

## The positive T wave

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### ABSTRACT

**Objective:** The instant of maximum slope (Tup) of the T wave in the unipolar electrogram is a well-established measure of repolarisation time (TR). Nevertheless, recent observations on positive T waves have caused a renewed debate. The purpose of this study was to elucidate the mechanism that leads to positive and negative T waves and to investigate which electrogram feature best predicts TR.

**Methods:** We simulated propagating action potentials (AP) and electrograms with a bidomain reaction-diffusion model of the human heart including heterogeneous ion-channel properties. To explain positive T waves we compared results with those of a much simpler model, which predicts T waves from local and remote AP.

**Results:** Repolarisation time was defined as the instant of steepest downstroke of the AP. T wave polarity was mostly determined by TR. Positive T waves occurred at early-repolarising sites. Correlation between Tup and TR was >0.99, in both negative and positive T waves. T wave area and peak value also correlated highly with TR.

**Conclusion:** The polarity of the T wave is primarily determined by TR. Positive T waves occur at early-repolarising sites. Local TR is best estimated by Tup, also in positive T waves. (*Anadolu Kardiyol Derg 2007; 7 Suppl 1; 164-7*)

**Key words:** unipolar electrogram, ventricular repolarisation, computer model

### Introduction

Measurement of repolarisation time from the unipolar electrogram (UE) is important for clinical studies of repolarisation abnormalities, as well as for experimental studies. It is therefore necessary to understand how the T wave in the electrogram is generated, and how it relates to local repolarisation time. The recent debate on repolarisation measurement in positive T waves (1-3) demonstrates that this understanding is incomplete.

Wyatt et al. (4) proposed to use the instant of steepest upstroke (Tup) of the T wave in the UE as a measure of local repolarisation. Experimental and theoretical studies have confirmed the validity of this method (1). Other authors have proposed that an exception should be made for positive T waves, using the instant of steepest downstroke (Tdown) of the T wave in the UE instead of Tup (5, 6).

In this study, we used a detailed 3-dimensional computer model of the human heart to show how, according to existent biophysical knowledge, the shape of the T wave is determined. We used the simulated electrograms to evaluate Tup and relate it to repolarisation time as determined from the underlying action potentials.

### Methods

Vm and extracellular potentials ( $\phi_e$ ) were simulated with a computer model of the human heart that has been described previously (7). This model has anisotropic myocardium and heterogeneity of membrane properties (Table 1). Propagating action potentials were computed by a monodomain reaction-

diffusion model. Ionic currents were computed with the TNNP (Ten Tusscher-Noble-Noble-Panfilov) model for the human ventricular myocyte (8). Some parameters of the ionic current were changed, and differences between the left ventricle (LV) and right ventricle (RV) were implemented according to published data (on canine hearts) (9, 10), as outlined in Table 1. The types XL and XS (Table 1) were used to implement abnormally long and short action potential duration (APD) in some experiments.

Two different models were used for the computation of  $\phi_e$ : a "realistic model" and a "simple model". The realistic model computed  $\phi_e$  from Vm throughout the heart by solving

$$\nabla \cdot ((G_i + G_e)\nabla\phi_e) = -\nabla \cdot (G_i\nabla V_m) \quad 1$$

where  $G_i$  and  $G_e$  are the intracellular and extracellular conductivity tensor fields, respectively (7). The reference potential for electrograms was taken from the roof of the right atrium.

If it is assumed that the heart and intracavitary blood are uniformly isotropic, and that the reference point is equally well connected with any position in the ventricles, then the UE at a point  $x$  is simply a scaled mirror image of the difference between the local Vm and the average Vm in the ventricular myocardium (Vavg):

$$\phi_{e,\text{simple}}(x) = -\frac{\sigma_i}{\sigma_i + \sigma_e} (V_m(x) - V_{\text{avg}}) \quad 2$$

where  $\sigma_e$  and  $\sigma_i$  represent the conductivities of the extracellular and intracellular domains, respectively. The "simple model" used this formula. For the fraction  $\sigma_i / (\sigma_i + \sigma_e)$  the value 0.25 was chosen.

Simulations were performed with a normal-heart model and models containing a modified zone of 10mm radius located in the LV free wall. This zone had either abnormally short or abnormally long APD.

