Heart Rate Variability Monitoring with Savvy ECG Sensor During Dental Surgery

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***Abstract* - Surgical procedures are accompanied with anxiety and stress for both patients and surgeons. This paper investigates the utility of various heart rate variability parameters, estimated from Savvy patch ECG recordings, obtained on patients during surgical extraction of impacted lower third molars under local anesthesia, to estimate psychological state of the patient, as well as pain levels, in real time. This could be particularly beneficial for patients with chronic conditions, such as cardiovascular diseases, that can deteriorate under psychophysical stress. Statistical analysis showed significant correlation between several heart rate variability parameters and changes in autonomous nervous system functionality. Additionally, there was a significant correlation between several heart rate variability parameters on one side, and patient reported anxiety, pain levels, and the procedure difficulty, on the other.**

Keywords - Patch ECG; Savvy; heart rate; heart rate variability; anxiety; stress; dental surgery; pain; local anestesia.

I. Introduction

Because of anxiety and stress, patients experience hemodynamic changes during and before surgical procedures [1]–[4]. Anxiety related to surgery, as well as anxiety caused by the local anesthetic injection; increase cardiac oxygen demand, which increases the risk for arrhythmic events [5], [6]. Oral surgical procedures are therefore riskier for hypertensive, cardiac, cerebrovascular, and senior patients. Healthy individuals cope with stress better, but sudden and asymptomatic heart rhythm disorders may occur during oral surgical procedures even for them [7]. Some disorders, such as hypertension or coronary vascular disease (CVD), might manifest only during psychophysical stress [8]. Monitoring of vital signs is therefore recognized as beneficial, and even necessary, in some dental procedures [9].

Pulse oximetry has been accepted as a reliable device, for monitoring oxygen saturation (SaO_2) and heart rate, in dental procedures [10]. Recently however, novel wearable ECG devices have emerged, among which patch ECG monitors are the most prominent [11]. In addition to the heart rate, they provide electrocardiogram (ECG) and respiratory rate. In this study we used Savvy patch ECG monitor which is CE certified as a medical device [12].

In our previous studies, we investigated heart rate (HR) and ECG recordings during surgical extraction of impacted lower third molars under local anesthesia, considering patients' gender and dental anxiety levels [13], [14]. This study calculates all the prominent heart rate variability (HRV) parameters and correlates them with reported anxiety and pain levels in patients, as well as with the procedure complexity.

A. HRV relation to anxiety and pain

HRV estimates are measures of balance between sympathetic (SNS) and parasympathetic (PNS) autonomous nervous systems. Increased SNS, or decreased PNS activity, causes an increase in HR, and vice-versa. Furthermore, the response time of PNS is shorter than the SNS (PNS has faster reaction). Consequently, SNS activity is associated with low-frequency measures of HRV, whereas PNS is associated with medium and high frequency measures of HRV [15], although some authors consider low-frequency to be influenced by both systems.

Stress, anxiety, and pain are in general associated with an increase in sympathetic and decrease in parasympathetic output [15]–[18].

Two previous studies that evaluated patient [19] and surgeon [20] stress during surgery, have reported increased stress as measured by frequency characteristics of the HR signal.

II. Methods

A. Data

Thirty (15 males and 15 females) healthy, normotensive, medication-free patients with ages ranging from 19 to 43 years, scheduled for surgical extraction of lower third molars, were enrolled in the study. The data was collected between Nov 2019 and March 2020 in the Department of Oral and Maxillofacial Surgery, University Hospital of Split, Croatia. The Bioethics Committee of the University Hospital of Split approved the study. The participants signed written informed consent. All procedures were performed in the same dental office, by the same oral surgeon during morning hours.

B. Study protocol

Before the procedure, while in the waiting room, patients were asked to fill Corah's Dental Anxiety Scale (DAS) [21]. It consists of four multiple-choice questions scoring from 4 to 20. At the end of the procedure, the visual analog scale (VAS) from 0 to 10 was handed to patients to report intraoperative pain.

ECG was recorded using the Savvy patch ECG monitor connected to a Smartphone through low-power Bluetooth. The sensor was placed with positive electrode on the sternum approximately 5 cm above the xiphoid, whereas the negative electrode was placed as much above and to the left as the connecting wire allowed, without causing tension on the electrode-skin contact.

All surgical procedures were performed in aseptic conditions using a buccal approach and rising mucoperiosteal flap with the vertical incision in the lower second molar area. The osteotomy site was irrigated with saline, and after bone removal, extraction was performed using either forceps or elevators, separating crown and roots if needed. The flap was repositioned and sutured using silk 3-0 stitches (Johnson & Johnson Medical Ltd Simpson Parkway, Krikton Campus, Livingston, United Kingdom).

