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The Precise Timing of Tachycardia Entrainment is Determined by the Post-Pacing Interval, the Tachycardia Cycle Length, and the Pacing Rate: Theoretical Insights and Practical Applications

Daniel W. Kaiser, MD^{*,‡}, Henry H. Hsia, MD, FHRSt, Anne M. Dubin, MD, FHRSt, L. Bing Liem, DO, FHRSt, Mohan N. Viswanathan, MD, FHRSt, Paul C. Zei, MD, FHRSt, Paul J. Wang, MD, FHRSt, Sanjiv M. Narayan, MD, PhD, FHRSt, and Mintu P. Turakhia, MD, MAS, FHRSt^{*,+}

^{*}Stanford University School of Medicine, Stanford, CA

[†]University of California, San Francisco, CA

[‡]El Camino Hospital, Mountain View, CA

⁺Veterans Affairs, Palo Alto Health Care System

Abstract

BACKGROUND—Previous observations have reported that the number of pacing stimuli required to entrain a tachycardia varies based on arrhythmia type and location, but a quantitative formulation of the number needed to entrain (NNE) that unifies these observations has not been characterized.

OBJECTIVE—We sought to investigate the relationship between the number of pacing stimulations (n), the tachycardia cycle length (TCL), the overdrive pacing cycle length (PCL), and the post-pacing interval (PPI) on the timing of tachycardia entrainment.

METHODS—First, we detailed a mathematical derivation unifying electrophysiological parameters with empirical confirmation in two patients undergoing catheter ablation of typical atrial flutter. Next, we validated our formula in 44 patients who underwent various catheter ablation procedures. For accuracy, we corrected for rate-related changes in conduction velocity.

RESULTS—We derived the equations, $NNE = |(PPI - TCL) / (TCL - PCL)| + 1$ and $[Advancement = (NNE - 1) * (TCL - PCL) - (PPI - TCL)]$, which state that the NNE and the amount of tachycardia advancement on the first resetting stimulation are determined by regularly measured intracardiac parameters. In the retrospective cohort, the observed PPI-TCL highly correlated with

Correspondence: Daniel W Kaiser, MD, 300 Pasteur Dr. MC 5319, Stanford, CA 94305, Tel: (615) 415-2586, Fax: (650) 723-8392, dwkaiser@stanford.edu.

Conflicts of Interest:

Dr. Hsia is a consultant for Medtronic and has served as a member of a speaker bureau for Biosense Webster. Dr. Narayan is coauthor of intellectual property owned by the University of California Regents and licensed to Topera Inc. He holds equity in Topera, and has received honoraria from Medtronic, St. Jude Medical, Biotronik, and Boston Scientific. He has received consulting fees from the American College of Cardiology Foundation and Topera and royalty income from UpToDate. Dr. Turakhia is a consultant to Precision Health Economics, Medtronic, St Jude Medical, and Biotronik. He has grant support from the VA, Gilead Sciences, Medtronic, IRhythm, and SenteHeart. The other authors report no conflicts of interest.

the predicted PPI-TCL ($r=0.97$, $p<0.001$, mean difference 5.8 ms), calculated as: $[(\text{PPI-TCL})=(\text{NNE}-1)*(\text{TCL-PCL})-\text{Advancement}]$.

CONCLUSIONS—The number of pacing stimulations required to entrain a reentrant tachycardia is predictable at any PCL after correcting for cycle-length dependent changes in conduction velocity. This relationship unifies established empirically-derived diagnostic and mapping criteria for supraventricular and ventricular tachycardia. This relationship may help elucidate when anti-tachycardia pacing (ATP) episodes are ineffective or proarrhythmic and could potentially serve as a theoretical basis to customize ATP settings for improved safety and effectiveness.

