Investigation of the Feasibility of Postoperative Pain Assessment Using Frequency Analysis of Photoplethysmogram Variability

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Abstract

Quantifying of pain is necessary for optimal dose of opioid. In pain quantification, there have been many attempts to analyze the photoplethysmography (PPG) waveform as a promising maker of autonomic function. In this paper, we investigate the feasibility of PPG amplitude variability (PPGV) as a novel marker of pain quantification. We derived 8 parameters related to the PPG amplitude and amplitude variability: $ACA_{baseline}$, ACA_{dia}, $PPGAV_{sys}$, $PPGAV_{dia}$, $PPGAV_{sys}/ACA_{baseline}$, $PPGAV_{sys}/ACA_{dia}$, $PPGAV_{dia}/ACA_{baseline}$ and $PPGAV_{dia}/ACA_{dia}$, and calculated frequency domain variables, TP, VLF, LF, HF, nLF, nHF and LF/HF, that have been used for heart rate variability analysis. Every parameter was derived in clinical dataset obtained before and after surgery, and a significant difference was statistically verified using paired *t*-test. Consequently, a significant difference ($p < 0.05$) was found in every derived variable except for most variables in $ACA_{baseline}$, ACA_{dia}, $PPGAV_{sys}$, $PPGV_{dia}$, in nHF of $PPGAV_{sys}/ACA_{baseline}$, in nHF, LF/HF of $PPGAV_{sys}/ACA_{dia}$, in nLF, nHF of $PPGAV_{dia}/ACA_{dia}$, and in nLF, nHF of $PPGAV_{dia}/ACA_{baseline}$. This result suggests that the possibility of frequency domain analysis of PPGV as a novel indicator of surgical pain quantification.

Keywords

Frequency analysis • Pain quantification
Photoplethysmography • Photoplethysmography variability

1 Introduction

Assessment of surgical pain has been attempted with difficulties because it is not easy to describe degree of pain objectively. There have been many attempts to quantify pain such as skin conductance-based method [1, 2], analgesia nociception index (ANI, Mdoloris Medical System, Lille, France) [3, 4] and surgical plethysmographic index (SPI, GE Healthcare, Chicago, USA) [5]. Skin conduction was reported to correlate significantly with a numeric rating scale (NRS) in postoperative pain [6] and ANI seems more sensitive than heart rate and systolic blood pressure to moderate nociceptive stimuli in propofol-anaesthetized patients [7]. Especially, SPI which based on continuous cardiovascular variables like heartbeat intervals (HBI) and photoplethysmography amplitude (PPGA) was evaluated as a promising index of postoperative pain assessment [8]. The result of SPI could be interpreted as changes of heart rate and blood volume with sympathetic activation [9, 10]. In this study, we consider the possibility of assessing surgical pain by analyzing PPG amplitude variability (PPGV) as another pain indicator. For this, we assumed that the PPGV has relevance with blood pressure variability (BPV), which is a method to measure systolic blood pressure and detect changes in the short or long term and estimates the physiological state via the mean of the measured blood pressure or a standard deviation [11], because blood volume could be proportionally changed with blood pressure excluding the consideration of vascular property. In analyzing PPGV, we adapted frequency domain analysis metric of heart rate variability (HRV).

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2 Methods

2.1 Dataset

Sixty surgical patients (29 males, 31 females, 52.1 ± 11.4 years old) were enrolled to the experiment, and 58 pair of dataset was used except 2 pair of dataset which has recording error. According to the protocol, PPG data was recorded before and after surgery, and dataset recorded before and after surgery were regarded as a painless and pain dataset, respectively. Every record has 6-min length of 300 Hz sampling frequency. To calculate the area of PPG waveform, every upper and lower peak location of the PPG waveform was detected and validated by proficient researchers.

