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Research Article

Improved Patient Outcomes by Normalizing Sympathovagal Balance: Differentiating Syncope—Precise Subtype Differentiation Leads to Improved Outcomes

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Syncope is difficult to definitively diagnose, even with tilt-table testing and beat-to-beat blood pressure measurements, the gold-standard. Both are qualitative, subjective assessments. There are subtypes of syncope associated with autonomic conditions for which tilt-table testing is not useful. Heart rate variability analyses also include too much ambiguity. Three subtypes of syncope are differentiated: vasovagal syncope (VVS) due to parasympathetic excess (VVS-PE), VVS with abnormal heart rate response (VVS-HR), and VVS without PE (VVS-PN). P&S monitoring (ANSAR, Inc., Philadelphia, PA) differentiates subtypes in 2,727 cardiology patients (50.5% female; average age: 57 years; age range: 12–100 years), serially tested over four years (3.3 tests per patient, average). P&S monitoring noninvasively, independently, and simultaneously measures parasympathetic and sympathetic (P&S) activity, including the normal P-decrease followed by an S-increase with head-up postural change (standing). Syncope, as an S-excess (SE) with stand, is differentiated from orthostatic dysfunction (e.g., POTS) as S-withdrawal with stand. Upon standing, VVS-PE is further differentiated as SE with PE, VVS-HR as SE with abnormal HR, and VVS-PN as SE with normal P- and HR-responses. Improved understanding of the underlying pathophysiology by more accurate subtyping leads to more precise therapy and improved outcomes.

1. Introduction

The current standard for diagnosing syncope is a positive tilt-table test performed according to one of the currently acceptable methods [1–5]. Presyncope and true syncope are difficult to definitively diagnose, even with tilt-table testing. Tilt-table testing may be useful for certain diagnoses, such as vasovagal syncope (VVS), neurocardiogenic (NCG) syncope, and postural orthostatic tachycardic syndrome (POTS). However, there are subtypes of VVS associated with autonomic conditions for which tilt-table testing is not useful in distinguishing. Tilt-tests, beat-to-beat (btb) blood pressure (BP) measurements, or in simpler form, pulse wave velocity measurements are also standards for autonomic testing. While btbBP is simpler to implement than tilt-table, it is often used in conjunction with tilt-table and, like tilt-table results, requires waveform assessment. Without overt symptoms, both are qualitative, subjective assessments, even in the hands of experts. Furthermore, measuring btb intervals from the BP waveform, with its much more rounded peaks as compared with the EKG waveform, introduces additional errors in the btb analyses. Heart rate variability
(HRV) analyses (based on the EKG) also include too much ambiguity.

A more quantitative and universal method of assessing autonomic state is applied to both improve the diagnostic yield of syncope and provide a simpler (quantitative) diagnostic criteria, especially for the nonspecialist. This method improves the differentiation between the parasympathetic and sympathetic (P&S) activity. This method, when used in response to postural change or standing, helps to differentiate four etiologies underlying dizziness and lightheadedness: (1) parasympathetic excess (PE, associated with vagal symptoms), (2) sympathetic withdrawal (SW) associated with orthostatic dysfunction [6, 24], (3) sympathetic excess (SE) associated with (pre)syncope [7], and (4) vestibular dysfunction, a diagnosis by omission since it is not an autonomic dysfunction. Sympathetic excess (SE) associated with (pre)syncope is the topic of this report.

Defined herein are three of the subtypes of SE as manifested in VVS and NCG syncope. They are based on the differences in pathophysiology present in the P&S nervous system responses. Improved understanding of the underlying pathophysiology demonstrates how this more accurate subtyping leads to more precise medical therapy and thus improved patient outcomes. In general, an S-excess (SE) response to the stand challenge is associated with syncope. Abnormal sympathetic responses to stand differentiate syncope (SE) from orthostatic dysfunction (e.g., POTS; SW) [8, 24]. The subtypes of syncope are defined by the demonstration of P-excesses (PE) somewhere during the clinical challenge [9] or an abnormal HR response to stand. The three subtypes of VVS and NCG syncope are as follows:

1. SE + PE, which is VVS due to PE (VVS-PE), is defined as the presence of SE upon standing with PE demonstrated during rest,Valsalva, or stand, regardless of the HR response to stand.