Keywords

arrhythmia; right ventricular overdrive pacing; entrainment; catheter ablation; anti-tachycardia pacing; number needed to entrain

Introduction

As elegantly described by Waldo and colleagues in 1977, persistent overdrive pacing at a rate faster than the native tachycardia will first advance a reentrant tachycardia (tachycardia reset) followed by continuous resetting (tachycardia entrainment), which accelerates the tachycardia to the pacing rate.¹ Since the initial description, various aspects of overdrive pacing have been described in order to identify critical components of the reentrant circuit, elucidate accessory pathways, and rule out automatic rhythms.^{2–11} Overdrive pacing algorithms have also been developed and incorporated into implantable cardiac devices to painlessly terminate malignant arrhythmias.¹²

In order to accurately interpret entrainment maneuvers and/or to successfully pace-terminate a tachycardia, the number of pacing stimulations must be sufficient to reach the reentrant circuit. The initial paced wavefronts may not reach the tachycardia circuit, since these wavefronts often collide with wavefronts exiting the circuit. Although the number of pacing stimulations required to entrain a tachycardia is dependent on the pacing rate and the distance to the reentrant circuit,^{13, 14} a quantitative relationship that determines the precise number of pacing stimulations needed to entrain has not been described. We sought to mathematically describe the timing of tachycardia entrainment using regularly measured intracardiac parameters.

Methods

Study Population

This study consisted of two parts. The first part is a mathematical derivation to express the number needed to entrain (NNE) as a function of the tachycardia cycle length (TCL), the pacing cycle length (PCL), and the post-pacing interval (PPI). For the “proof of concept”, we analyzed the intracardiac electrogram intervals and characterized the mathematical function in two patients undergoing ablation of typical (counterclockwise, cavotricuspid isthmus dependent) atrial flutter. We used this population because the reentrant circuit of typical atrial flutter is anatomically well-defined and less susceptible to decremental conduction.

In the second part, we then empirically validated our mathematical formula by retrospectively examining the intracardiac electrograms of consecutive 44 patients who had clinical electrophysiology studies and ablation of atrioventricular reentrant tachycardia (AVRT), atrioventricular nodal reentrant tachycardia (AVNRT), and monomorphic ventricular tachycardia (VT) at Stanford Hospital and Clinics, from March 2012 to March 2015. All intracardiac measurements were performed by a single interpreter (DWK). A second interpreter (MPT) adjudicated caliper position for measurements when the timing of local activation was difficult to ascertain. The study was approved by the local Institutional Review Board with a waiver of consent.

Overdrive Pacing Maneuvers

In the patients with atrial flutter (part I), overdrive pacing was performed from within the coronary sinus by a standard multipolar electrode catheter. In the first patient, four overdrive pacing maneuvers were performed from the same location with increasing number of extra-stimuli (all at the same pacing rate). In the second patient, entrainment was obtained from within the coronary sinus at three different progressively faster pacing rates.

In the second part of the study, we reviewed the intracardiac recordings from various catheter ablation procedures. Each case was reviewed in entirety and the first entrainment maneuver meeting study criteria was included. Only cases where a sustained tachycardia was induced and the entrainment maneuver did not terminate the tachycardia were included. The PCL was required to be within 30ms of the TCL. Cases demonstrating spontaneous beat-to-beat variability in the TCL of greater than 30ms were excluded from the study.

Overdrive pacing was typically performed from the right ventricular (RV) apex. For VT cases, entrainment maneuvers from the ablation catheter, usually in the left ventricle, were included. The PPI was measured from the last pacing stimulus to the bipolar electrogram in the first return beat on the pacing catheter. The TCL was measured immediately before overdrive pacing ensued. During programmed overdrive pacing, the prematurity of the first captured beat was measured and used to calculate the total pacing prematurity. Tachycardia reset was determined when overdrive pacing first advanced the tachycardia circuit, as evidenced by a premature sensed event. Tachycardia entrainment was determined when overdrive pacing first advanced the tachycardia to the PCL (which occurred after the first reset stimulation). In AVRT and AVNRT cases, a high right atrial catheter was utilized. For cases involving VT, the pacing catheter and the reference/sensing catheter were in opposite chambers (such as an ablation catheter in the left ventricle and a bipolar pacing catheter in the RV apex).

We determined the number of pacing stimulations needed to entrain the tachycardia and the amount of tachycardia advancement on the first pacing stimulation that reset the tachycardia. In order to correct for AV nodal decremental conduction, we calculated the corrected PPI by subtracting A-H prolongation associated with the shorter PCL, as previously described.⁴ Bipolar electrograms were filtered between 30 and 500kHz. For supraventricular tachycardia (SVT), pacing output was typically twice the diastolic pacing threshold at 20 ms pulse width. For ventricular tachycardia (VT), pacing output was set at minimal outputs to ensure

consistent capture. All data were recorded on a digital acquisition system (Cardiolab, Prucka Engineering, Inc., Houston Texas).

