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Original Article

Poincaré plot indexes of heart rate variability detect dynamic autonomic modulation during general anesthesia induction

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A B S T R A C T

Purpose: Beat-to-beat heart rate variability (HRV) is caused by the fluctuating balance of sympathetic and parasympathetic tone. The Poincaré plot has been used to evaluate HRV. In this study, we validate that this new method may qualitatively and quantitatively assess the sympathovagal fluctuation in patients during induction of anesthesia with sevoflurane.
Methods: Twenty-eight young patients were allocated for the study. The patients received a tilt test and on the next day they sustained anesthesia induced with inhaled anesthetics. Electrocardiography signals from the patients were relayed to an analogue-digital converter. The Poincaré plot is quantified by measuring SD1, SD2, and SD1/SD2. Power spectral analyses were performed and LF, HF and HF/LF were calculated.
Results: The LF power and the SD2 of the Poincaré plot increased while subjects were tilt-up from the supine position. Additionally, a significant correlation were found between LF and SD2, HF and SD1 ($p < 0.05$), and LF/HF and SD2/SD1 ($p < 0.01$). Sevoflurane inhalation for 10 minutes had no effect on heart rate, but diminished LF, total power and SD1, SD2 of the Poincaré plot respectively. However, the LF, SD2 and LF/HF increased; the HF, SD1 and SD1/SD2 ratio decreased after intubation stimulation.
Conclusion: Poincaré plot and power spectral analysis of HRV during tilt test and sevoflurane induction significantly correlate. Poincaré plot analysis is easier and more sensitive at evaluating the sympathovagal balance and observing the beat-to-beat HRV.

1. Introduction

Beat-to-beat heart rate variability (HRV) is caused by a fluctuating balance between sympathetic tone and parasympathetic tone at the sino-atrial node. It is used for markers of autonomic modulation of the heart. The standard methods for analyzing HRV include: statistical (time domain), power spectral (frequency domain) and nonlinear geometrical analysis. Time and frequency domain methods provide a noninvasive, linear means of assessing the regulation of the autonomic system. It has been used in several clinical investigations, such as cardiac autonomic function, post-myocardial infarction risk stratification, etc. However, time and frequency domain methods have got some technical limitations such as stationary requirement and the linear assumptions in which these techniques are based, and in some cases these methods are insensitive and more susceptible to interference by ectopic rhythm.

The Poincaré plot analysis is a geometrical and nonlinear method to assess the dynamics of HRV.[1] It is a diagram in which each R-R interval is plotted as a function of the previous R-R interval where the values of each pair of successive R-R interval define a point in the plot. Poincaré plots have been evaluated in a qualitative way using their visual pattern whereby the shape of the plot is categorized into functional classes that indicate the degree of heart failure[2] and can be evaluated quantitatively through the

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computation of the SD indexes of the plot. The plot provides summary information as well as detailed beat-to-beat information on the behavior of the heart.[3] The previous studies have focused on the change in spectral components of HRV during perioperative events in surgery.[4,5] However, the continuous change in Poincaré plots of HRV and the possible effects of the various events especially during induction have not been investigated. Using Poincare plot analysis may be a better way to monitor the dynamic change of autonomic function during anesthesia.

Therefore, the objectives of this study are to validate this new method of qualitative and quantitative assessment of Poincaré plot, and to apply Poincaré plot analysis in the evaluation of the perturbation of autonomic function during induction of general anesthesia.

2. Method

This study has been approved by the Ethical Committee on Human Research of our institute. After informed consent had been obtained, 28 American Society of Anesthesiologists (ASA) physical status I patients who had undergone elective surgery, were included. The age distribution was 22 $\pm$ 5 years. They were free of cardiovascular, pulmonary, neurological, diabetic and thyroid disorders. The day before operation, the tilt test was performed for each patient. No premedication was administered before surgery.

2.1. *Tilt test*

In the afternoon of the day before surgery, the patients underwent cardiovascular autonomic function tests using continuous monitoring with electrocardiography (ECG). Postural changes in ECG were measured for three segments, with each segment measuring lasting for 5 minutes. The collection of HRV in the supine position data began 5 minutes after the tilt to 85 degrees to allow the heart rate to stabilize. Blood pressure was continuously monitored and recorded by noninvasive blood pressure measurement every 1 minute.

