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Analysis of heart rate and blood pressure variability to assess autonomic reserves: its role in anesthesiology

By Alain Deschamps, MD and André Denault, MD

The discovery of general anesthesia was one of the most important advancements in medicine during the last century; however, this advancement came at a price. General anesthesia inhibits pain, but it also results in the inhibition of the autonomic nervous system (ANS), such that, in certain conditions it can be life-threatening. Therefore, anesthesiologists must constantly monitor their patients' ANS, relying on end-organ responses such as heart rate (HR) and blood pressure (BP) for this purpose. As a result, the measurement of baseline autonomic tone, its response to disease states and the various stimuli associated with anesthesia and surgery are of great interest to the anesthesiologist. New noninvasive methods are currently being developed to obtain precise measurements of parasympathetic and sympathetic output, allowing an ability to detect autonomic dysfunction and to monitor perioperative autonomic tone. These measurements are based on heart rate variability (HRV) and blood pressure variability (BPV). This issue of *Anesthesiology Rounds* explains the analysis principles for HRV and BPV, and discusses their usefulness for anesthesiologists.

In his acceptance lecture, in 1949, the Nobel Price winner in Physiology and Medicine, Walter Hess, offered the best description for the significance of the ANS in the orchestration of systemic interactions:

"A recognized fact, which goes back to the earliest times, is that every living organism is not the sum of a multitude of unitary processes, but is, by virtue of interrelationships and of higher and lower levels of control, an unbroken unity."

In the operating theatre, anesthesia monitors are a constant reminder of the patient's autonomic balance through the display of HR, BP, respiratory rate (with resulting end-tidal CO_2 and O_2 saturation), and temperature. In fact, anesthesiology textbooks have chapters dedicated entirely to the ANS. Throughout their residency and practice, anesthesiologists must gain expertise in maintaining the fragile balance between autonomic outflow and maintenance of cardiorespiratory, endocrine, and temperature homeostasis.

Nevertheless, none of the patient's preoperative testing and none of the monitoring tools available in the perioperative period include measurements of baseline autonomic function. Consequently, pharmacological adjustments to apparent changes in autonomic tone are made without knowledge of the direction and amplitude of the changes in parasympathetic and sympathetic output, the two branches of the ANS. Indeed, the question of concern is how do we evaluate the ANS?

Autonomic tone can be measured directly, through electrodes implanted into autonomic nerves, but these methods are invasive and should be reserved for research protocols. There is growing evidence that noninvasive techniques of analysis for HRV and BPV could be used to obtain measures of autonomic dysfunction preoperatively and determine the balance between the parasympathetic and sympathetic nervous systems intra- and postoperatively. The ability to use preoperative baseline measurements of the ANS as part of the risk stratification process could represent an invaluable tool for the anesthesiologist; this approach is currently being pursued in several centres.

University of Montreal
Department of Anesthesiology
Faculty of Medicine

Université de Montréal
Faculty of Medicine
Department of Anesthesiology

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AUTONOMIC DYSFUNCTION AND THE CONTROL OF CARDIOVASCULAR AND RESPIRATORY SYSTEMS BY CARDIOVASCULAR REFLEXES

It is not a coincidence that the integrated balance between parasympathetic and sympathetic outflow is responsible for maintaining adequate oxygen delivery to tissues without our conscious knowledge. It is because human consciousness is too busy "burning up" oxygen. The cardiovascular and respiratory reflex control of oxygen delivery to tissues in health is well described in physiology textbooks. However, the functioning of these reflexes in the disease state is poorly understood. Intensive care specialists have been at the forefront of attempts to understand these reflex behaviors in disease contexts. Schmidt and colleagues published an excellent review of autonomic dysfunction in the intensive care unit (ICU) patient.[1] They stressed the importance of different reflex arches that maintain the balance between the parasympathetic and the sympathetic systems and, therefore, tissue oxygenation. These include the arterial baroreflex, the peripheral arterial chemoreflex, the central arterial chemoreflex, and the pulmonary stretch reflex. The interactions between these reflexes are key to proper tissue oxygenation and alterations in the activity of any of these reflexes can lead to a change in the opposing reflex response and to tissue ischemia. The integrity of these reflexes can be evaluated through analysis of HRV and BPV, baroreflex sensitivity, and chemoreflex sensitivity. This issue reviews the use of HRV and BPV analysis to evaluate the integrity of the ANS and to search for autonomic dysfunction.