T waves could be positive, negative, biphasic, or multiphasic. To allow a division into positive and negative T waves, we evaluated the areas enclosed by the zero line and the electrogram, from the instant 100 ms after local depolarisation to the end of the simulation. A T wave was defined as positive when the positive area exceeded the negative area. Repolarisation time (TR) was defined as the instant of steepest downstroke of Vm. Repolarisation time and Tup were evaluated in the interval from 100 ms after local depolarisation to the end of the simulation (500 ms after the first activation). For positive T waves, Tdown was evaluated in the interval from Tup to the end of the simulation. For negative T waves, Tdown was not assessed.

### Results

Figure 1, panel A, demonstrates the simple model for one site in the heart. In panel B, electrograms are compared that were computed with the "simple" and "realistic" models. These simulated electrograms were highly similar. The two models agreed on the polarity of the T wave in 90% of the analysed positions (panel C, N=10<sup>4</sup>). Correlation between the T wave area computed by the two models was 0.96 (N=10<sup>4</sup>).

These comparisons show that the T wave is essentially determined by the local Vm and by Vavg. The electrogram is positive when local Vm is lower than Vavg. This happens in particular for early-repolarising cells. The electrogram remains positive as long as there are depolarised cells elsewhere in the heart. This implies that all T waves, except for the latest repolarising area, must end positively. The examples in Figure 1 illustrate this.

The simple model does not define electrogram shapes outside the myocardium. The realistic model reproduced the well-known shape of the cavity potential (11).

The simple model also failed to reproduce the low-amplitude electrograms that the realistic model predicted in thin trabeculae.

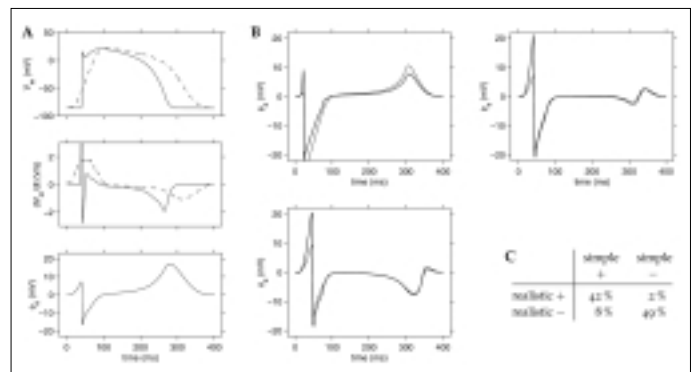
In the normal heart, positive T waves were found in 44% of the analysed positions. Average TR at locations with positive T waves was 40 ms earlier than at locations with negative T waves. In Figure 2, panel A, TR distribution is shown separately for positive and negative T waves. Most positive T waves were associated with TR that were earlier than those of negative T waves, but some overlap between the two distributions was present. Figure 2, panels B and C, show that T wave area and peak value correlate highly with TR.

Figure 3 shows a sample of electrograms taken from various sites in the heart, selected to show the variation in T wave shape

from entirely positive through biphasic to negative. Local repolarisation times are indicated with dots in the electrograms. These are invariably located on the upslope of the T wave. All T waves in this example end positively, and at the same time, as in the simple model.

Differences between repolarisation parameters were computed for N=10<sup>4</sup> individual positions, and the average and standard deviation of the difference were computed. For positive T waves, Tup underestimated TR by 0.1±2.3 ms and Tdown overestimated TR by 28.7±8.1 ms. Figure 4 shows scatter plots comparing electrogram-based estimates of repolarisation with TR. For negative T wave morphologies, Tup correlated very well with TR. The slope of the regression line was close to 1. For positive T waves the correlation was somewhat lower, but still very high. Correlation between Tdown and TR was much lower, and associated with a slope of only 0.65.

A simulation was performed with a small area in which cells had a very short APD (type XS in Table 1). Statistics were compared with those of the normal heart. While differences in Tup ( $\Delta$ Tup) correlated well (r=0.995) with differences in TR ( $\Delta$ TR), the differences in Tdown ( $\Delta$ Tdown) were more weakly related (r=0.769). Regression slopes were 1.015 for Tup and 0.392 for Tdown. Analysis was limited to those waves that were positive both with and without XS zone (N=4280).