2.2. *General anesthesia induction*

In the operating room, ECG, noninvasive arterial pressure, pulse oximetry, end-tidal CO_2, and the anesthetic agent were monitored (Compact, Datex Corp., Finland). General anesthesia was induced with 5.1% sevoflurane and N_2O in 50% O_2 (6 L/minute O_2) for 10 minutes, then, suxamethonium 2 mg/kg was given for tracheal intubation after priming with a small dose of rocuronium. During the induction of anesthesia with inhalation agents, the patients were encouraged to breathe spontaneously at a fixed rate of 10 breaths per minute, and after intubation, mechanical ventilation, set at a rate of 10 breaths per minute, and tidal volume set at 10 mL/kg. All patients were well hydrated during induction with normal saline solution 250 mL to forestall hypotension. We recorded the electrocardiogram continuously using an analog data recorder (Compact, Datex Corporation, Finland) registered throughout the procedure. Indirect blood pressure and heart rate were also recorded every 1 minute (model BP-508; Colin, Komaki, Japan). HRV was evaluated using computer software (Chart Extensions, MacLab version 3.5; AD Intruments, Castle Hill, Australia) and analyzed at 5-minute intervals for the following four periods: (1) baseline, 5 minutes before the start of sevoflurane (5.1%) inhalation; (2) preintubation, 5 minutes after sevoflurane (5.1%) inhalation to the time of laryngoscopy (the patient was under the effect of sevoflurane during this period); (3) postintubation, 5 minutes after laryngoscopy and tracheal intubation; (4) maintenance, 5-minute intervals after post-intubation period under 5.1% sevoflurane inhalation for 5 minutes.

2.3. *Analysis of heart rate variability*

ECG signals were recorded by a 12-bit analog to digital converter and sampled at 500 Hz on a personal computer using a program based on commercially available software (Lab-VIEW; National Instruments, Austin, TX) as designed by our group. The signals were filtered digitally and processed to extract QRS peaks which determine the R-R intervals. These QRS peaks were automatically detected and were reviewed visually for R-wave determination and ectopic beats by a single investigator. Areas in which identification of beats was poor or ectopic beats were noted were excluded. The geometric and frequency domain indices were computed from 5-minute segments. In the tilt test, the procedure was divided into three segments, including supine, tilt, and supine period. During general anesthesia, the four segments including baseline, preintubation, postintubation, and maintenance periods were computed for analysis.

2.4. *Nonlinear geometric measures*

These have been derived from the 5-minute Poincaré plot representing a diagram in which each R-R interval of tachogram is plotted against the previous R-R interval. Quantitative analysis of the shape of the plot was performed using these segments during general anesthesia and tilt test. The markings of the plot are gathered around a line (slope $=$ 1) of unitary slope (line of identity) passing through the origin. The center point of the plot represents the average R-R interval length for the tachogram. The quantitative analysis of a plot entails fitting an ellipse to the plot, with its center coinciding with the center point of the markings,[6] and comparing points from two lines traversing through the center point of the data, longitudinal and transverse. The line describing the slope of the longitudinal axis was defined as the long axis (LA), while the transverse slope, which is perpendicular in direction to long axis, was defined as short axis (SA). The length of the longitudinal line is defined as the SD2 of the plot data. The length of the transverse line is defined as the SD1 of the plot data in perpendicular direction. The Poincaré index (SD1, SD2, SD1/SD2 ratio) was computed. We have used previously presented criteria for the patterns of the plots. A normal configuration of the plot was defined as a fan or comet shape. Abnormal forms were a random pattern characterized by asymmetrical RR-interval clusters; a torpedo-shaped pattern with narrow configuration that lacked RR-interval dispersion.

2.5. *Frequency domain measures*

From the R-R intervals originating from the 5-minute segment, power spectral analyses of each consecutive 5-minute recording were performed in a sequential fashion with the use of a fast Fourier transform. Careful manual editing of the RR-interval series with inspection of the ECG data by deleting premature beats and noise was also performed. A fixed re-sampling frequency of 1024 equally spaced points per 5-minute period was used. The powers in the LF band (0.04–0.15 Hz) and in the HF band (0.15–0.50 Hz) were calculated for each 5-minute density spectrum by integrating the power spectral density in the respective frequency bands. The HF/LF ratio also was analyzed.