WHAT ARE HRV AND BPV?

Heart rate variability is a term that comes from the work of S. Hales in 1773.[2] In his book, *Haematastaticks*, he describes the extraction of the time between beats on an electrocardiogram as a series of numbers whose variability could be analyzed. Hales also recognized the variability of continuous BP measurements. He divided these variations into first order (beat-to-beat), second order (associated with respiration), third order (slow variations over minutes), and day-night variations (circadian variations, Figure 1). The HRV is obtained by extracting the time between R-R intervals on the electrocardiogram (Figure 2). The values of the R-R intervals are then plotted over time resulting in curves called HRV tachograms (Figure 2). Mathematical transformations can be performed to analyze these signals and statistical analysis used to describe the data. Another method of analysis is to imagine the R-R interval curves as a combination of sine waves with differing frequencies that can be separated or extracted from the curve using a technique called Fast-Fourier transformation (FFT; Figure 3). The FFT separates the R-R interval curves into the sine waves that compose it and displays the results in a power density spectrum. In Figure 3, the X-axis describes the different frequencies of the sine waves composing the signal; the Y-axis describes the power of these frequencies in the R-R curve. For the purpose of this article, the frequencies represented by the curve of R-R intervals can be divided in two sections, low frequency (LF, between 0.04 Hz and 0.15 Hz) and high frequency (HF, between 0.15 Hz and 0.4 Hz; Figures 3 and 4). In terms of autonomic function, the

FIGURE 1: Examples of first, second, and third order variations in continuous blood pressure measurements.

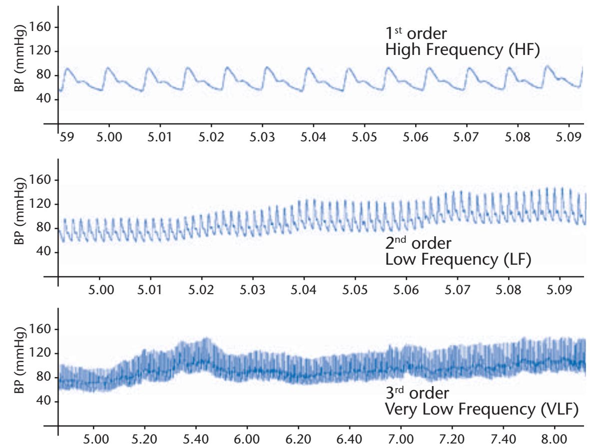


FIGURE 2: Example of how heart rate variability is obtained by measuring the time between R-R intervals in the QRS complex of the ECG. The plot of all these R-R intervals joined together give a curve called the HRV Tachogram.

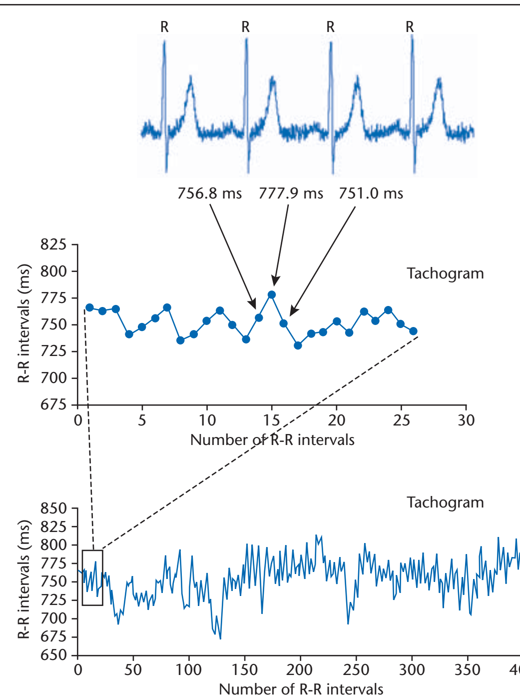
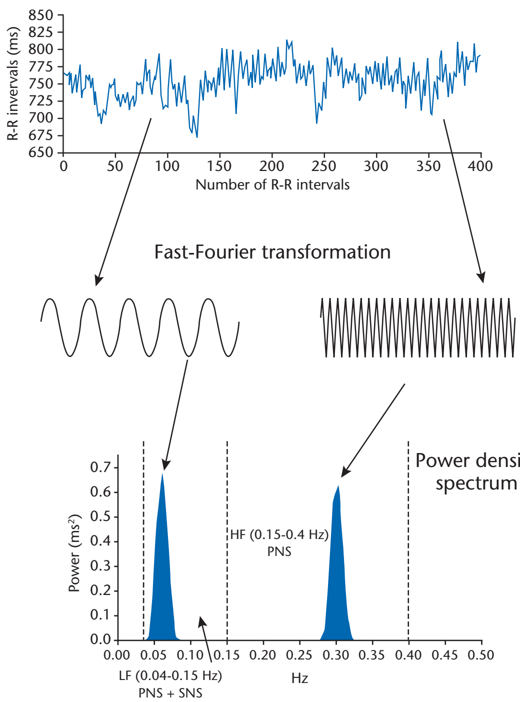