The procedure's difficulty was assessed by the modified Parant scale (PARANT) [22]. Since all patients required osteotomy, grade II was the minimal grade. The procedure duration time was measured from the time of incision until the placement of the last suture. Each patient received the inferior alveolar nerve block using the same local anesthetic 4% articaine with a vasoconstrictor (adrenalin 1:100000) in 1.8 ml dose (Ubistesin 40 mg/ml+0.005 mg/ml injection solution, 3M ESPE). No more than 5.4 ml (3 carpules) of anesthetic solution was used in each case.

By using the MobECG app that accompanies Savvy, various time moments were marked during the procedure, enabling the total time to be split in the following intervals: 1-Waiting room; 2-Anestesiation; 3-Procedure; 4-After procedure. Patients were aware of each stage in the procedure.

C. HR and HRV estimates used

HRV parameters were calculated in MATLAB from the raw ECGs by using PhysioNet Cardiovascular Signal Toolbox [23], [24].

Measures of normal R-R intervals (NNs) rate used:

- NNmean (ms) - mean value of NN intervals
- NNskew - skewness of NN intervals
- NNkurt - kurtosis of NN intervals.

Measures or NN intervals variability used:

- NNiqr (ms) - interquartile range of NN intervals
- SDNN (ms) - standard deviation of NN intervals
- RMSSD (ms) - square root of the mean of the sum of the squares of differences between adjacent NN intervals
- pnn50 (%) - number of pairs of adjacent NN intervals differing by more than $50\,ms$, divided by the total number of all NN intervals.

Since RMSSD and pnn50 measure faster changes in NNs, they are considered as estimates of parasympathetic activity, whereas NNiqr and SDNN are measures of sympathetic activity.

Frequency domain measures (using Lomb periodogram method):

- ulf (ms^2) - power in the ultra-low frequency range (< 0.003 Hz)
- vlf (ms^2) - power in very low frequency range ($0.003 <=$ vlf < 0.04 Hz)
- lf (ms^2) - power in low frequency range (0.04Hz $<=$ lf < 0.15 Hz)
- hf (ms^2) - power in high frequency range ($0.15 <=$ hf < 0.4 Hz)
- lfhf - ratio lf/hf]
- ttlpwr (ms^2) - total spectral power.

The hf component is seen as indicators of parasympathetic activity, whereas the lf component represents the activity of the sympathetic nervous system, although some studies suggest that it reflects both the sympathetic and parasympathetic nervous system. The lfhf-ratio is used as indicator of the balance between the sympathetic and parasympathetic nervous system; higher values of lfhf indicate a predominance of the SNS, whereas lower values indicate a predominance of the PNS. ttlpwr is the total variance in the heart rate [25].

Other HRV measures:

- ac (ms) - acceleration capacity
- dc (ms) - deceleration capacity

dc of heart rate is a measure of cardiac parasympathetic modulation as it captures the lengthening of NN interval within 2-4 successive beats. ac of heart rate captures the shortening of NN interval.

Poincaré plot (PP) features:

- SD1 (ms) - standard deviation of projection of the PP on the line perpendicular to the line of identity ($y = -x$)
- SD2 (ms) - standard deviation of the projection of the PP on the line of identity ($y = x$)
- SD1SD2 - SD1/SD2 ratio.

SD1 is related to the short-term variability, whereas SD2 describes the longer-term variability [15]. The ratio SD1/SD2 describes the relationship between the two.

Entropy measures: SampEn - Sample entropy and ApEn – Approximate entropy, are measures of the regularity and complexity of time series. ApEn decreases as the NN variation decreases. The only difference between dSampEn and ApEn is a small computational difference.

D. Statistical analysis

Linear mixed effect models were fitted between each HRV measure, as the output variable, and interval number, as input variable. All the models were corrected for gender and age, since there is a well-established relation between HRV and these two variables [15], [26]. Additionally, the influence of DAS, VAS and PARANT were estimated as slopes in each time interval. All the models included

random intercept per patient to model dependency between measurements on the same patient.

In the continuation we used asterisk (*) to mark p values lower than 0.05. Influences that are not presented were not found to be statistically significant. All graphs show mean and 95% confidence intervals.

The first time-interval (waiting room) was set as the baseline for HRV analysis, so the other intervals are contrasted to the first.

III. Results

Fig. 1 presents HR properties, whereas Fig. 2 presents time domain HRV measures. Figures 3 and 4 present frequency domain HRV properties whereas other, Poincaré and entropy measures are presented in figures 5, 6, and 7, respectively.