Statistical Analysis

Continuous variables are expressed as the mean $\pm$ standard deviation and categorical variables are presented as counts and percentages. Analysis of variance between the three groups of patients (AVRT, AVNRT, VT) was evaluated with the one-way ANOVA test. The correlation between the observed PPI-TCL and the predicted PPI-TCL (calculated as $[(NNE-1)*(TCL-PCL)-tachycardia\ advancement]$) was examined using a Spearman rank test. P values of 0.05 or less were considered statistically significant. The data were analyzed using SPSS Statistics version 22.0 (SPSS Inc. Chicago, IL, USA).

Results

Part I results: Mathematical reasoning

We hypothesized that overdrive pacing would begin to advance a reentrant tachycardia precisely when the total pacing prematurity exceeds the PPI-TCL. The total pacing prematurity is calculated by adding together the prematurity of each extra-stimuli. The total pacing prematurity is equal to the number of pacing stimulations multiplied by the prematurity of the pacing rate [$n*(TCL-PCL)$]. The relationship between the return interval and the total pacing prematurity can be understood by examining Figures 1 and 2. Figure 1 is an illustrative representation of a reentrant tachycardia with delivery of synchronized single, double, and triple extra-stimuli. The first two overdrive pacing attempts do not reset the tachycardia; instead there is a compensatory pause. However, the third overdrive pacing attempt resets the tachycardia. Figure 2 presents the intracardiac recordings from an ablation procedure depicting the same characteristics. In Figure 2, the TCL is 233ms. We delivered successive pacing stimulations up to four extra-stimuli with of PCL of 210ms. As can be appreciated in these figures, the return interval of each compensatory pause (the tachycardia was not reset) is equal to the TCL plus the amount of pacing prematurity (equation 1). Therefore, the return interval prolongs with each additional stimulation.

Compensatory pause

$$Return\ interval = TCL + stim\ number(n) * (TCL - PCL) \quad (1)$$

Once the stimulated pacing wavefront reaches the arrhythmic circuit and resets the tachycardia, the return interval is shorter than would be predicted from a compensatory pause. Assuming negligible changes in conduction properties due to the shorter cycle length, once the tachycardia has been reset, the return interval at the cessation of pacing, no matter the number of entrained pacing stimulations, will always equal the PPI of the first reset stimulation. As can be seen in the figure, the PPI can be determined by adding TCL to the total amount of pacing prematurity, minus the amount of tachycardia advancement (equation 2).

At Tachycardia Reset

$$PPI = TCL + n * (TCL - PCL) - tachycardia\ advancement \quad (2)$$

By subtracting the TCL from each side, we obtain equation 3:

$$PPI - TCL = n * (TCL - PCL) - tachycardia\ advancement \quad (3)$$

It can be appreciated from equation 3 that overdrive pacing will begin to advance a tachycardia precisely when the total pacing prematurity $n*(TCL-PCL)$ exceeds the PPI-TCL. Furthermore, we can then solve for the number of pacing stimulations required to reset a tachycardia. Since the amount of tachycardia advancement on the first reset stimulation must be less than the pacing prematurity (TCL-PCL), we can remove the ‘advancement’ component and perform a ceiling function (“round-up”) to quickly calculate the number of pacing stimulations required to reset a tachycardia at any pacing rate (equation 4):

$$Number\ of\ pacing\ stimulation\ required\ to\ advance\ (reset)\ a\ tachycardia = \left\lceil \frac{PPI - TCL}{TCL - PCL} \right\rceil \quad (4)$$

From equation 4 it should be appreciated that if the pacing prematurity (TCL-PCL) exceeds the PPI-TCL [(TCL-PCL) > (PPI-TCL)], then a single pacing stimulation will reset the tachycardia (assuming the pacing location is not refractory to the prematurity required). After resetting the tachycardia, the next pacing stimulation will entrain the tachycardia. Therefore, the number of pacing stimulations required to entrain a tachycardia at any PCL can be calculated (equation 5):

$$NNE = \left\lceil \frac{PPI - TCL}{TCL - PCL} \right\rceil + 1 \quad (5)$$

We can then re-arrange equation 3 by substituting the NNE in order to obtain equation 6:

$$PPI - TCL = (NNE - 1) * (TCL - PCL) - tachycardia\ advancement \quad (6)$$

In our study, we used this equation to predict the PPI-TCL by counting the number of pacing stimulations required to entrain the tachycardia and the amount of tachycardia advancement on the first reset stimulation. In addition, we evaluated these equations by calculating the amount of tachycardia advancement on the first reset stimulation at varying pacing rates (three different PCL’s) using equation 7 (see Figure 3).