FIGURE 3: Schematic representation of the extraction of the sinusoidal components of the Tachogram (R-R interval curve) by a Fast-Fourier transformation into high (HF) and low (LF) frequency power components.

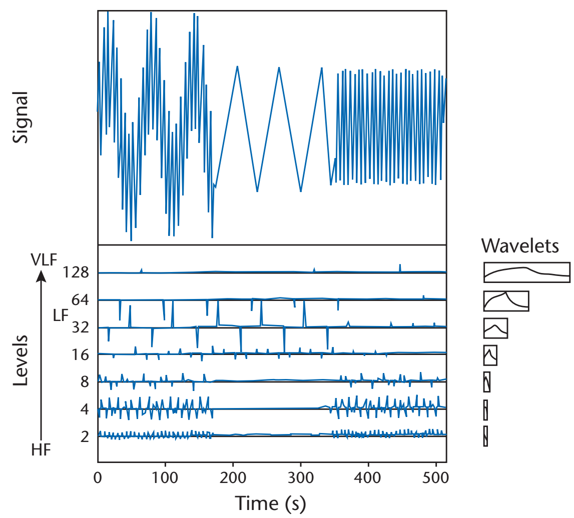


PNS = parasympathetic nervous system; SNS = sympathetic nervous system

frequencies in the HF range of the spectrum are mainly related to the parasympathetic nervous system, while the frequencies in the LF range contain information from both the sympathetic and the parasympathetic nervous systems. If the values of the LF power spectrum are divided by the values of the HF power spectrum, a ratio LF/HF is obtained that is thought to describe the sympatho-vagal balance. The analysis by FFT, however, does not describe the moment in time at which the frequencies change, only that they are present in the R-R interval curve. In other words, FFT analysis does not describe the temporal localization of the spectrum components; therefore, it cannot describe the evolution of the ANS over time, it can only demonstrate that the ANS has changed from one condition to another.

To describe the evolution of the ANS in real time, another technique called wavelet transformation (WT) was developed and an example is shown in Figure 4. A detailed description of this technique is beyond the scope of this review, but simply stated, the technique is equivalent to performing multiple FFTs on sections of the R-R intervals with curves of increasing length, small sections reflecting HF and long sections reflecting LF. Thus, a temporal evolution of changes in the ANS is obtained. The BPV, the beat-to-beat changes in BP, can be analyzed using the techniques mentioned above. The analysis of BPV primarily gives information about the sympathetic nervous system.

FIGURE 4: Schematic representation of a wavelet transformation showing its ability to give the temporal evolution of the changes in frequency of a signal (eg, the R-R interval curve). In the first third of the signal, both high (HF) and low (LF) frequencies are present. This is described in the lower graph where the analysis over time (time, X-axis) shows activity (little bars) in both parts, the HF and LF of the spectrum. The second part of the signal drops the high frequency and contains only the low frequency. This is immediately reflected in the analysis where there is no more activity in the HF region. In the last part of the signal, only the high frequency remains and this is again immediately reflected in the analysis where now the low frequency region is silent and the high frequency region shows activity.