2.2 Parameter Extraction

Derived parameters were defined as the amplitude from baseline to systolic peak ($ACA_{baseline}$), the amplitude from diastolic peak to systolic peak (ACA_{dia}), the amplitude difference of adjacent systolic peaks ($PPGAV_{sys}$), the amplitude difference of adjacent diastolic peaks ($PPGAV_{dia}$), the ratio of $PPGAV_{sys}$ to $ACA_{baseline}$ ($PPGAV_{sys}/ACA_{baseline}$), the ratio of $PPGAV_{sys}$ to HPH ($PPGAV_{sys}/HPH$), the ratio of $PPGAV_{dia}$ to ACA ($PPGAV_{dia}/ACA$), and the ratio of $PPGAV_{dia}$ to HPH ($PPGAV_{dia}/HPH$). Figure 1 shows the graphical representation of parameters, and Eqs. (1)–(5) represents mathematical equation of ACA_{dia}, BP, $ACA_{baseline}$, $PPGAV_{sys}$, $PPGAV_{dia}$, respectively (see Table 1).

$$ACA_{dia} = PPGA_{sys}(k) - PPGA_{dia}(k) \tag{1}$$

$$BP(k) = \frac{PPGA_{dia}(k+1) - PPGA_{dia}(k)}{Time_{dia}(k+1) - Time_{dia}(k)} \left\{Time_{sys}(k) - Time_{dia}(k)\right\} + PPGA_{dia}(k) \tag{2}$$

$$ACA_{baseline} = PPGA_{sys}(k) - BP(k) \tag{3}$$

$$PPGAV_{sys} = PPGA_{sys}(k+1) - PPGA_{sys}(k) \tag{4}$$

$$PPGAV_{dia} = PPGA_{dia}(k+1) - PPGA_{dia}(k) \tag{5}$$

2.3 Validation

Every parameter was derived in pain and painless dataset, and it was verified whether there is significant different using paired *t*-test.

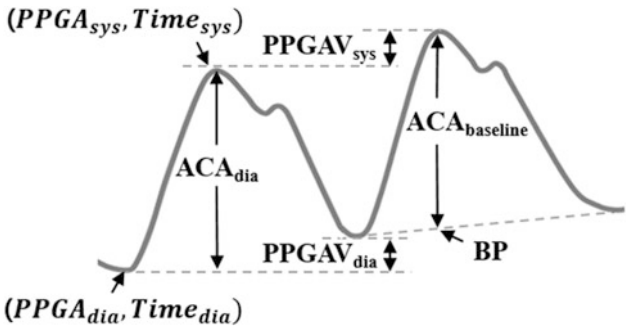

Fig. 1 PPG waveform and derived parameters

3 Result and Discussion

Table 2 shows that the mean, standard deviation, coefficient of variation and significance of difference of the result according to the nociceptive pain. As a result, statistical difference was not found in TP, VLF, LF, HF, nLF of $ACA_{baseline}$, TP, LF, HF, nLF of ACA_{dia}, TP, VLF, KF, HL, nHF of $PPGAV_{sys}$, TP, VLF, LF, HF, nLF, nHF of $PPGV_{dia}$, nHF of $PPGAV_{sys}/ACA_{baseline}$, nHF, LF/HF of $PPGAV_{sys}/ACA_{dia}$ and nLF, nHF of $PPGAV_{dia}/ACA_{dia}$, nLF, nHF of $PPGAV_{dia}/ACA_{baseline}$. LF component of BPV reflects sympathetic vasomotor activity which is known as Mayer wave [12–17]. Otherwise, high frequency component of BPV reflects mechanical function of hemodynamics