2.6. *Statistics*

Data were processed using SPSS version 14.0 (SPSS Inc., Chicago, IL, USA). All data were expressed as the mean $\pm$ standard deviation. The hemodynamic variables, LF, HF, LF/HF ratio, SD1, SD2, SD1/SD2 ratio were analyzed by repeated-measures analysis of variance with Bonferroni correction. Correlations between the HRV measures

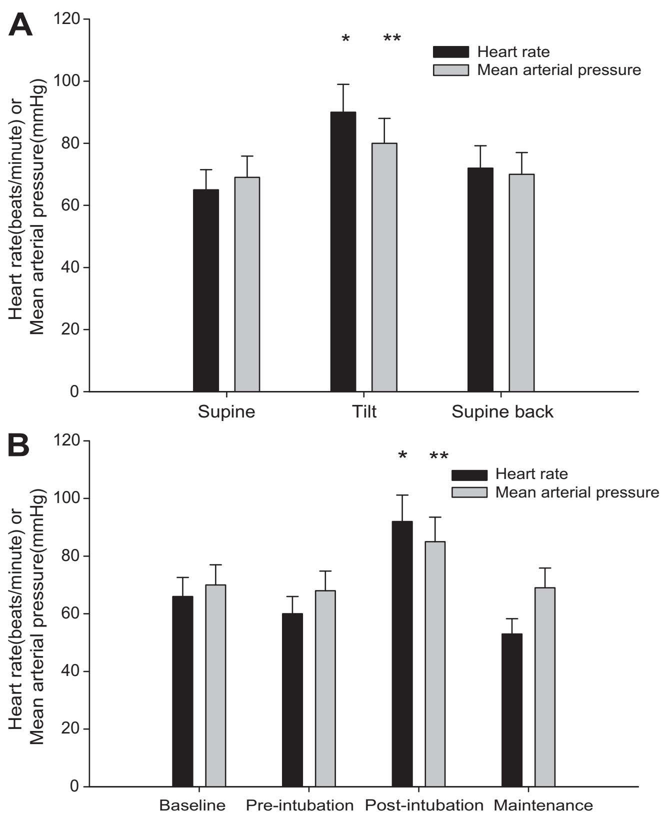

Fig. 1. Mean arterial pressure and heart rate during (A) the tilt test and (B) induction of anesthesia. *Compared with supine and pre-intubation, $p < 0.05$ statistically significant. **Compared with supine and pre-intubation, $p < 0.05$ statistically significant.

were assessed by using the Pearson correlation test. A value of $p < 0.05$ was considered significant.

3. Results

The hemodynamics during the study is shown in Fig. 1. All subjects were of male gender with age 22 ± 5 years, height 169 ± 4 cm, and weight 63.6 ± 12 kg. In the tilt test, to facilitate the comparison of HRV change between the supine and tilt positions, the average HRV in the baseline supine position (LF, HF, LF/HF, SD1, SD2, SD1/SD2) in 28 subjects was standardized as 1.000. During the tilt position, the LF and SD2 turned higher than the supine position (LF, $p < 0.05$). The HF, SD1 turned lower (SD1, $p < 0.05$). The LF/HF, SD1/SD2 ratio showed a significant change ($p < 0.05$). When the patients turned back to the supine position, the HRV indexes returned back. The results are summarized in Table 1. In the Poincaré plots, during the supine position, the plots showed an oval shape; during the tilt position, the plots turned into a torpedo shape (Fig. 2).

In the general anesthesia, the baseline HRV indexes were set as 1.000. The end-tidal concentration of sevoflurane was 3 ± 0.4% at intubation, 5 minutes after intubation 3.2 ± 0.3%, and 10 minutes after intubation 3.5 ± 0.17% respectively. During the preintubation period the patients were under the sevoflurane inhalation, and the LF, HF, SD1, SD2 were lower (LF, SD2 $p < 0.05$), and LF/HF, SD1/SD2 showed no obvious changes. During the postintubation period, as compared with the preintubation period the LF and SD2 turned higher than that in the supine position (LF, SD2, $P<0.05$). The HF, SD1 turned lower (HF, SD1, $p < 0.05$). The LF/HF, SD1/SD2 ratio all showed a significant change ($p < 0.05$). During the maintenance period, there was a universal decrease in the HRV. The results are summarized in Table 2. In the Poincaré plots, the shape turned from oval to torpedo in the postintubation period, as illustrated in Fig. 3.