$$[(NNE - 1) * (TCL - PCL)] - (PPI - TCL) = Tachycardia\ Advancement \quad (7)$$

Figure 3 demonstrates how these concepts can accurately predict the number of overdrive pacing stimulations required to reset/entrain the reentrant tachycardia and the amount of

tachycardia advancement on the first reset stimulation. These mathematically concepts can also be understood visually (see supplemental material Figure S3).

Part II Results

We reviewed 9, 18, and 17 cases of AVRT, AVNRT, and VT, respectively. The baseline characteristics and intracardiac recording measurements are shown in Table 1. The AVNRT group had longer AH-corrected PPI-TCL times compared to the AVRT group ($p<0.001$). A cut-off of 110ms correctly classified 18 out of 18 AVNRT patients and 7 out of 9 AVRT patients. The two AVRT cases with the prolonged PPI-TCL were due to left lateral pathways. In all cases, the observed corrected PPI-TCL revealed a near perfect correlation to the predicted PPI-TCL (Table 1); which was calculated as the number of pacing stimulations required to first advance the tachycardia (NNE-1) multiplied by the pacing prematurity (TCL-PCL) minus the tachycardia advancement on the first reset stimulation [PPI-TCL=(NNE-1)*(TCL-PCL) - tachycardia advancement] ($r=0.97$, $p<0.001$). The mean difference between the observed PPI-TCL and the predicted PPI-TCL was 3.2, 2.1, and 10.6ms for AVNRT, AVRT, and VT cases, respectively ($p<0.001$) (Figure 4). An example of intracardiac recordings used to calculate the AH-corrected PPI-TCL and the predicted PPI-TCL for an AVRT and an AVNRT are displayed in Figure 5 and Figure 6, respectively.

Discussion

Overdrive pacing is the primary maneuver utilized by electrophysiologists to investigate and terminate tachyarrhythmias. Our findings indicate overdrive pacing begins to advance a reentrant tachycardia precisely when the total pacing prematurity exceeds the PPI-TCL after correcting for conduction velocity changes associated with the shorter cycle length.

This concept unifies various relationships previously observed in entrainment maneuvers for diagnostic purposes. For example, in supraventricular tachycardias with concentric atrial activation pattern, His-synchronous and His-refractory premature ventricular contraction (PVC) have been described to differentiate AVNRT from AVRT. In this maneuver, a premature stimulation is delivered from the RV apex simultaneously or slightly prior to (35–55ms) the His-deflection (the total prematurity is typically <110 ms depending on the HV interval). Since the AV node will be refractory, this premature stimulation cannot affect an AVNRT. However, in the presence of a septal pathway, the premature stimulation may advance or terminate the tachycardia. Our findings suggest a premature stimulation can only affect a tachycardia if the prematurity exceeds the AH-corrected PPI-TCL that would occur from the pacing location. The AH-corrected PPI-TCL from the RV apex is typically well less than 90ms for all septal bypass tracts.⁴ In contrast, the AH-corrected PPI-TCL for all AVNRT and some free wall AVRT exceed 110ms. Therefore, if a His-refractory PVC is delivered to a tachycardia which is less than 100ms premature, an AVNRT cannot be affected, since the AH-corrected PPI-TCL for all AVNRT exceed 100ms. However, in the presence of a septal pathway where the AH-corrected PPI-TCL might be 40ms (mean of 44 ± 20 ms)⁴; our data suggest that a 100ms premature stimulation would reach the reentrant circuit after 40ms; and the remaining prematurity (100-40ms) would then advance the tachycardia by 60ms. This advancement would be readily apparent or might terminate the

tachycardia. Other thoughtful application of this principle can be used to help unify various seemingly disparate methods of differentiating AVNRT from AVRT, including the PPI-TCL,² the pre-excitation index,³ the summed preexcitation index,⁶ the entrainment index,⁷ and the behavior of atrial electrograms in the transition zone⁸ (Online Supplement).