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Clinical implications of HRV were recognized very early. In 1963, Hon and Lee noticed that fetal distress was preceded by changes in the R-R interval without any noticeable change in fetal HR per se.[3] Indeed, the variability between R-R intervals can change (HRV), while the absolute heart rate does not vary. The same is true for analysis of BPV; BP can remain stable while the beat-to-beat variations in blood pressure change. Changes in HRV and BPV could give an early warning of autonomic instability.

CLINICAL IMPLICATIONS OF AUTONOMIC DYSFUNCTION MEASUREMENTS WITH ANALYSIS OF HRV AND BPV

The clinical implications, which were a result of changes in the variability of R-R intervals, accumulated in the late 1960s and 70s. In 1973, for example, Sayers described the physiological rhythms associated with variations in R-R intervals.[4] At that time, patients with a reduced HRV following myocardial infarction (MI) were found to have a higher risk of mortality than patients without.[5] Very few studies included analyses of BPV in their protocol, mostly because of the difficulty in obtaining noninvasive continuous measurements of BP. Yet, sixteen years ago, Madwed and Cohen[6] suggested that combining both HRV and BPV analyses provides a more complete picture of ANS activity. The need to use both HRV and BPV in evaluating the ANS results primarily from the requirement to observe both arms of the ANS, the parasympathetic nervous system through the HF power of HRV and the sympathetic nervous system with BPV. The following section reviews some of the literature pertaining to the application of HRV and BPV analysis in clinical settings.

Noncardiac disorders

Diabetic neuropathy is characterized by a progressive diminution of HRV.[7] Reversal of the HRV profile in diabetic patients is a predictor of recovery from diabetic neuropathy. This correction of HRV occurs before clinical signs of neuropathic recovery become noticeable.[7] In patients undergoing open repair of abdominal aortic aneurysms, a postoperative decrease in HRV suggests high perioperative morbidity and a lengthier hospital stay.[8]

Cardiac disease

A decrease in the HF power density spectrum of HRV (mainly parasympathetic activity) is associated with acute phase MI,[9] but also with progression of congestive heart failure,[10] stratification of high-risk patients following MI,[11] and increased risk for ventricular arrhythmia in patients with coronary artery disease.[12] Changes in BPV are associated with progression of hypertensive disease in pregnancy[13] and have been used to follow the progression of hypertension in mildly hypertensive patients.[14] Changes in HRV were correlated with left ventricular diastolic dysfunction intensity,[15] and severity of both pulmonary hypertension[16] and aortic valve stenosis.[17] Furthermore, improvements in autonomic dysfunction as assessed by HRV analysis were seen in the first year following aortic valve repair.[17]

Patients undergoing cardiac surgery for coronary artery bypass were found to have baseline, as well as, postoperative suppression of HR variability.[18] Another study, however, was unable to use HRV analysis to predict short-term cardiac instability following coronary artery bypass.[19] As expected, after cardiac transplantation both the HF and LF power density spectrum of HRV disappear, but they reappear with reinnervation. Thus, it has been suggested that HRV could be used to monitor the reinnervation process after cardiac transplantation.[20]

Intensive care unit (ICU)

Critical care physicians have been using HRV analysis to assess the degree of autonomic dysfunction in their patients.[1,21] There appears to be a correlation between the severity of illness, autonomic dysfunction, and outcomes.[22] A decrease in the HF of HRV indicating reduced parasympathetic activity was found to be an independent predictor of multiple organ dysfunction and mortality in ICU patients.[22] The absence of response to an anticholinergic agent (eg, atropine) is a characteristic feature of brain death and the analysis of HR variability has been used for rapid diagnosis of potential donor patients.[23]

In septicemia, all patients show an early diminution of HRV and BPV. Patients who demonstrate a faster recuperation of sympathetic tone have improved chances of survival, while patients with a gradual decrease in the LF of HRV exhibit higher mortality rates.[24] In ICU patients requiring cardiorespiratory resuscitation, those with a decreased baseline in HRV and BPV are more likely to die by a ratio of 13 to 1.

