Ambulatory pain evaluation based on heart rate variability analysis: application to physical therapy

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Abstract— **Pain assessment is critical for efficient pain management. Clinicians usually use self-report or behavioral pain scales. In practice, the choice of the most adaptive scale depends on several parameters like the clinical context, the patient consciousness or its age, but all evaluation scales are known to be more or less subjective and to present high inter and intra individual variability. Recently, several innovative medical devices have been developed in order to provide to the clinicians a physiological measure of pain. These technologies are mainly used for the continuous monitoring of patients in intensive care or during surgery. As an example, we have developed a heart rate variability analysis based technology for analgesia/nociception monitoring in patients undergoing surgery under general anesthesia. Even if this technology is now used in other clinical settings, the resulting device presents some mobility constraints. In this paper, we describe the adaptation of this technology to the ambulatory pain evaluation and its clinical validation in the particular context of physical therapy. In the frame of this validation, we showed the device usability and efficiency for pain evaluation during physical therapy sessions.**

I. Introduction

According to the International Association for the Study of Pain (IASP), pain assessment and management are integral aspects of physical therapy management. Therapists need to be familiar with pain assessment and measurement and should be able to implement a broad variety of evidence-based pain management strategies [1]. The first step for effective pain management is therefore to provide optimal pain assessment tools to therapists [2]. There are different ways to assess pain: self-report scales, behavioural scales or physiological measures [3].

In conscious adults or children, pain is usually assessed by using self-report scales such as Visual Analogue Scale (VAS) that consists on a 100 mm graduated ruler equipped with a cursor moved by the patient. A VAS of more than 30 is considered to be related to a significant pain.

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When patients are unable to self-report, behavioural scales are used to measure pain intensity: for young (e.g. 4 years and below), distressed, or cognitively impaired children, the FLACC (Face, Legs, Activity, Cry, Consolability) score is recommended to evaluate acute pain [4]. The FLACC scale contains five items (Face, Legs, Arms, Cry, Consolability), each item is scored between 0 and 2 by a nurse in order to provide a total score between 0 and 10 [5]. A FLACC score between 0 and 3 can be interpreted as mild pain, a FLACC score between 4 and 6 is interpreted as moderate pain and a FLACC score higher than 6 interpreted as severe pain.

The APN (Acute Pain Newborn) score [6] can be used for newborn or preterm infants for short-term pain: three items describe facial motricity (coded between 0 and 4), corporal motricity (coded between 0 and 3) and vocal expression (coded between 0 and 3). This score is evaluated before, during and after the noxious stimulus. An APN score higher than 2 is interpreted as a significant pain response.

In newborns, the EDIN (Echelle de la Douleur et de l'Inconfort du Nouveau-né; Neonatal pain and discomfort scale) evaluation scale can be used for long-term pain measurement: five items (corporal and facial, consolability, motricity, sleep, relationship with healthcare provider) are evaluated during one hour. EDIN scale is the sum of the 5 items and ranges from 0 to 15; a score up to 5 is considered as a sign of significant pain [7].

Even if self-report or behavioral scoring systems allow bedside evaluation and help decision making for managing pain, the main limitation of the different pain assessments is their reliability with high inter or intra observer variability. A further limitation comes from the intermittent scoring, with a risk of overlooking painful episodes during the inter-rating period.

Nowadays, several medical devices allow physiological evaluations of pain intensity. For example, the Algiscan (IDMed, France) is a device that measures the pupillary reflex dilation as a surrogate for nociception intensity during surgery [8]. The Surgical Plethysmographic Index (SPI, GE Healthcare, Finland) is a measure of sympathetic activity based on both plethysmographic waveform magnitude and heart rate variability [9]. Skin conductance (MedStrom, Norway) is another way to assess one's response to pain [10]; this system is mostly used in neonatal intensive care unit.

We have developed an instantaneous Heart Rate Variability (HRV) analysis method that measures the relative

parasympathetic activity as a surrogate for analgesia/nociception balance during surgery under general anesthesia [11, 12]: a decrease in the Analgesia Nociception Index (ANI) has been shown to be related to noxious stimulations in adults [13] as well as in newborns [14]. The ANI index is now commercially available (Physiodoloris® monitor, MDoloris Medical Systems®, Lille, France [15]).

However, all these devices have been designed to be used in a surgery room or in intensive care units, so that their use on the ward or outside a hospital cannot be recommended [16].

In this paper, we present a new ambulatory monitoring device that measures the relative parasympathetic tone through HRV analysis as a way to estimate pain and comfort during physical therapy.