Table 1 Extracted parameters

No.	Parameter name	Unit	Parameter definition
1	$ACA_{baseline}$	a. u.	AC amplitude from baseline to systolic peak
2	ACA_{dia}	a. u.	AC amplitude from diastolic peak to systolic peak
3	$PPGAV_{sys}$	a. u.	Systolic PPGA variation
4	$PPGAV_{dia}$	a. u.	Diastolic PPGA variation
5	$PPGAV_{sys}/ACA_{baseline}$	n. u.	Ratio of $PPGAV_{sys}$ to $ACA_{baseline}$
6	$PPGAV_{sys}/ACA_{dia}$	n. u.	Ratio of $PPGAV_{sys}$ to ACA_{dia}
7	$PPGAV_{dia}/ACA_{baseline}$	n. u.	Ratio of $PPGAV_{dia}$ to $ACA_{baseline}$
8	$PPGAV_{dia}/ACA_{dia}$	n. u.	Ratio of $PPGAV_{dia}$ to ACA_{dia}

Table 2 Statistical changes of derived parameters

No.	Parameters		Mean (standard deviation)		Coefficient of variation		*p*-value
			Before	After	Before	After	
1	$ACA_{baseline}$	TP	8.75 (12.53)	8.50 (11.43)	143.16	134.50	0.348
2		VLF	1.43 (1.59)	1.20 (1.42)	110.68	118.55	0.052
3		LF	0.72 (0.60)	0.60 (0.57)	83.72	95.34	0.108
4		HF	0.44 (0.37)	0.51 (0.50)	84.42	98.49	0.990
5		nLF	13.55 (5.04)	11.92 (5.58)	37.23	46.81	0.059
6		nHF	8.42 (3.63)	9.96 (4.39)	43.11	44.08	<0.05
7		LF/HF	1.73 (0.58)	1.29 (0.58)	33.30	44.60	<0.001
8	ACA_{dia}	TP	9.35 (16.07)	9.16 (12.57)	171.97	137.27	0.321
9		VLF	1.48 (1.95)	1.23 (1.51)	131.85	122.09	0.039
10		LF	0.73 (0.61)	0.61 (0.58)	83.58	95.41	0.115
11		HF	0.48 (0.41)	0.55 (0.58)	85.22	100.72	1.000
12		nLF	12.94 (5.05)	11.43 (5.49)	39.01	48.09	0.078
13		nHF	8.56 (3.76)	10.11 (4.51)	43.98	44.62	<0.05
14		LF/HF	1.63 (0.55)	1.22 (0.5)	33.54	44.85	<0.001
15	$PPGAV_{sys}$	TP	8.47 (36.17)	5.58 (7.28)	426.92	130.55	0.526
16		VLF	1.10 (5.37)	0.61 (0.88)	488.30	145.36	0.171
17		LF	0.22 (0.27)	0.40 (0.66)	124.88	163.13	0.059
18		HF	0.28 (0.23)	0.42 (0.50)	81.81	119.38	0.423
19		nLF	8.65 (4.72)	10.51 (5.32)	54.52	50.60	<0.05
20		nHF	13.13 (7.01)	12.65 (5.58)	53.39	44.09	0.642
21		LF/HF	0.78 (0.58)	0.85 (0.29)	74.41	33.83	<0.01
22	$PPGAV_{dia}$	TP	4.62 (13.77)	3.09 (3.33)	298.19	107.88	0.515
23		VLF	0.55 (2.00)	0.25 (0.26)	362.65	104.57	0.251
24		LF	0.18 (0.18)	0.29 (0.33)	103.11	115.52	0.160
25		HF	0.23 (0.21)	0.35 (0.40)	88.84	114.23	0.459
26		nLF	9.49 (5.09)	10.74 (4.91)	53.60	45.66	0.091
27		nHF	14.01 (6.69)	13.58 (4.88)	47.79	35.97	0.646
28		LF/HF	0.77 (0.56)	0.79 (0.23)	72.73	29.31	<0.05
29	$PPGAV_{sys}/ACA_{baseline}$	TP	5.56 (32.57)	3.76 (5.36)	585.51	142.62	<0.001
30		VLF	0.78 (4.82)	0.41 (0.65)	620.06	158.08	<0.001
31		LF	0.08 (0.21)	0.30 (0.63)	258.91	210.15	<0.001
32		HF	0.08 (0.05)	0.31 (0.45)	68.66	145.99	<0.001
33		nLF	8.29 (4.68)	10.07 (5.04)	56.44	50.01	<0.05
34		nHF	12.84 (7.06)	12.30 (5.39)	54.97	43.79	0.592
35		LF/HF	0.75 (0.57)	0.87 (0.34)	75.26	39.55	<0.01
36	$PPGAV_{sys}/ACA_{dia}$	TP	2.35 (11.53)	1.82 (1.82)	490.70	99.84	<0.001
37		VLF	0.31 (1.71)	0.16 (0.15)	542.32	95.16	<0.001
38		LF	0.06 (0.08)	0.17 (0.20)	138.54	118.12	<0.001
39		HF	0.07 (0.04)	0.20 (0.20)	62.41	100.84	<0.001
40		nLF	9.38 (4.88)	10.45 (4.53)	52.04	43.38	0.133
41		nHF	14.04 (6.60)	13.35 (4.83)	47.03	36.17	0.447
42		LF/HF	0.76 (0.57)	0.79 (0.24)	74.90	30.44	<0.01