**Figure 1. Comparison between the simple and realistic models of the UE. Panel A shows how an electrogram is reconstructed according to the "simple model". The top panel shows Vavg (dashed line) and local Vm (drawn line) at a position in the right-ventricular subepicardium. The middle panel shows their temporal derivatives (dashed for dVavg/dt). The lower panel shows the reconstructed electrogram. In panel B, electrograms according to the simple model (black lines) are compared to the realistic model (gray lines). In panel C, T wave polarity according to the two models is compared for a sample of 10<sup>4</sup> positions randomly distributed in the ventricles.**

UE- unipolar electrogram, Vavg- average Vm in the ventricular myocardium

**Table 1. Selected parameters of the ionic model**

Parameters	LV epi	LV M	(LV&RV) endo	RV M	RV epi	XS	XL
Gto, nS/pF	0.294	0.294	0.073	<b>0.504</b>	<b>0.882</b>	0.294	0.073
Gks, nS/pF	0.245	0.062	0.245	<b>0.112</b>	<b>0.490</b>	<b>0.735</b>	<b>0.010</b>
Gkr, nS/pF	0.096	0.096	0.096	0.096	0.096	0.096	<b>0.020</b>

Parameter values that are different from the original TNNP model (8) are printed in bold type. The affected parameters (8) are:

Gto- the maximal conductance of the transient outward current, Gks- the maximal conductance of the slow component of the delayed rectifier current, Gkr- the maximal conductance of the rapid component of the delayed rectifier current

Units are: nS- nanoSiemens, pF- picoFarad,

endo- endocardium, epi- epicardium, LV- left ventricle, M- M-cell (mid-mural cell), RV- right ventricle, XL- abnormally long action potential duration, XS- abnormally short action potential duration

### Discussion

Our model predicts that 1) the polarity of the T wave is mostly determined by the difference between local membrane potential and the average of all membrane potentials in the ventricles. Positive T waves occur therefore at early-repolarising sites, negative T waves at late-repolarising sites. 2) Local repolarisation time is best estimated by the instant of maximum slope of the T wave, whatever its polarity. 3) Failure of this method is to be expected in thin isolated bundles. 4) All T waves end at the same time. 5) All but the very latest T waves end positively. We have shown that at least for T waves in healthy tissue the UE can be understood as a downscaled and inverted difference between the local Vm and the average Vm in the heart. With this simple model, the meaning of the T wave in the UE is immediately clear. The signal is positive when the local Vm is more negative than the average, and negative when the local Vm is more positive. The most early repolarising sites are

therefore characterized by positive T waves. Later sites have an initially negative T wave, due to the decrease of the average potential caused by the earlier sites. When they repolarise themselves, their Vm quickly becomes more negative than the average, causing a rapid change in their UE from negative to positive. Only the latest repolarising sites have entirely negative T waves. In a computer model, not disturbed by noise and electrical interference, it is possible to see that all T waves are either positive or biphasic with a positive second phase, except at the very latest repolarising sites. In addition, all T waves end simultaneously. Both the "simple model" and the more realistic bidomain model demonstrate that the steepest upslope of the T wave is associated with the steepest downslope of local Vm.