II. Methods and Materials

A. HRV index computation

The HRV index computation has been described elsewhere [11, 12, 13, 14, 15]. Briefly, The ECG signal is acquired using classical ECG electrodes and digitized at a sampling rate of 250 Hz. R waves are detected and the corresponding RR series is built against time; ectopic beats and electrical artifacts are filtered [17] before the RR series is re-sampled at 8 Hz. The RR series is analyzed in a 64 s moving window in which it is mean centered, normalized and band pass filtered between [0.15-0.4 Hz] using a wavelet transform. Upper and lower envelopes are plotted between local maxima and minima respectively (fig. 1, green curves). The surfaces between the envelopes are then measured in four 16 s sub-windows: A1, A2, A3 and A4. In order to keep a good reactivity regarding painful stimuli, we defined AUCmin as the smallest of these four surfaces. Indeed, a painful stimulus will induce a sudden decrease in the mean centered normalized RR series. Taking into account the minimum surface allows AUCmin to decrease immediately at the stimulus occurrence while keeping the information during the whole moving window duration.

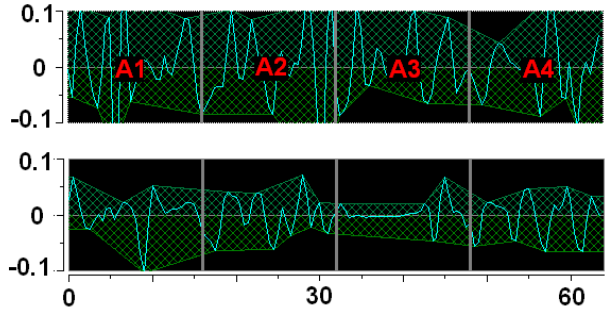

Fig. 1: normalized, mean centered and band pass filtered RR series. Upper panel represent the pattern in the case of a comfortable patient (VAS<3) whereas lower panel represent a painful patient (VAS>5)

The HRV Index is computed from AUCmin in order to obtain a value between 0 and 100:

$$\text{HRV index} = 100 * [a*\text{AUCmin}+b] / 12.8 \quad (1)$$

Where a = 5.1 and b = 1.2 have been determined in a population of more than 200 anesthetized patients [11, 18]. The averaged HRV_a is computed as the mean of the HRV index over four minutes.

B. Ambulatory measurement

From a functional point of view, the device needs to integrate four main functions:

- ECG signal acquisition,
- Digital signal processing,
- Signal visualization,
- User interface.

In an architectural point of view, the ambulatory monitoring system integrates a signal conditioning unit, a Microchip DSPIC-33F (μP_1), a mikromedia PIC24 graphic card (μP_2) including a display unit, a lithium battery (fig. 2).

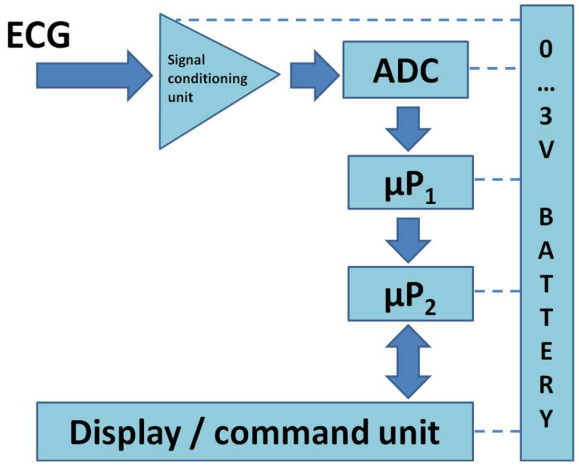

Fig. 2: Hardware architecture of the ambulatory monitoring system.

The first microcontroller μP_1 implements the ECG signal processing up to HRV_a computation as described in the *A* section. Digitalized ECG samples, R waves detections and HRV_a values are transmitted in real time to the second microcontroller (μP_2) for data displaying: a specific user interface has been developed for HRV_a ambulatory use (fig. 3).

A continuous display of ECG and R waves enables the user to check signal quality. A bar graph displays HRV_a intuitively, and elementary descriptive statistics of HRV_a (min, max and mean) are displayed on the right side of the screen. Touch sensitive screen zones permit device and ECG gain re-initialization.

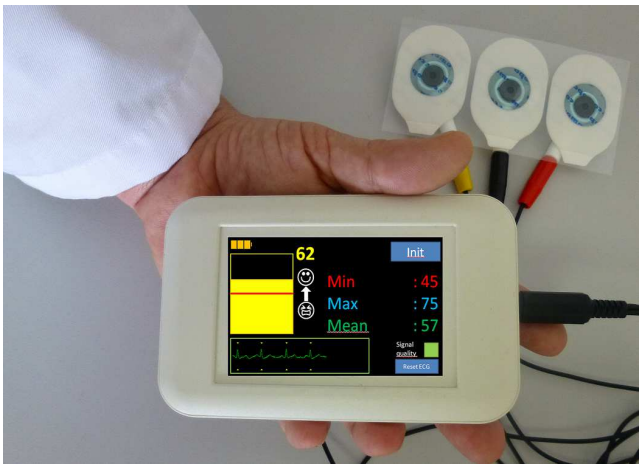

Fig. 3: Ambulatory HRV_a monitoring device and user interface.