(continued)

Table 2 (continued)

No.	Parameters		Mean (standard deviation)		Coefficient of variation		*p*-value
			Before	After	Before	After	
43	$PPGAV_{dia}/ACA_{baseline}$	TP	5.05 (28.66)	4.03 (5.99)	567.37	148.51	<0.001
44		VLF	0.70 (4.24)	0.44 (0.75)	604.91	169.14	<0.001
45		LF	0.08 (0.18)	0.34 (0.78)	237.98	229.36	<0.001
46		HF	0.08 (0.05)	0.34 (0.53)	64.32	158.31	<0.001
47		nLF	8.22 (4.65)	10.08 (5.10)	56.58	50.54	<0.05
48		nHF	12.83 (7.11)	12.34 (5.42)	55.44	43.90	0.635
49		LF/HF	0.75 (0.57)	0.87 (0.36)	75.83	42.05	0.050
50	$PPGAV_{dia}/ACA_{dia}$	TP	2.20 (10.21)	2.06 (2.31)	464.54	112.24	<0.001
51		VLF	0.29 (1.51)	0.17 (0.18)	519.13	106.60	<0.001
52		LF	0.05 (0.07)	0.19 (0.26)	126.73	131.65	<0.001
53		HF	0.07 (0.04)	0.24 (0.28)	64.80	120.16	<0.001
54		nLF	9.20 (4.81)	10.36 (4.48)	52.25	43.27	0.113
55		nHF	13.91 (6.66)	13.44 (4.82)	47.88	35.87	0.606
56		LF/HF	0.75 (0.56)	0.78 (0.25)	74.27	31.57	<0.01

according to the pressure change inside thoracic cage [15]. In the result of this study, LF value of $ACA_{baseline}$ and ACA_{dia} was decreased but there is no statistical significance, moreover, $PPGAV_{sys}$ and $PPGAV_{dia}$ also shows increases with no significance. However, in every normalized parameter, LF value is increased with statistical significance ($p < 0.05$). This result could be interpreted that normalization reduced the ambiguity of PPG amplitude which is measured as an arbitrary unit. In terms of parameters, amplitude variability parameter, $PPGAV_{sys}$, $PPGAV_{dia}$ shows clear classification result compared with simple amplitude-based variables, $ACA_{baseline}$ and ACA_{dia}. This result suggests that the frequency domain variables of PPGV has a possibility in pain quantification and that the significant changes were reflected better in normalized variables.

4 Conclusion

In this study, we investigated PPGV in surgical pain quantification. We derived frequency domain variable of PPGV before and after surgery and found that there is a significant difference ($p < 0.05$) in PPGV variables according to the pain stimuli. Especially, result indicated that a clear difference was found in normalized PPGV variables. Consequently, the result of this study suggests that the possibility of frequency domain analysis of PPGV as a novel indicator of surgical pain quantification.

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