2. SE + abn-HR, which is VVS with abnormal HR response (VVS-HR), is defined as the presence of SE upon standing with an abnormal HR response to stand (stand HR compared with resting HR).

3. SE (alone), which is VVS without PE (VVS-PN; “PN” for normal P-response), is defined as only the presence of SE upon standing. In these cases, the patients do not demonstrate an abnormal HR response to stand nor PE.

Using these subtype definitions, the P&S measurements from patients diagnosed with VVS-PE and VVS-HR are presented.

2. Methods

A database of 3670 consecutive, serial patients was followed in a large cardiology practice drawing from both urban and suburban populations. P&S function was assessed non-invasively using the ANSAR Medical Technologies, Inc. (Philadelphia, PA) software (ANX 3.0 autonomic function monitor). The ANX 3.0 computes simultaneous, independent measures of P&S activity based on continuous, time-frequency analysis of HRV with concurrent, continuous, time-frequency analysis of respiratory activity (RA). Time-frequency analyses employ a normalized CMORL wavelet with a Q of 5 and a spectral update of 4 seconds.

While this method facilitates reading P&S responses in the presence of arrhythmia [10], to permit comparison with standard HRV responses, 943 patients were omitted from this database due to high burden of ectopy (a run of more than two consecutive arrhythmic heart beats). Of the remaining patients, 2727 (50.5% female; average age: 57 years; age range: 12 to 100 years) were followed with more than one assessment over four years (an average of 3.3 assessments per patient). The mean time between assessments is 442.7 days. The patients carry diagnoses of cardiovascular disease (CVD) or a condition at high risk of future CVD, such as hypertension (32.7%), heart failure (35.2%), history of MI (16.2%), type 2 diabetes (36.2%), renal disease (17%), or COPD (8.7%). The patients are on standard therapy [11].

HRV-alone analyses compute mixed measures of P&S activity. For example, spectral HRV analyses result in a low frequency (LF) and a high frequency (HF) term [12, 13]. LF is a mix of both P&S activity (Figure 1) unless the subject’s
breathing rate is greater than about 13 breaths per minute [12, 13]. HF is a broad-band term [12, 13] (Figure 1), more than twice as broad as the known parasympathetic frequency range [14–19]. Therefore, even if the subject’s breathing rate is >13 breaths/min, the HF term is mixed with noise, including harmonics. Both LF and HF require assumption and approximation to specify the P&S activity.

To eliminate the need for assumption and approximation required by LF and HF, independent spectral analyses of RA are added to spectral analyses of HRV [23]. This second independent P&S measure (RA) satisfies the algebraic requirement for a system with two independent components, fully characterizing the system, eliminating the need for assumption and approximation. Wavelet analysis eliminates the time-frequency approximations required by Fourier transforms and enables a significantly shorter data collection time to compute P&S activity. This enables autonomic transients and the dynamic activity of P&S interactions to be captured and analyzed. The resulting P&S terms are respiratory frequency area (RFA) and low frequency area (LFA), respectively, and sympathovagal balance (SB = LFA/RFA) is computed as a true ratio of independent parameters [8]. See the differences between LF and HF and LFA and RFA in Figure 1 [8].

The clinical study employed to determine P&S activity includes four well-known autonomic challenges, separated by resting baseline periods. These six periods are labeled in the figures as (A) resting baseline, (B) deep breathing, (C) baseline, (D) Valsalva maneuvers, (E) baseline, and (F) stand (postural change). The stand challenge, in the clinical study, includes instantaneous HR, instantaneous breathing, and instantaneous P&S responses (trends) to the standard clinical study from a syncopal, 23-year-old male. Note the instantaneous S-excess (SE, red trace) during the stand challenge (section “F”) of the trends plot (right plot). The SE correlates with the abnormal HR response to stand (left plot). HR remains high during stand, and there is no return to baseline. See text for details and Methods for abbreviations.

