure 1), the processing electronics includes analog pre-processing to compensate for the disturbing effects caused by ambient light, which also vary with movements artifacts. The functional architecture of the system is shown in Figure 8. The processing unit modulates periodically the sources of light in order to be able to subtract the background noise. The modulation frequency is chosen in such a way as to eliminate the perturbation due to the flickering of fluorescent lamps.

The capability of independently addressing four light sources and to analyze their influence into two separate photo-diodes determines the main different of the proposed electronic against classical approaches. In total, eight data channels are continuously provided to the algorithm.

Once the processing of data has been performed, the output parameters (Heart Rate and SpO2) are available as analog outputs and may also be transmitted in digital form to an external receiver (Body Area Network).

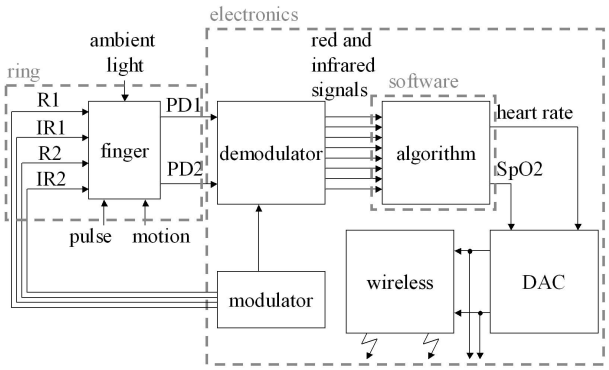

Fig. 8. Functional architecture of the electronic platform

VI. SIGNAL PROCESSING ISSUES

Perfusion Indexes (PI) at phalanx are considerably smaller than they are at the finger tip (in Figure 5 a two-fold factor is shown). In the state-of-the art [7] the post-processing of raw optical signals is based on the detection of the pulsating pattern of arterial blood. Once detected, the pulsating amplitude is matched with Beer-Lambert's Law and by means of a look-up table, an index of hemoglobin saturation is obtained. However, those techniques based on a ad-hoc pulse detection rules (i.e. Nellcor Oxismart from [7]) are not suitable when, due to low-perfusion, the SNR of the pulsating waveform has been considerably decreased.

In 1990, Conlon [12] introduced an ECG-synchronized method to resolve the problematic derived from low perfusion and motion artifacts: the electrical activation of the heart was proposed as a marker of the arrival an arterial pulse at the probe placement. However, this method requires the recording of electrical heart activity by increasing the complexity of the devices (i.e. Nellcor N-200) and, what is more important, measurements can be biased by modifications in the velocity of propagation of pulses along the arterial tree (e.g. PWV).

The Finger Ring overcomes the limitations of Conlon's technique by means of a novel distribution of optical sensors around the phalanx: a proprietary technology concerning this optical approach is to be patented by CSEM.

VII. RESULTS

During the development of the finger ring a testing environment was built at CSEM laboratories. The setup consisted of two reference pulse oximeters (Nellcor N595 and BIOPAC OXY100C), a finger ring prototype and a mask for altitude simulation (AltiTrainer). A small database of 10 subjects (age 36 ± 9 yr) performing two driven-hypoxia periods each (SpO2 $< 90\%$) during 30 minutes was recorded. Figure 9 shows the typical setup during the recordings.

The development of the database allowed optimizing the LED-skin interface (we observed superficial skin-deformation after long-period uses that were overcome by the injection of opaque silicon in between the optical components), optimization of values of optical emission power (because of the differential absorption in tissues, red and infra-red lights require very different intensities) and first-time algorithm tuning.

Fig. 9. Typical setup during hypoxia tests performed at CSEM. Two pulse oximeters and an altitude simulation mask were used to prove the ability of the finger ring to monitor oxygen desaturation at high altitudes

In March 2006 a validation campaign started in a clinical environment. The goal of the undergoing campaign is to probe the clinical usability of the finger ring for Sleep Apnoea Syndrome (SAS) detection. The campaign is being performed at FORENAP Pharma in France and a total of 20 subjects is to be monitored. Preliminary results show that the finger ring successfully detects the SpO2 modifications due to micro-apnoea periods in the same way the reference pulse oximeter does. In Figure 10 the analyze of 1 hour of sleep data is showed.

The self-adjusting mechanism is, up-to-date, demonstrating to be crucial in improving the sleeping comfort: several patients have underlined the lack of "pumping-feeling" at the finger where the sensor has been placed, in contrast to the Omeda fingertip probe.

VIII. CONCLUSIONS

The main innovations of a novel finger ring concept for the monitoring of SpO2 have been presented in this paper. Due to the improvement of wearing-comfortability, the sensor is well suited for sleep monitoring purposes. First results from a clinical validation campaign suggest that the finger ring successfully detects Sleep Apnoea Syndrome (SAS) while

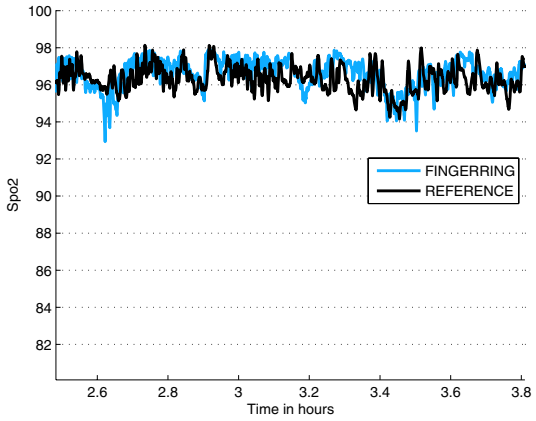

Fig. 10. About one hour of oxygen desaturation monitoring of a subject presenting Sleep Apnoea Syndrome (SAS). The reference device was an Omeda Pulse Oximeter. The data was collected at FORENAP Pharma facilities under its own medical supervision

improves sleeping quality. The sensor has been also tested in altitude-simulated environments proving its applicability to hypoxia detection in other domains such as aviation and high altitude sports (i.e. alpin climbing).

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