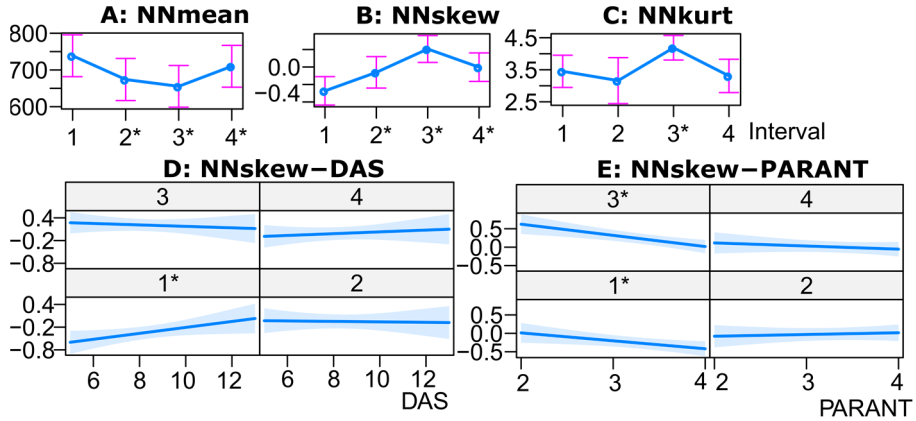

Figure 1. Estimates for NN central tendency (mean) and departure from normality (skewness and kurtosis) (D – skewness as a function of DAS per interval; E – skewness as a function of PARANT per interval)

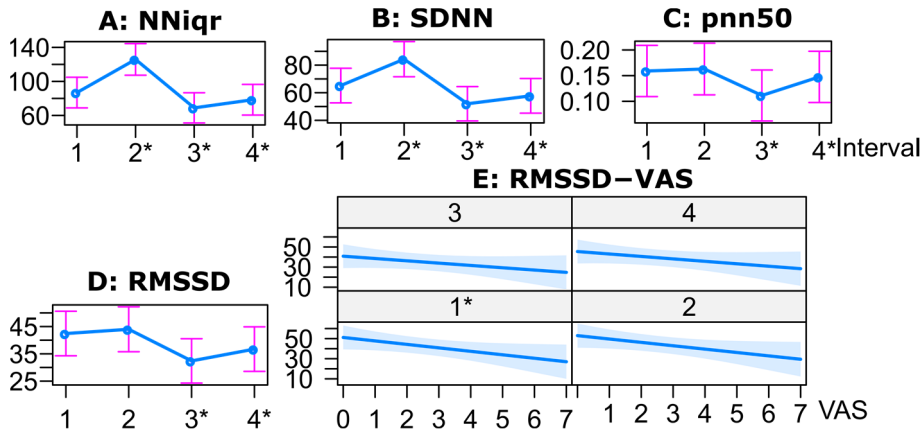

Figure 2. Estimates of NN intervals variability (D- RMSSD as a function of VAS per interval)

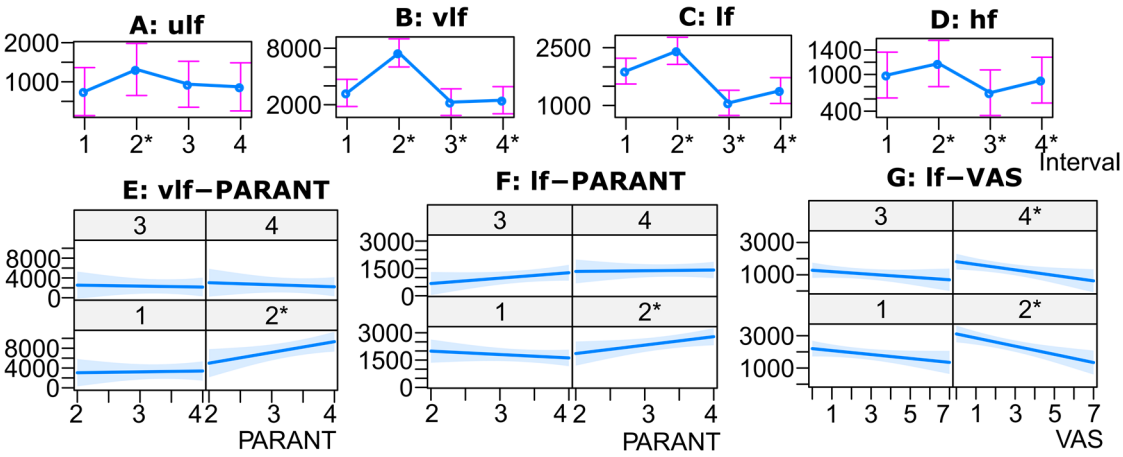

Figure 3. Frequency domain measures (E - vlf as a function of PARANT per interval; F – lf as a function of PARANT per interval; G – lf as a function of VAS per interval)