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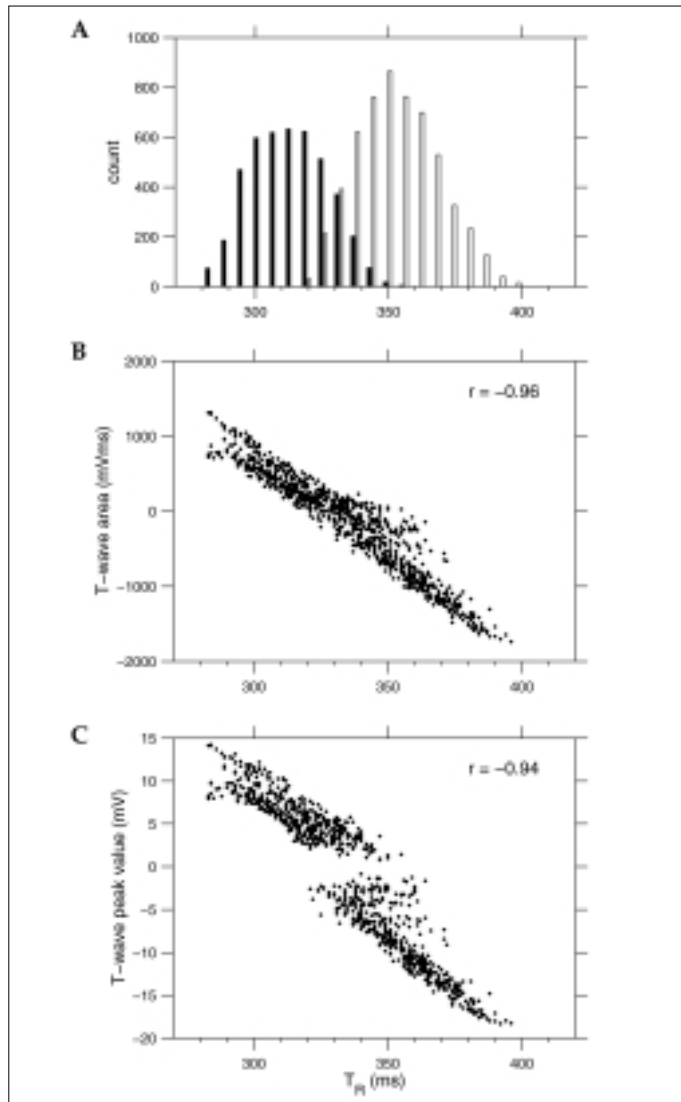


Figure 2. Panel A: Distribution of TR for positive T waves (black bars) and for negative T waves (white bars); N = 10<sup>4</sup>. Panel B: scatter plot demonstrating the correlation between TR and T wave integral; N=1000 for clarity. Panel C: scatter plot demonstrating the correlation between TR and T wave peak value; N=1000

TR- repolarization time

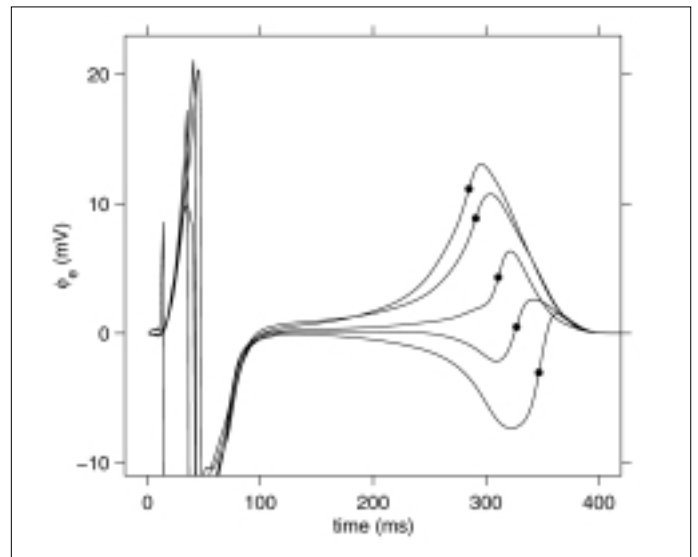


Figure 3. Simulated electrograms from various sites in the ventricles, selected to show a variety of T wave shapes from positive through biphasic to negative. Local TRs are indicated with dots

TR- repolarization time

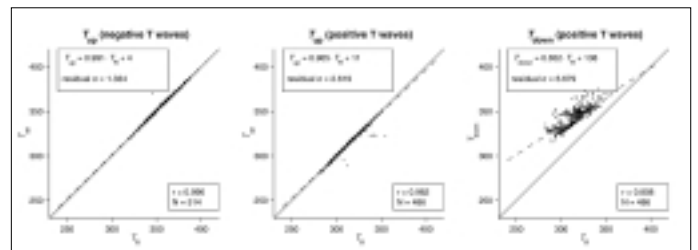


Figure 4. Correlation between TR and electrogram-based estimates. Tup was compared with TR, for negative T waves (left) and for positive T waves (middle). Tdown was only evaluated for positive T waves (right). Insets show parameters for a linear fit, correlation coefficient (r) and number of sites included (N). The dashed line in each panel shows the linear fit; solid lines show the identity relation. Tdown - instant of steepest downstroke of the T wave

TR- repolarization time, Tup - instant of steepest upstroke of the T wave

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