ANALYSIS OF HRV AND BPV IN ANESTHESIOLOGY

Attempts have been made to use HRV analysis as an indication of the depth of anesthesia. Sleigh and Donovan found the power density spectrum of HRV to be a useful tool, but the bispectral index was superior for this purpose.[25] It would be interesting to test whether analysis of BPV could be a useful indicator of consciousness, since it is a better index of sympathetic tone. Several authors have compared the effect of different anesthetic agents on the ANS. Propofol appears to decrease the HF power of HRV (parasympathetic activity), while sevoflurane does not.[26] Most volatiles, as well as propofol and thiopental, have a depressive effect on the LF power density spectrum of HRV and on the HF power of BPV, and this decrease in variability appears to persist for days following anesthesia.[27]

Intraoperative analysis of HRV and BPV could be influenced by the use of vasoactive drugs. Nevertheless, studies have not shown modifications in the analysis of HRV with pure α-adrenergic blockade.[28] Further, Yien et al found no changes in the power density spectrum with cardiopulmonary resuscitation;[29] however, as expected, pure β-adrenergic agonists decrease HRV.[28] On the other hand, β-adrenergic blockade, whether acute or chronic, increases HRV and vagal tone, which may partly explain their protective effects on the heart.[30]

Other studies using HRV and BPV analysis in anesthesiology have found an increased sympathetic tone with pneumoperitoneum,[31] and differential effects of calcium channel blockers on parasympathetic and sympathetic tone.[32] Others have compared the effects of propofol and midazolam on autonomic tone with neuraxial blocks,[33] the effects of propofol and thiopental on autonomic tone during induction of general anesthesia,[34] and the effects of total intravenous versus balanced general anesthesia on the ANS. Analysis of HRV has been used to study the stress response;[35] another study showed a correlation between HRV and levels of anxiety.[36]

Unfortunately, there has been little effort in the literature to standardize measurements in HRV and BPV analysis, causing difficulties in correlating these indices with patient outcomes. Nevertheless, HRV and BPV analyses have recently been used to predict hypotensive episodes with spinal anesthesia for elective cesarean sections[37] and other surgeries.[38] In addition, Laitio et al studied preoperative HRV for predicting the risk of silent prolonged myocardial ischemia after hip surgery.[39] Our group has used WT to evaluate changes in autonomic tone with epidural anesthesia for labour,[40,41] to assess the association between somatosensory block progression during cesarean section and changes in parasympathetic and sympathetic tone, and to predict nausea and vomiting in high-risk patients (Li Pi Shan, Hatzakorsian, and Deschamps, personal data). The current focus should be to define the indices of HRV and BPV, which would provide anesthesiologists with monitoring tools that could be used for the prevention of perioperative complications.

FUTURE DIRECTIONS FOR HRV AND BPV ANALYSIS

Evaluation of the ANS to stratify risk in patients undergoing anesthesia is only as good as the quality of the available data. Thus, it will be necessary to standardize the analysis of nonstationary signals. New methods are constantly being evaluated and the importance of correlating these results with precise physiological processes that relate to the ANS cannot be overemphasized. While obtaining baseline values in patients with disabilities is important, equally needed are baseline values in healthy individuals of different ages and genders. The ANS is always active and adapting to environmental conditions. Therefore, maneuvers that test ANS integrity could be better predictors of perioperative risks for autonomic failure than baseline measurements. Such maneuvers include tests with a tilt table, the Valsalva maneuver, or even an intraoperative phenylephrine challenge. These tests could help evaluate patient ANS responsiveness and reserves.

Another area requiring development is intraoperative, real-time measurements of sympathetic and parasympathetic activity. The ablity to evaluate the autonomic balance of a patient under anesthesia could change the actual practice of the discipline. Pain, both acute and chronic, are areas of anesthesiology that have not been well evaluated in terms of the ANS. Some studies have been done in the pediatric population,[42] but reports in the adult population are scarce. For example, HRV and BPV monitoring could be used to evaluate the progress of treatment or the worsening of symptoms in chronic pain.

In summary, although the evaluation of the ANS preoperatively and intraoperatively in still in its infancy, research will be expanding in the coming years. The clinical application and usefulness of these methods will depend greatly on the quality of ongoing work in this field, and on the capacity to standardize the measurements for practical use.

Dr. Deschamps *and* ***Dr. Denault*** *are both anesthesiologists at the Montreal Heart Institute.*

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