In addition to unifying criteria for supraventricular tachycardias, this concept can explain phenomena seen in other reentrant tachycardias. For example, Maruyama and colleagues recently demonstrated in intra-atrial reentrant tachycardias, that the NNE was proportional to the PPI-TCL and inversely proportional to the TCL-PCL (in agreement with equation 5).⁹ Furthermore, the PPI-TCL has been shown to correlate with the 'N+1 Difference' in patients with atrial flutter and ventricular tachycardia after myocardial infarction.¹⁵ Assuming there is no decremental conduction due to overdrive pacing, the N+1 difference is mathematically equal to the pacing prematurity required to reach the tachycardia circuit (Online Supplement). Therefore, the N+1 difference, the corrected PPI-TCL, and the total pacing prematurity required to reach the reentrant circuit are all equivalent, independent of the chamber involved.

In our study, the observed PPI-TCL was on average slightly longer than the predicted PPI-TCL which was likely due to conduction slowing in response to overdrive pacing at a faster rate. For AVNRT and AVRT cases, we corrected for AH prolongation; therefore, the delay was likely due to conduction slowing in the intervening tissues and/or within the bypass tract or the AV node in the retrograde direction. We did not correct for conduction delay within ventricular tachycardias, which likely explains why there was increased error (~10ms on average) in this subset of patients. When using relatively long pacing cycle lengths, most ventricular tachycardias demonstrate a constant return interval. However, as demonstrated by Callans and colleagues, when overdrive pacing at shorter cycle lengths (80% of the TCL in their study), the return cycle frequently prolongs.¹⁶ In our study, we required the PCL to be within 30ms of the TCL (on average 94% of the TCL), which suggests that in the majority of cases we interacted with a fully excitable gap with minimal decremental conduction delay, which likely explains the high correlation between the observed and predicted PPI-TCL. However, pacing at faster rates may result in conduction slowing and PPI prolongation that may be difficult to identify, limiting the accuracy of our formula in these situations.

These relationships may enable new inferences from pacing maneuvers to differentiate supraventricular tachycardias (SVTs). For example, during the diagnostic EP study, RV overdrive pacing frequently terminates SVTs (56% in one series)⁸, precluding measurement of the PPI. Our study found that the total pacing prematurity at the moment of tachycardia advancement, minus the amount of atrial advancement, approximates the corrected PPI-TCL. Therefore, if overdrive pacing reproducibly terminates the tachycardia without advancing the atrium, our findings suggest the total pacing prematurity at the moment of tachycardia termination must exceed the corrected PPI-TCL – even though the amount of atrial advancement cannot be measured because of termination. If the total pacing prematurity is < 110ms at tachycardia termination, then it would suggest that the corrected PPI-TCL is also < 110ms, which would strongly favor a non-decremental septal AVRT rather than AVNRT. In another example, a PPI-TCL difference of < 30ms has previously

been associated with sites of successful catheter ablation.¹⁷ From our findings, we can infer that if a single stimulation with 30ms prematurity advances or terminates a tachycardia, then the PPI-TCL at this location must also be 30ms or less, and therefore indicative of a location within the re-entrant circuit and a potential target for catheter ablation. Finally, since these concepts appear to accurately estimate the timing of entrainment and the number of pacing stimulations required to reach the reentrant circuit, large deviations from predicted values may imply a non-reentrant tachycardia mechanism. Additional and prospective study is warranted to evaluate the accuracy and clinical utility of these concepts to facilitate SVT differentiation and other diagnostic maneuvers.

Similarly, from our findings, we may be able to further extrapolate that the effectiveness of anti-tachycardia pacing (ATP) algorithms might be improved by exploiting the PPI of failed ATP attempts. Nominally tested ATP strategies include burst pacing at 88% of the TCL for 8 pulses. However, the number of pulses delivered will influence ATP success.^{18, 19} Persistent overdrive pacing after tachycardia termination, particularly at faster rates, frequently induce new arcs of functional block and thus create potential reentrant circuits; often resulting in tachycardia re-initiation, acceleration and occasionally ventricular fibrillation.^{20–22} By recording the PPI of a failed ATP attempt, the number of pacing stimulations required to entrain the reentrant circuit for subsequent ATP attempts can be estimated (Table 2). However, even after obtaining entrainment, additional pacing stimulations (or more prematurity) may be necessary to terminate the tachycardia. Our study suggests the return interval of a failed ATP attempt may help estimate the number of pacing stimuli required to reach the tachycardia circuit, however, additional research is warranted to understand how to translate these concepts into clinical practice to facilitate tachycardia termination.

