Adapting Trigger Delays to Heart Rate for Coronary MR Angiography

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Motivation:
Recent work has shown that heart rate variations can significantly compromise cardiac gating, and demonstrated that sharper coronary artery MR images can be obtained by rejecting gated data acquired during unacceptably high heart rates [1]. Our work explores how heart rate variations can affect cardiac imaging windows and justifies the use of heart rate adaptive trigger delays in a correction scheme.

Background:
Diastole is composed of phases of isovolumic relaxation, rapid filling, and diastasis (slow filling) in the left ventricle, followed by atrial filling. Trigger delays are usually landmarked near the beginning of diastasis wherein lies the onset of a period of acceptably low global heart motion. In a normal 70 bpm beating heart, this is roughly 550 ms after the R peak on the electrocardiogram (ECG) and yields an imaging window of approximately 100-300ms in duration before ventricular systole depending on the region of interest (ROI). The durations of the diastolic phases before diastasis are fairly independent of heart rate [2]. Therefore, the ideal trigger delay should be a subject-dependent time constant after ventricular systole, which corresponds to the RT interval on the ECG. Detection of the T-wave terminus is, however, difficult in MRI due to the magnetohemodynamic effect and gradient switch noise. Recognizing that the interval RT_n is dependent on the rate of cardiac pacing, particularly the preceding RR interval (RR_{n-1}) [3],[4], we hypothesize that by adapting trigger delays to a varying heart rate, one can identify longer imaging windows. As a first step in the study, we demonstrate the relationship between RT_n and RR_{n-1}.

Methods:
Electrophysiological data: 3 volunteers were monitored with a 4-lead ECG system. Various steady state RR intervals within a dynamic range of roughly 600-900ms were achieved by the subjects' performance of leg raises at varying degrees of intensity. For each steady state, the corresponding RT_n mean is calculated to form a RT_n vs RR_{n-1} relationship.
Data fitting: We considered and modified the model used by *Malfatto et al*., which, in contrast to the popular Bazett's formula [3], was derived from parameters with explicit physical meaning to describe the rate dependency of repolarization [4]. Rather than constraining the model to cross the origin, however, it was thought appropriate to incorporate an asymptote to reflect an upper limit in heart rate, as follows:

$$RT_n(RR_{n-1}) = \hat{RT}_{\max}\frac{(RR_{n-1} - \hat{RR}_{\min})}{\hat{K} + (RR_{n-1} - \hat{RR}_{\min})} \qquad \text{Eq.1}$$

The data was fitted by minimizing the weighted least squared errors, and compared with: (A) the original *Malfatto et al*. model; and (B) a general linear model, a subject-adaptive version of the model used in previous MR work [5],[6].
Non-steady state data: Non-steady pacing will introduce to RT_n dependency on RR_{n-m}, where $m > 1$, through the hysteretic effects of memory, and restitution [7]. RT_n vs non-steady state RR_{n-1} data were achieved subjects performing leg raises to increase the heart rate, and then stopping to establish a recovery period, during which data was acquired. The ability of each of the steady state models to predict RT_n is compared.