C. Clinical validation

After institutional approval for a prospective study, we included adult patients planned to undergo physical therapy 24H after a total hip replacement under general anesthesia. Patients with history of autonomic or cardiac disease, body mass index (BMI) over 40, diabetes or autonomic nervous system altering medications were not included. All patients gave written informed consent. For each patient, HRV_a and VAS of pain were recorded during the 1st and the 2nd physical therapy session (respectively 24H and 48H after surgery). ECG electrodes were placed on the patient and ambulatory HRV_a device was started 5 minutes before the beginning of the procedure. The physical therapy procedure consisted in several leg flexions and abductions movements helped by the therapist. A VAS of more than 30 was considered to reflect significant pain. Correlation between the highest VAS and lowest HRV_a was measured using a Spearman correlation rank test. A Mann Whitney U- test was performed to compare HRV_a values between VAS > 30 and VAS ≤ 30. A p value of 0.05 was considered as significant. A Receiver Operating Characteristic was drawn to test the ability of HRV_a to discriminate between VAS > 30 and VAS ≤ 30. All tests were performed with SPSS 22.0.

III. Results

Twelve patients have been included, leading to a 48-paired data set (HRV_a – VAS): a pair of values before and after each physical therapy session. Twenty-four values corresponded to VAS >30 and Twenty-four other values to VAS ≤ 30.

A significant inverse correlation between HRV_a and VAS was found (r = - 0.50, p=0.002). HRV_a was significantly lower in the VAS > 30 subgroup than in the VAS ≤ 30 one (p=0.002).

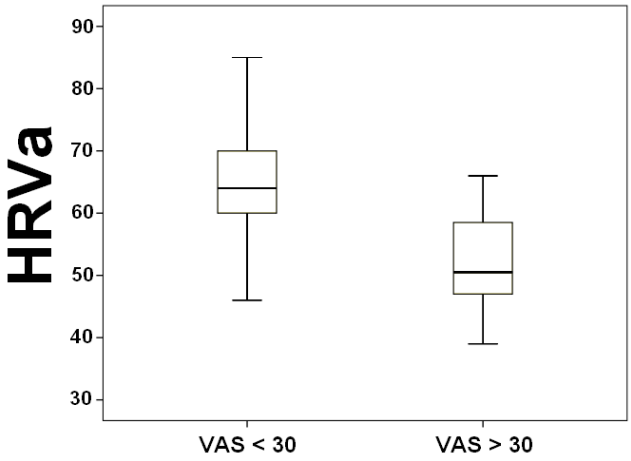

Fig. 4: Boxplot for HRV_a values between VAS ≤ 30 and VAS > 30. Data are presented as median and 25 – 75 centiles.

A ROC curve analysis (Fig. 5) led to an area under the surface of 0.76, with an HRV_a "best fitting" threshold of 59 (Se=76%, Sp=78%, PPV=79.2% and NPV=75%).

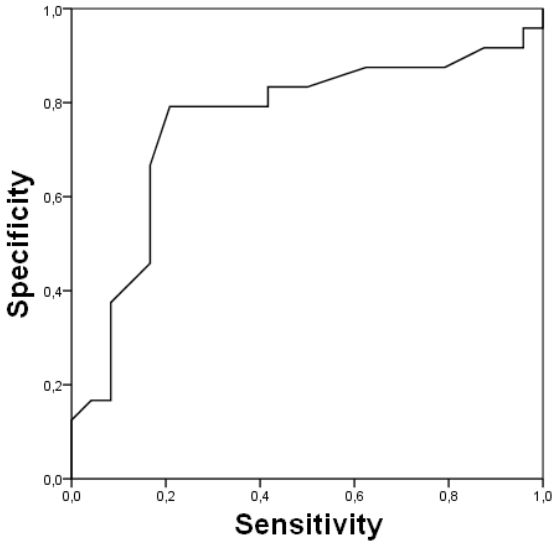

Fig. 5: ROC curve analysis of HRV_a during Physical Therapy.

IV. Conclusion

In this paper, we describe the integration in an ambulatory device of algorithms that have been previously implemented in a clinical monitoring device for analgesia/nociception balance evaluation during surgical procedures under general anesthesia, or in intensive care. This microcontroller based technology allowed to investigate the pain response to physical therapy at 24H and 48H after total hip replacement on the surgical ward.

In this preliminary clinical study, we observed a relatively good correlation between HRV_a and the VAS self-reported pain measure. Despite a low number of cases, this clinical

study suggests that the device may provide an efficient way to evaluate pain in conscious patients undergoing an uncomfortable procedure such as physical therapy.

As it is only of mild interest to measure pain in adult patients able to communicate, this study constitutes a first step in this device clinical validation. A further study will investigate the benefit of this device during physical therapy in young non-verbal children suffering from cerebral palsy and evaluate the correlation between HRV_a and the FLACC score.

A further clinical validation will be conducted in newborns after instrumental delivery or during the first vaccination procedure. HRV_a measurements will then be correlated with behavioral scales such as EDIN and APN score.

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