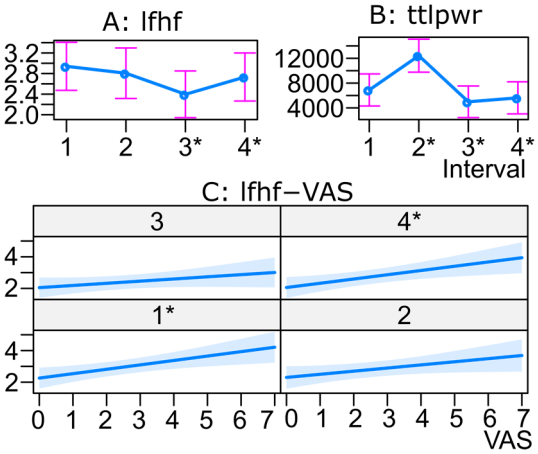

Figure 4. Low-to-high-frequency ratio and total power
(C – lfhf as a function of VAS per interval)

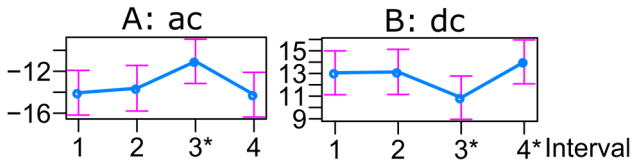

Figure 5. Other HRV measures.

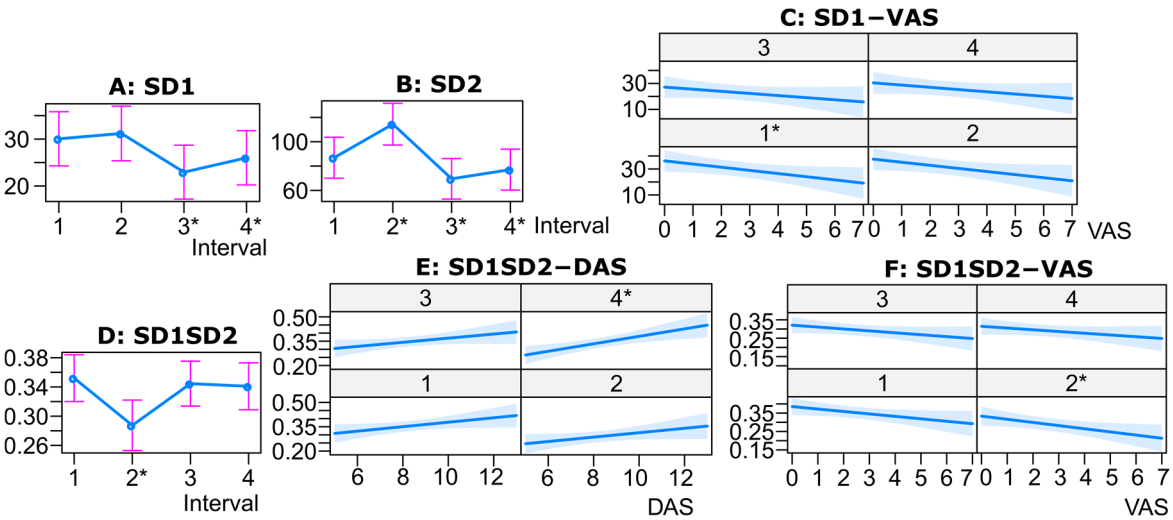

Figure 6. Poincaré plot features (E – SD1SD2 ratio as a function of DAS for each interval; F – SD1SD2 ratio as a function of VAS for each interval)

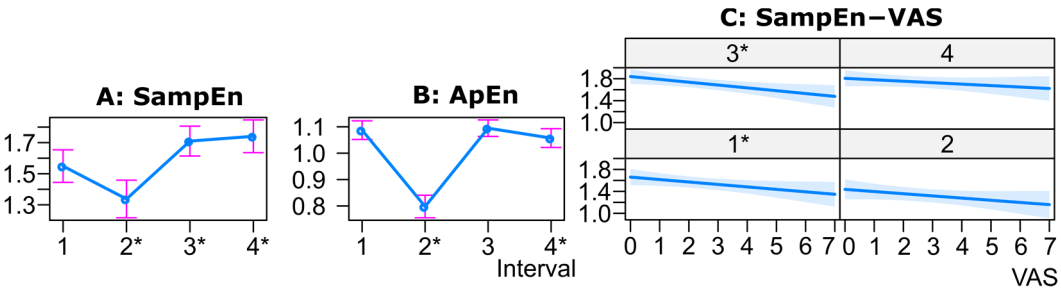

Figure 7 Entropy measures (C – SampEn as a function of VAS per interval)