The time requirement, as well as the safety factor, is further improved with the implementation of a spectral analysis technique that eliminates the time-frequency compromise: the wavelet transform [18, 19, 22–29]. P&S monitoring [30] employs the wavelet transform, along with the appropriate time and safety considerations. Noninvasive BPs were taken during each phase of the clinical study [9]. This is an observational study. Patient testing and clinical outcomes measures were collected as an authorized part of the subjects’ care and treatment given their clinical history. All data were handled in accordance with HIPPA regulations. Data were analyzed, statistically, with SPSS v 22.0, with the null hypothesis indicating significance at $p \leq 0.05$.

3. Results

Figure 2 presents a patient’s responses to the standard clinical study, including instantaneous HR, breathing, and P&S data (parasympathetic trend (blue) and sympathetic trend (red) plot). The patient was previously diagnosed with syncope based on a positive tilt-test. For comparison, Figure 3 presents a normal subject’s responses. Note that, while the resting (A) and paced, or deep, breathing (B) sections of the plots are similar, the Valsalva (D) and standing, or postural change (F), sections are not. In fact, they are essentially the opposite of each other. For the normal subject, the Valsalva S-response is significantly greater than that for stand. This is as it should be given that a series of short Valsalva maneuvers should induce a significantly greater physiologic stress response than changing posture from sitting to standing. However, for the syncpe patient, the S-response to stand is greater than that for the Valsalva challenge.

The instantaneous SE, as seen in the trends plot of Figure 2, is important to note because there are cases, especially younger patients, where the average S-response to stand is normal. Meanwhile, these patients complain of lightheadedness (LH), and their instantaneous S-activity in response to stand is similar to that from the patient in Figure 2. This patient’s peak S-response (the red curve)
Figure 3: Instantaneous HR, breathing, and P&S responses (from left to right) to the standard clinical study from a healthy, 44-year-old female. Her average resting responses are a HR of 65 bpm, BP of 102/59 mmHg, S-activity (LFa) of 1.65 bpm$^2$, P-activity (RFa) of 1.66 bpm$^2$, and an SB (LFa/RFa) of 1.00 (unitless). See text for details and Methods for abbreviations.

Figure 4: Average challenge responses from instantaneous responses in Figure 1. Patient’s average resting responses included a HR of 84 bpm, BP of 109/73 mmHg, S-activity (LFa) of 2.38 bpm$^2$, P-activity (RFa) of 0.68 bpm$^2$, and a sympathovagal balance (LFa/RFa) of 2.49 (unitless). All average responses are within published normal limits (as represented by the grey areas) [5], except the stand response which indicates SE. See text for details and Methods for abbreviations.

during stand (section “F” in the trends plot) is greater than the patient’s peak S-response during Valsalva (section “D” in the trends plot). This is an “instantaneous SE” and is also associated with syncope, including tilt-positive patients [8]. The normal peak S-response relationship between Valsalva and stand is greater than 3:1, as exemplified in Figure 3.

These differences are also reflected in the heart rate response plots (Figures 2 and 3). The normal subject’s instantaneous HR response to stand peaks during the gravitational reflex (during the first 30 seconds of stand) and quickly returns to resting baseline levels and remains near resting levels for the duration of quiet standing (Figure 3). However, the syncope patient’s instantaneous HR response also peaks during the gravitational reflex but does not return to resting levels (Figure 2). Thereafter, the syncope patient’s instantaneous HR tends to remain high (as compared with the resting response) and often begins to rise again and may continue to rise throughout quiet standing.