When we correlated the power spectral indexes with Poincaré plot indexes in the tilt test, we found a close correlation between LF and SD2 ($r = 0.561$, $p < 0.05$); HF and SD1($r = 0.621$, $p < 0.01$); LF/HF and SD2/SD1($r = 0.881$, $p < 0.01$) in our study, as illustrated in Table 3 and Fig. 4.

4. Discussion

The results of our study show that during stress events in the tilt test and anesthetic induction, the sympathetic changes are reflected both by the spectral and Poincaré plot analysis of HRV. In the spectral analysis, during the tilt-up position and postintubation period, the patient's sympathetic activity is stimulated with concomitant parasympathetic withdrawal; the HF reduces, the LF increase, and LF/HF ratio increases just as previous study has shown.[4] However, the Poincaré plots have more advantages; they can offer an instant and visually-presented change of sympathovagal balance. In the Poincaré plots, during the tilt-up position and postintubation period, the SD1 decreases, the SD2 increases, and SD1/SD2 ratio decreases instantly after the sympathetic stimulation with a concurrent change of shape. The plots changes from a fan shape to a narrower torpedo-like shape and with deepening of anesthesia, the plots converge to a small range of points.

The spectral and Poincaré plot analysis of HRV are applied widely to monitor the sympathovagal change.[3,7,8] The significance of all the HRV measurement has been verified under the correlation with various physiological variables which reflect the changing of autonomic balance.[9] The HF reflects parasympathetic activity, the LF reflects the sympathetic modulation, and LF/HF ratio indicates sympathovagal balance.[3,7] However, the method is often interrupted by sudden changes in heart rate, because it must assume that the data within the samples are stationary.[10] The change of breathing pattern from controlled to spontaneous breathing also affects the HRV data decreasing the HF component significantly.[10] Therefore, it may not be an ideal method in the assessment of cardiac vagal outflow during the operation with variable rate and depth of breathing.

The Poincaré plot is a geometrical representation that permits the visual identification of the presence of non-linear HRV components.[11] In the Poincaré plots, the SD1 width reflects the parasympathetic activity; and the SD2 length reflects the sympathetic modulation.[12] The shape of Poincaré plot can be used to visually evaluate the sympathovagal activity. An elongated, torpedo-like shape with decreased SD1/SD2 ratio is associated with elevated

Table 1
Power spectral indexes (LF, HF, LF/HF) and Poincaré plot indexes (SD1, SD2, SD1/SD2) during tilt test ($n = 28$).

Tilt test	LF	HF	LF/HF	SD1	SD2	SD1/SD2
Supine	1.000	1.000	1.000	1.000	1.000	1.000
Tilt	1.649 ± 0.269*	0.896 ± 0.093	1.841 ± 0.181*	0.653 ± 0.067*	1.203 ± 0.129	0.542 ± 0.044*
Supine	0.987 ± 0.069	1.102 ± 0.132	0.959 ± 0.113	1.204 ± 0.092	1.135 ± 0.119	1.104 ± 0.064

* Compared with supine, statistically significant $p < 0.05$.