Results and discussion:
Steady-state RT_n vs RR_{n-1} fit: The results in Table 1 show that Eq.1 is a better model for adapting RT to steady or slowly drifting pacing rates. Graphically, from Figure 1, it can be observed that the model's consideration of an upper heart rate (low RR) limit allows it to fit more accurately the physiological data. It is worth noting that the mean errors for all three models are much lower than that achieved by a previous method using neural networks to predict a prospective RR, which was then input into a non-subject adaptive trigger delay formula [5]. The framework suggested in this study finds trigger delays directly based on physiological understanding. As well, comparison of the two methods shows that the detailed RT_n vs RR_{n-1} relationship cannot be assumed, and must be characterized per individual per study.
Trigger delay adaptation: The 3 subjects were observed to have a mean dynamic range of RT of 50ms, RR of 259ms, and heart rate of 22bpm. A 50ms dynamic range in ideal trigger delays can mean, for gated imaging, a significant proportion of the cardiac cycle is unused, or a significant amount of data is corrupted by motion. Suppose Subject 1 experiences a heart rate increase from 70 to 90bpm (see Fig.1). A fixed trigger delay tuned to 70bpm will forgo roughly 30ms of imaging per cardiac cycle, which is 15% of a 200ms imaging window (reasonable at 70bpm); the gain is actually higher at 90bpm since the imaging window would be shorter.
Sources of error: Each of the models has two sources of errors. First, each observed (RR_{n-1}, RT_n) data point contains an RT distribution about that point. This distribution reflects both physiological dispersion of RT as well as measurement uncertainty of the RT duration. It was found that for each subject, considering all points, this distribution fits a Gaussian function well ($0.85 < \chi_\upsilon^2 < 0.9$), implying no measurement bias. The second source of error comes from assuming constant RRs in the fits while in reality, each data point is constrained to have $\sigma_{RR} < 20$ms. Iterative data fits were performed to confirm that this small RR distribution does not significantly increase error estimates of RT.
Non-steady pacing relation: Transient pacing introduces memory and restitution errors in determining RT_n from RR_{n-1}. It appears that these higher order effects can be crudely modelled as an RT bias to Eq.1. If this is true, then, looking at Table 1, the error for non-steady pacing (MAE) can be replaced by the smaller stdErr. We can do this provided: (1) we are able to characterize the bias for an individual before scanning; and (2) we know when pacing is steady *vs*. transient.

Pacing Type	Errors	Subject 1			Subject 2			Subject 3		
		Eq. 1	A	B	Eq. 1	A	B	Eq. 1	A	B
Steady state	MAE	3.6	5.5	5.5	6.2	8.6	8.8	2	3	4.4
Non-steady state	MAE	6.5	7.4	8.3	33	42	44	12	11	11
	stdErr	4.8	8.5	9.6	14	12	12	4	4.4	4.7

MAE = mean absolute error; stdErr = standard deviation of error — Note: all quantities are expressed in ms.

Table 1: Evaluation of RT_n vs RR_{n-1} in different models for 3 subjects for steady and non-steady pacing.

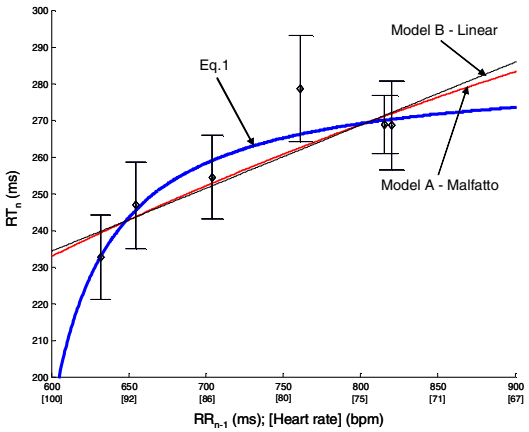

Figure 1: RT_n vs RR_{n-1} in different models for Subject 1

Conclusion:
Trigger delays can shift earlier as heart rate increases. This observation becomes more valuable at higher heart rates as diastole duration shortens correspondingly. Based on this analysis, the use of subject and heart rate adaptive trigger delays based on RR_{n-1} could improve gated cardiac imaging efficiency for a target image quality. We are currently evaluating this implication in experimental studies.

References:
[1] Leiner T. et al., *JRMI*, **22**:577–582 (2005); [2] Chung C.S. et al., *AJP–Heart*, **287**:2003-2008(2004);
[3] Bazett H.C., *Heart*, **7**:353-367(1920); [4] Malfatto G. et al., *Europace*, **5**:163-170(2003);
[5] Buehrer M. et al., *Proc. ISMRM 2005*, p.2240; [6] Stuber M. et al., *Radiology*, **212**:579-587(1999);
[7] Surawicz B., *Electrophysiological Basis of ECG and Cardiac Arrhythmias*, Lea & Febiger, 1994.