Limitations

This is a proof of concept study and thus is limited by small numbers. Our hypothesis will need to be corroborated with further observation. However, this theory accurately explains aspects of entrainment that have been previously extensively validated. Furthermore, the ability of this principle to predict the timing of entrainment and the precise amount of tachycardia advancement is compelling. Second, overdrive pacing may alter the conduction velocities and repolarization properties of the intervening tissues or critical pathways involved in reentry. To minimize these changes, we required the PCL to be within 30ms of the TCL and adjusted for decremental orthodromic AV nodal conduction. However, we could not correct for all changes in the arrhythmic circuit that occurs from overdrive pacing. Therefore, as with all entrainment maneuvers, potential changes in myocardial properties due to overdrive pacing need to be considered. Finally, these concepts and equations may not be applicable in situations of abnormal conduction properties resulting from prior scar or extensive ablation. For example, if the reentrant circuit is surrounded by myocardial tissue with prolonged refractory periods or unidirectional conduction, distant stimuli may be delayed or prevented from reaching the tachycardia circuit. Therefore, these concepts help form a fundamental framework to understand and guide entrainment maneuvers, while realizing clinical electrophysiology may not always behave precisely according to mathematical theory.

Conclusion

Overdrive pacing begins to advance a reentrant tachycardia precisely when the total pacing prematurity exceeds the observed PPI-TCL after correcting for cycle-length dependent changes. Therefore, the number of pacing stimulations required to entrain a tachycardia is predictable from measured intracardiac parameters. These relationships help unify various attributes of overdrive pacing previously reported to differentiate reentrant tachycardias and may help guide catheter ablation procedures. This relationship may help elucidate when anti-tachycardia pacing (ATP) episodes are ineffective or proarrhythmic and could potentially serve as a theoretical basis to optimize ATP settings (adjusting cycle length and stimulation number) for improved safety and effectiveness.

Clinical Perspectives

Delivery of a critically timed extra-stimulus or a series of extra-stimuli (overdrive pacing) are the predominant electrophysiological methods to investigate and terminate tachyarrhythmias. This study investigated the relationship between the post-pacing interval (PPI), the tachycardia cycle length (TCL), and the pacing cycle length (PCL) upon the timing of tachycardia entrainment. We found that overdrive pacing began to advance the reentrant tachycardia precisely when the total pacing prematurity (calculated by adding together the prematurity of each extra-stimuli) exceeded the observed PPI-TCL after correcting for PPI prolongation occurring due to the shorter pacing cycle length. This principle unifies various seemingly disparate methods previously described to differentiate supraventricular tachycardias and suggests the AH-corrected PPI-TCL can be accurately estimated even if overdrive pacing terminates the tachycardia. Further, our findings suggest that the number of pacing stimulations required to entrain a reentrant tachycardia can be estimated at any pacing rate from regularly measured intracardiac parameters. Therefore, this concept may serve as a theoretical basis to optimize anti-tachycardia pacing therapies (ATP) by exploiting the PPI from previously failed ATP attempts.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

ABBREVIATIONS

ATP	anti-tachycardia pacing
AVNRT	atrioventricular nodal reentrant tachycardia
AVRT	atrioventricular reentrant tachycardia
NNE	number needed to entrain
PPI	post-pacing interval
PCL	pacing cycle length
TCL	tachycardia cycle length

VT   ventricular tachycardia

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Figure 1.

Analysis of the return interval between a tachycardia that was reset versus not reset. Note the return interval from a compensatory pause prolongs with additional pacing. When the tachycardia is reset, the return interval is shorter than would be expected from a compensatory pause. The components of the post-pacing interval (PPI) can be determined. Overdrive pacing will advance the tachycardia precisely when the total pacing prematurity $[n * \text{TCL} - \text{PCL}]$ exceeds the PPI-TCL.

Figure 2.

Intracardiac tracings of a patient with one, two, three, and then four overdrive pacing stimulations at the same synchronized PCL. These intracardiac recordings demonstrate the differences in the return interval between a compensatory pause and a reset/entrained tachycardia. Note the return interval prolongs with additional pacing until tachycardia reset/entrainment is obtained.

Figure 3.