Figure 4 presents the response plots from the syncope patient in Figure 2. These plots quantify the patient’s average responses to challenge for comparison against published normal (average) ranges [9]. The response plots are to the clinical study’s four challenges (as labeled: baseline (rest), deep breathing, Valsalva, and stand). Again for this syncope patient, the average responses over the 5-minute, resting, baseline, and 1-minute, deep breathing challenges are within normal limits (the grey areas on the plots). Note that deep breathing and Valsalva normal ranges are age as well as baseline adjusted. The patient’s Valsalva response is low for the patient’s age, as noted above. On average, over the 5-minute stand challenge, the normal P-response to stand is a decrease (any decrease) with respect to stand. The normal S-response to 5-minute stand is a 10% to 500% increase over rest [31] (Figure 3). An S-increase in response to stand greater than 500% is excessive (sympathetic excess, or SE) and is associated with syncope [9]. The stand response plot in Figure 4 demonstrates SE, reflecting the trends plot findings above (Figure 2).

Within this cohort at baseline, 38.6% of patients complain of lightheadedness (LH, not of vestibular etiology). Of the cohort, 31.4% (81.3% of the LH patients) were diagnosed with some form of orthostatic dysfunction, including POTS. Orthostatic dysfunction is associated with sympathetic insufficiency, or sympathetic withdrawal, upon standing (a decrease in S-activity from baseline (rest) to stand (postural change)). Of the remaining 7.2% of those complaining of LH, 3.9% were diagnosed with syncope (tilt-positive) or presyncope from other clinics. From the entire cohort, 5.2% of the patients demonstrate SE upon stand. All of these
patients complained of LH, and all of the patients diagnosed with (pre)syncope elsewhere demonstrated stand SE.

From Figure 2, instantaneous SE is demonstrated in the stand portion of the trends plot and supported by the SE demonstrated in the stand response plot, as in Figure 4. Again, this is not always the case as shown in Figure 5. In fact, many younger (12 to 30 years old), otherwise healthy patients complaining of LH present with similar results, and most of these are tilt-negative [8]. Younger (healthier), tilt-table-positive, syncope patients, often demonstrate normal, average autonomic responses (see the stand response plot in Figure 5); however, the instantaneous S-response to stand is comparable to (less than a 3:1 ratio) or greater than that to Valsalva (see the parasympathetic response analysis plot in Figure 5). Both are examples of VVS-PE.

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4. Discussion

One of the most difficult forms of syncope to diagnose is VVS. Often tilt-table testing itself causes patients worry, anxiety, or stress. This stress (an S-stimulus) changes the patient’s typical physiological response, the Vagal (or P-) excess, associated with VVS. In effect, the patient is temporarily treated by being placed on the tilt-table. As a result, the tilt-test may be falsely negative [8]. From the above, syncope with PE may be separately demonstrated, without overt symptoms. Then, if VVS-PE is demonstrated (preclinical), VVS subtype is confirmed. PE may be demonstrated during one or more of three challenges (Figures 5 and 6).
Given the difficulty of differentiating VVS from POTS, adding another parameter improves this differentiation. Again, stand SE is associated with syncope and SW is associated with orthostatic dysfunction [6]. In this way, VVS (indicated with SE) is reliably differentiated from POTS (indicated with SW). From the cohort, SE versus SW helps to improve differential diagnosis, including diagnosing presyncope where no cause of LH was determined. Corresponding modifications in therapy to properly address SE or SW, history dependent, helped to confirm the diagnoses, and in many cases, once the S-dysfunction was relieved, patients were weaned of their autonomic therapy. Often patients, especially older patients, have more than one pathology underlying LH, including both SW and instantaneous SE upon standing (DePace, personal communication). Identifying both enables simultaneous treatment of both.

BTB analyses, including heart rate variability (HRV), may be quantified with spectral analyses and other methods [12, 13]. However, care must be taken as to the selection of the protocol, the analysis technique, and the time duration over which data are collected. All choices impact the mathematical requirements, especially for the spectral analysis technique. The standard tilt-test, including with btBBP recordings, does not satisfy the mathematical requirements, especially for the spectral techniques (i.e., Fourier transforms or fast Fourier transforms (FFTs) [12]) and is a reason for the need to assess waveforms. A significant limitation of the Fourier transform is its inherent time-frequency compromise, forcing assumption and approximation to theorize activity specific to the parasympathetic and sympathetic branches of the autonomic nervous system, thereby reducing specificity and repeatability [32].