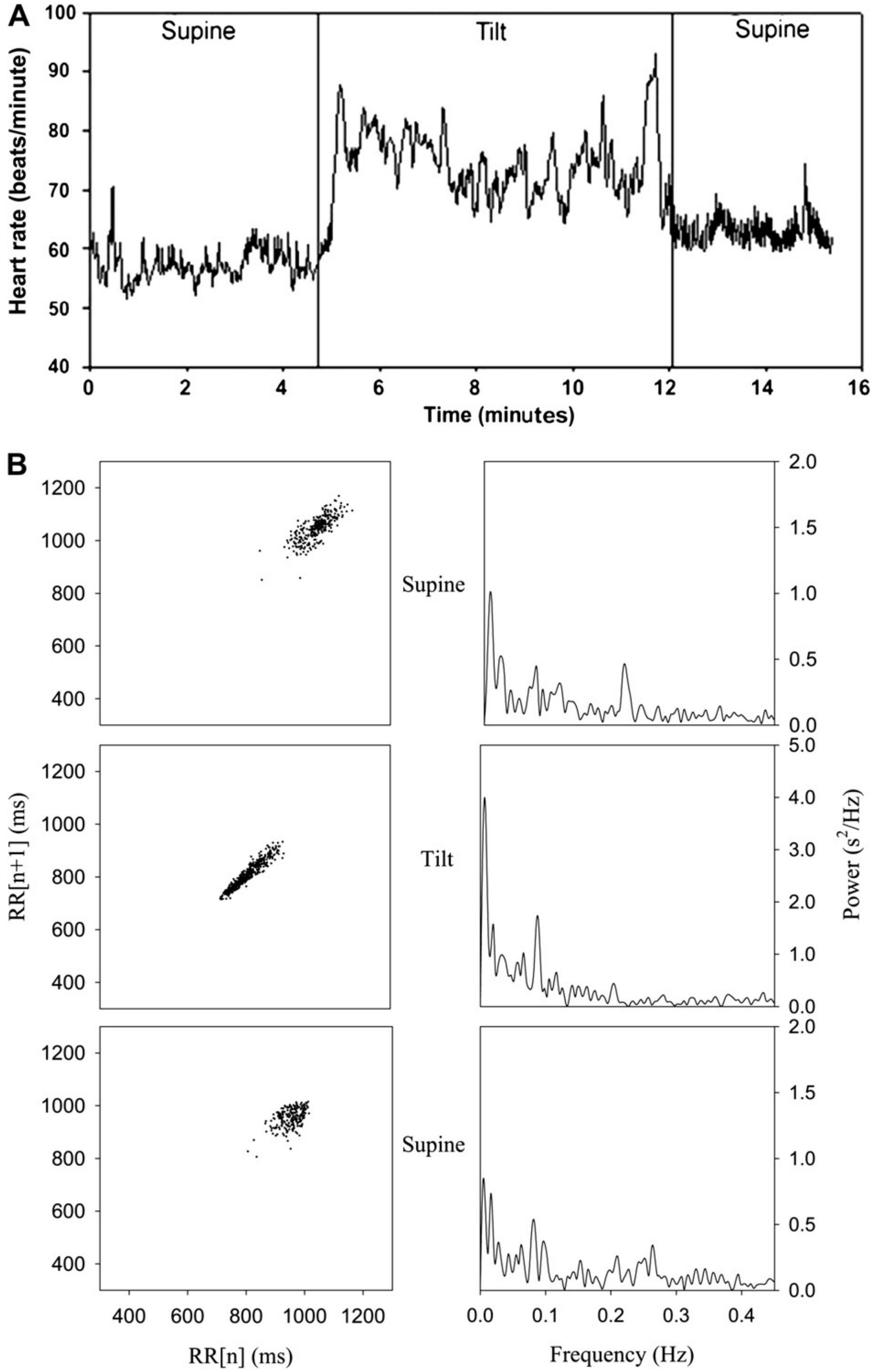

Fig. 2. (A) Representative heart rate changes and (B) power spectral and Poincaré plot during tilt test.

Table 2
Power spectral indexes (LF, HF, LF/HF) and Poincaré plot indexes (SD1, SD2, SD1/SD2) during induction of anesthesia ($n = 28$).

	LF	HF	LF/HF	SD1	SD2	SD1/SD2
Baseline	1.000	1.000	1.000	1.000	1.000	1.000
Pre-intubation	0.574 ± 0.142*	0.617 ± 0.141	0.983 ± 0.161	0.695 ± 0.170	0.597 ± 0.106*	1.089 ± 0.151
Post-intubation	1.016 ± 0.051**	0.602 ± 0.066*	1.751 ± 0.186*,**	0.556 ± 0.091*	1.670 ± 0.198*,**	0.313 ± 0.061*,**
Maintenance	0.353 ± 0.067*	0.266 ± 0.072*	1.558 ± 0.306	0.394 ± 0.09*	0.338 ± 0.093*	1.250 ± 0.133

* Compared with baseline, $p < 0.05$ statistically significant.
** Compared with pre-intubation, $p < 0.05$ statistically significant.