Intracardiac recordings of a patient with typical atrial flutter undergoes three entrainment maneuvers from an electrode positioned in the distal coronary sinus using a duo-deca multipolar electrode at three different PCLs of 270ms (top), 260ms, (middle), and 250ms (bottom). Initiation of overdrive pacing (left) reveals a TCL of 284ms. The PPI for each drive train (right) is 354ms. Using the PPI-TCL (70ms), the number of pacing stimulations required to obtain entrainment and the amount of tachycardia advancement on the first reset stimulation can be calculated. When pacing at 260ms, we predict four pacing stimulations are required to obtain entrainment (equation 4), and the third pacing stimulation will advance the tachycardia by 2ms (equation 7). When pacing at 250ms, we predict four pacing stimulations are required to obtain entrainment (equation 4), and the third pacing stimulation to advance the tachycardia by 32ms (equation 7). These calculations/predictions are accurate within 1 millisecond.

Figure 4.

The observed PPI-TCL and the predicted PPI-TCL for all cases. When applicable, the observed PPI-TCL was corrected for AH-prolongation. The predicted PPI-TCL (calculated as $(NNE-1) \times (TCL-PCL) - \text{Tachycardia Advancement}$) highly correlated with the observed PPI-TCL.

Figure 5.

Intracardiac recordings of an entrainment maneuver (initiation and termination) in a patient with AVRT are shown. The TCL was 321ms and the overdrive PCL was 310ms; therefore the pacing prematurity of each pacing stimulation is 11ms. The 6th pacing stimulation (total pacing prematurity of $11\text{ms} \times 6 = 66\text{ms}$) advances the atrial electrogram by 7ms ($321 \rightarrow 314\text{ms}$). Therefore, the predicted PPI-TCL is 59ms. As demonstrated, this was equal to the observed PPI-TCL.

Figure 6.

Intracardiac recordings of overdrive stimulation initiation (left) and termination (right) in a patient with AVNRT are shown. The TCL was 375ms and the overdrive PCL was 350ms. Each pacing stimulation gains on the tachycardia by the TCL-PCL (375-350ms), or 25ms. The 6th stimulation advances the atrial signal by (375-364ms), or 11ms. Therefore, the predicted PPI-TCL (6×25 minus 11ms) is 139ms. The observed AH-corrected PPI-TCL was 145ms (error of 6ms).

Table 1

Patient Characteristics and intracardiac measurements between the AVRT, AVNRT, and VT groups.

	AVRT	AVNRT	VT	P value
Number of patients	9	18	17	
Age (years)	41.6±13.4	52.0±17.4	57.1±10.5	0.04
Males (%)	5 (56%)	4 (22%)	14 (82%)	<0.001
TCL (ms)	364±48	361±92	394±70	NS
PCL (ms)	342±47	339±89	369±71	NS
Observed PPI-TCL (ms) [†]	79±32	143±20	101±55	<0.001
Predicted PPI-TCL (ms)	77±32	140±22	90±55	<0.001
Mean Error (ms) [‡]	2.1±2.8	3.2±9.4	10.6±9.7	0.02
NNE (mean, range)	7.4 (3–13)	8.8 (6–18)	5.5 (2–10)	<0.001

[†] When applicable, the observed PPI-TCL was corrected for AH-prolongation.

[‡] The mean error was calculated as the difference between the predicted PPI-TCL and the observed PPI-TCL.

Table 2

The estimated number of pacing stimulations required to advance (reset) and then entrain the tachycardia for VTs with different characteristics.

	VT Rate	ATP pacing rate (88% of TCL)	Return interval (PPI*)	PPI-TCL	TCL-PCL	$\frac{(PPI - TCL)}{(TCL - PCL)}$	Stim number required to advance (reset) the tachycardia.	Stim number required to entrain the tachycardia to the PCL [NNE]
Slow VT Close to circuit	TCL 333ms (180 BPM)	293ms	373ms	40ms	40ms	1	1	2
Slow VT Far from circuit	TCL 333ms (180 BPM)	293ms	523ms	190ms	40ms	4.75	5	6
Fast VT Close to circuit	TCL 250ms (240 BPM)	220ms	290ms	40ms	30ms	1.33	2	3
Fast VT Far from circuit	TCL 250ms (240 BPM)	220ms	440ms	190ms	30ms	6.33	7	8

* The measured return interval after a failed ATP attempt does not correct for changes in conduction velocity and therefore the estimated number of pacing stimulations required to reset/entrain the tachycardia would likely be overestimated.