Differentiating the underlying abnormalities of the autonomic nervous system into specific subtypes based on pathophysiology significantly aids in therapy planning. In cases of VVS-PE, it has been found that PE should be treated as the primary autonomic disorder to effectively treat symptoms and underlying autonomic dysfunction. It is known that the parasympathetics set the threshold around
which the sympathetics react. By treating the para-
 sympathetics as the primary autonomic dysfunction and
normalizing them, often the reactionary sympathetics
(e.g., the SE) is naturally relieved, followed by BP or HR.
When total relief is not experienced, what remains is
a function of end-organ disorder (including vestibular) and
typically requires less therapy.

In patients who are diagnosed with autonomic neuropathy or autonomic dysfunction and also heart diseases, hyper-
tension, CAD, heart failure, or post-MI, the recommended
therapy to treat both PE with SE and the cardiology diagnoses
is carvedilol [33]. Carvedilol has a double effect, with both
beta-blocker and alpha-blocker components and in low doses
has antidepressant properties. In the presence of autonomic
neuropathy, carvedilol seems to indirectly affect P-activity
[34]. For VVS-PE without additional autonomic neuropathy,
very low-dose anticholinergic therapy (e.g., tricyclics or
SNRs) is recommended to treat the PE [35].

In summary, traditional testing modalities (i.e., btb-cardiac activity measures in response to postural change,
including tilt-table testing or standing) are confounded due
to their measures mixing both P- and S-activity in a single
parameter. Frequency analysis of standard btb-cardiac activity (with HRV or btbBP) in response to the stand chal-
lenge is further compromised by the nature and definition of
Fourier transforms or fast Fourier transforms (FFT), in-
cluding short-term FFT (st-FFT) [12]. Fourier transforms, of
any sort, carry the mathematical requirement of long-
duration, stationary (or stable) signals. Signal stationarity
requires that the characteristics of the signal not change significantly (remain quiescent) over the analysis period.

During the course of the first five minutes after a head-up postural change (including sitting to standing), there are
several physiologic changes that affect the stand response,
including (1) the response to the gravitational challenge, (2)
the response to the exercise reflex, and (3) the recovery from
both. Even a normal gravitational response comes and goes
over a 30 second period, invalidating the use of Fourier
transforms. An abnormal response to any one of these three
physiologic changes may underlie LH and lead to syncope. As
a result of these changes, the stand challenge is not stationary
(quiescent), even st-FFTs with a 32-second analysis window,
as per the standard practice [12, 13]. Therefore, the use of the
Fourier transform is inappropriate and nondiagnostic.
Wavelet analyses address and avoid these issues by addressing
time and frequency together, rather than attempting a com-
promise between time and frequency. Wavelets with in-
dependent RA analyses allow for independent computation of
P- and S-activity, which in turn clarifies the actual underlying
pathophysiology associated with VVS and its different sub-
types, as described herein. The wavelet is valid in all instances,
including those encountered during the clinical, autonomic
assessment protocol employed in this study, which includes
the stand or postural change challenge and its reflexes [25–29].

5. Conclusions

VVS-PE is perhaps the most common subtype of syncope.
Further differentiating syncope by identifying the autonomic
components helps to improve differential diagnosis, which
improves therapy planning, resulting in improved outcomes.
Independent P&S monitoring provides more specific data
regarding the pathophysiology of VVS. Improved subtype
differentiation allows for more precise therapeutic modalities
and improved symptom management. In the case of VVS-
HR, ruling out VVS-PN may lead to lower doses of medi-
cation prescribed while still improving patient outcome.

Conflicts of Interest

Dr. Vinik has been paid honoraria for lecturing on behalf of
ANSAR Medical Technologies, Inc. Otherwise, the authors
have no conflicts of interest in this study.

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