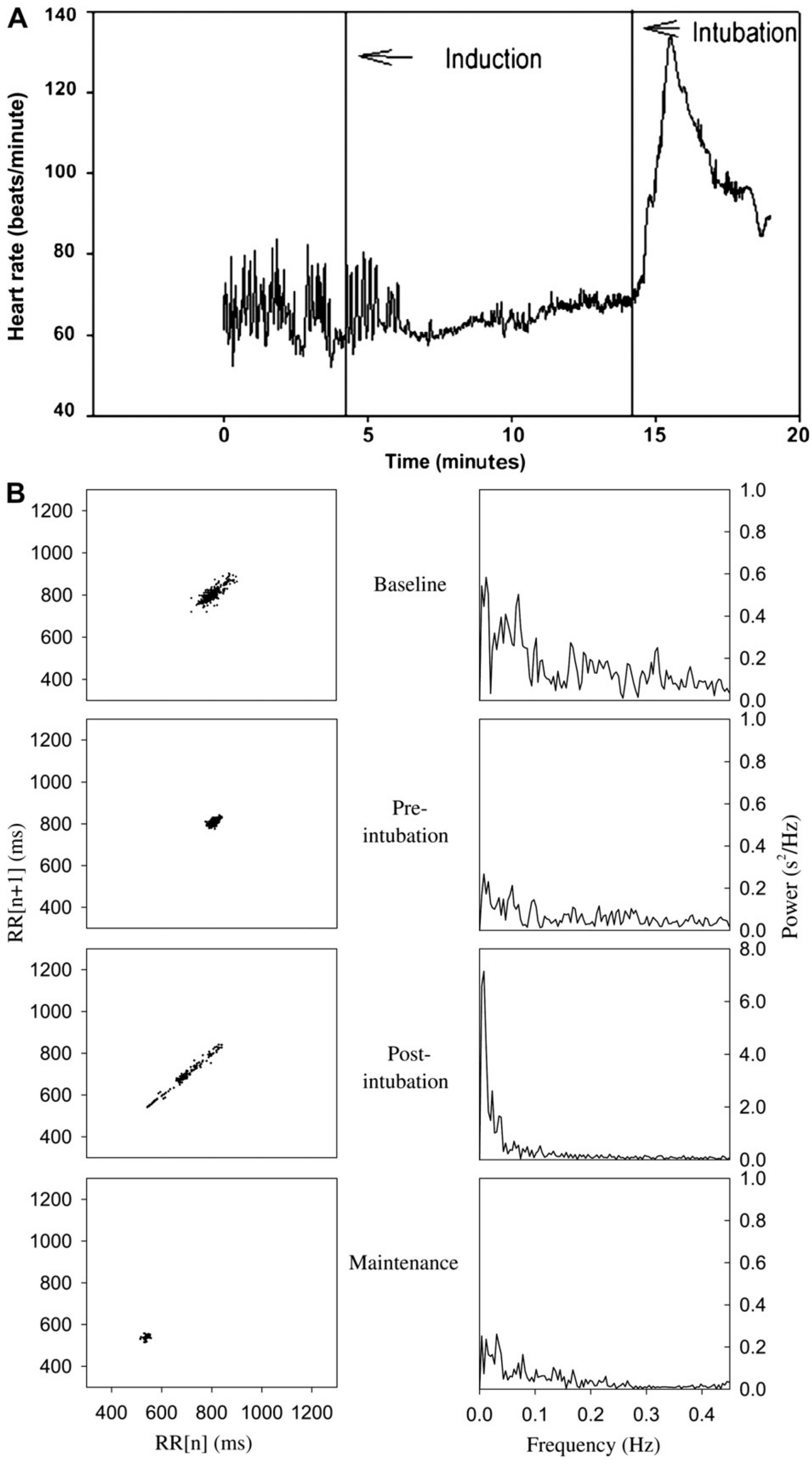

Fig. 3. (A) Representative heart rate changes and (B) power spectral and Poincaré plot during induction of anesthesia (baseline, preintubation, postintubation, maintenance).

Table 3
Correlation of power spectral indexes (LF, HF, LF/HF) and Poincaré plot indexes (SD1, SD2, SD1/SD2) during tilt test.