IV. Discussion

Panel A in Fig. 1 shows that patients are excited because of the procedure since NNmean is less than 850 ms for all time intervals (average value can be considered to be 926 ms [26]). Mean and skewness of NN intervals were significantly different for all intervals compared to the baseline. Kurtosis however was significantly different only during the procedure. There is a significant correlation between skewness and DAS in the waiting room. Skewness decreases with PARANT during procedure but also in the waiting room indicating that patients might have been informed about the severity of the foregoing procedure.

In Fig. 2 NN variability (panels A, B) increases during anesthesia, indicating increased sympathetic activity caused by pain and/or fear [18]. Variability decreases significantly during procedure (for all estimates), indicating lower parasympathetic activity (panels C, D). Panel E shows that even though RMSSD drops with VAS for all intervals, the drop was significant only during baseline, which is interesting because there is no pain in the waiting room. This is however in accordance with previous research showing that lower rest parasympathetic activity means lower resilience to stress [25].

lf is significantly increased in the anesthesia segment, and significantly decreased during the procedure and after the procedure (Fig. 3). This indicates higher sympathetic activity during anesthesia and calming during procedure. This is in accordance with previous findings in fig. 2, and with panel D, which shows that parasympathetic activity follows sympathetic activity for homeostasis. The significant increase in sympathetic activity (lf) in interval 2 is probably not caused by pain, but by stress. This is because pain is accompanied by a decrease in parasympathetic activity [18]. Panel E and F show significant increase in power of low frequencies with PARANT during anesthesia, which is possibly because of more intensive anesthetizing required for more complicated procedures. Panel G shows that lf in interval 2 can be used as a predictor of perceived pain. Interestingly, sympathetic activity is significantly lower for patients who reported pain that is more intensive.

In Fig. 4 we see that lfhf ratio drops in time from the baseline value of about 2.9 which is slightly above the average value of 2.8 [26]. The drop becomes significant during the procedure, indicating imbalance in the nervous systems caused by the surgery. In other words, PNS becomes significantly more prevalent compared to SNS, which we already observed in the previous figure. This is in accordance with the previous study, which also showed a drop in lfhf ratio during the procedure [19]. Panel C shows an increase in lfhf ratio with higher reported pain. This is expected since sympathetic activity is increased with pain but considering we have seen decrease of PSN with VAS in the first time-interval on Fig. 2 panel E, the decrease of the lfhf ratio was probably because of a drop in PNS activity. It is interesting that the increase was significant also in the waiting room, indicating that anxiety before the procedure causes higher perception of pain. The anxiety before surgery (in the waiting room) might have been increased by the details of surgery that patients have received [27], which in turn could have increased the perception of pain.

Fig. 5. shows significantly decreased ac and dc during procedure.

Both SD1 and SD2 drop significantly during procedure, whereas the ratio SD1SD2 is significantly lower during anesthesia (Fig. 6). Panel C and F show that the SD1 and SD1SD2 could be used as indicators of VAS, whereas SD1 is significant already in the waiting room. We can see on panel E that SD1SD2 increases with DAS (significantly in interval 4).

Since HRV increases in segment 2 (Fig. 2), one might expect that entropy also increases, but surprisingly Fig. 7 shows a significant decrease in entropy. Panel C shows a significant correlation between SampEn and VAS, already in the waiting room.

V. Conclusion

Several HRV parameters significantly change during dental surgery, indicating changes in the balance between SNS and PNS, caused by anxiety and pain during the procedure. In particular, NNiqr, SDNN, and SD2 were significantly different in all time intervals with respect to the waiting room.

We confirmed the significance of the lfhf parameter for monitoring patients during surgery. Moreover, lfhf has potential for estimating postoperatively reported VAS, already in the waiting room. RMSSD, SD1, SD1SD2 as well as SampEn, also significantly correlated with VAS. On the other hand, NNskew and SD1SD2 have shown a significant correlation with DAS, which makes them DAS estimates. Even though vlf and lf significantly correlated with PARANT, it is only the NNskew that correlated significantly with PARANT during the procedure.

The estimates of HRV were calculated offline, but they could be integrated in the mobile application MobECG, that receives data in real time from the Savvy ECG monitor. This will enable real time assesment of stress, pain, and anxiety during dental procedures. Additionally, patients' responses to VAS and DAS could be predicted already in the waiting room.

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