	LF	HF	LF/HF	SD2	SD1	SD2/SD1
LF	1.00	0.686*	0.507*	0.561*	0.129*	0.332
HF		1.00	−0.24	0.626**	0.621**	−0.295
LF/HF			1.00	0.108	−0.484	0.811**
SD2				1.00	0.674**	0.074
SD1					1.00	−0.653
SD2/SD						1.00

* $p < 0.05$.
** $p < 0.01$.

sympathetic tone, and a more oval, fan-shaped configuration resulting from increased SD1/SD2 ratio indicates less sympathetic tone.[2,13] The points get more scattered when vagal activity increases, or the sympathetic activity decreases. When anesthesia deepens, the autonomic activity lessens which results in decreased SD1, SD2, and converged Poincaré plots. This shape may be seen in the condition of brain death in which the total autonomic activity is lost.[14] Moreover, the width of SD1 can be used to quantify the short-term vagal modulation of the heart rate.[3,15] The abruptly-decreased SD1 is shown in a rapid manner, especially after the autonomic changes, such as during laryngoscopy or intubation, and therefore it can be used as a sensitive indicator of sympathovagal changes.

The Poincaré plot may uncover abnormalities that are not easily detectable with traditional time and frequency domain measures.[16] In clinical settings, Poincaré plot analysis of R-R intervals provides prognostic information on patients with heart failure and on patients vulnerable to life-threatening arrhythmias.[17,18] It has been shown that during accentuated sympathovagal activation the heart rate behavior becomes remarkably unstable. These features of heart rate dynamics can be better identified by dynamic analysis of Poincaré plot than by traditional analysis techniques of HRV.[19] The Poincaré plots which use the unfiltered data have a relatively high intra-individual reproducibility than other measures of HRV.[20] It has an advantage of being able to identify beat-to-beat cycles and patterns in the data.[2,21] Moreover, the Poincaré plot index SD1 is less affected by changing breathing rate.[22] The interfering factor by respiratory sinus arrhythmia (RSA) can be easily identified and removed in the plots.[13] In our study, the breathing rate and depth are kept as steady as possible to reduce the respiratory modulation on the HF component, and facilitate the analysis. Thus, the Poincaré plot may be better in the use of dynamic analysis than spectral analysis.

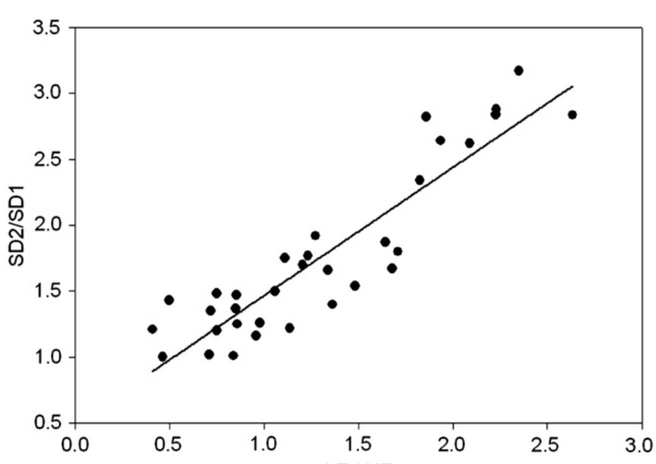

Fig. 4. Correlation between LF/HF and SD2/SD1, r = 0.811.

The spectral measures and Poincaré plots are fundamentally based on the measurement of the magnitude of HRV, even though the computation and analysis of are different. Therefore, it is not surprising that Poincaré plot analysis and spectral measures have a relatively strong correlation with each other. In our study, we have found a good correlation between spectral and Poincaré analysis. The LF/HF has a good correlation with the SD2/SD1 ratio. The relations (SD1, HF), (SD2, LF) and (LF/HF, SD2/SD1) are mathematically equivalent measures.[13,23] Like HF/LF ratio, the SD1/SD2 ratio can reflect the sympathovagal balance; moreover, it offers better discrimination capability among the maneuvers of different vagal activity level[9] and can even discern the nonlinear information of HRV which is not evident in the linear analysis.[24]

In conclusion, we can more readily detect the sympathovagal changes through the change of shapes in the plots especially during the tilt position and in the postintubation period. The Poincaré plot is visually more discernible to detect this autonomic change, showing the potential to evaluate the dynamic change during anesthesia. For a better dynamic monitoring during the anesthetic course, the Poincaré plot provides a qualitatively and quantitatively visual measure of autonomic nervous system activity.

Acknowledgments

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