Computers in Biology and Medicine 71 (2016) 205–213

Contents lists available at ScienceDirect

Computers in Biology and Medicine

journal homepage: www.elsevier.com/locate/cbm

Formation of reentrant circuits in the mid-myocardial infarct border zone

Edward J. Ciaccio [a,*], James Coromilas [c], Andrew L. Wit [b], Nicholas S. Peters [d], Hasan Garan [a]

[a] Division of Cardiology, Department of Medicine, Columbia University Medical Center, New York, United States
[b] Department of Pharmacology, Columbia University Medical Center, New York, United States
[c] Division of Cardiovascular Diseases & Hypertension, Rutgers Robert Wood Johnson Medical School, New Brunswick, NJ, United States
[d] Myocardial Function Section, Imperial College and Imperial NHS Trust, London, United Kingdom

ARTICLE INFO

Article history:
Received 2 November 2015
Accepted 8 February 2016

Keywords:
Circuit
Curvature
Reentry
Ventricular tachycardia
Wavefront

ABSTRACT

Introduction: In this study, the mechanisms for onset and maintenance of mid-myocardial (intramural) reentrant circuits are considered, based upon anatomical structure.
Method: A model of electrical activation wavefront curvature in the mid-myocardial postinfarction border zone is developed. Two arrhythmogenic structures are considered: 1. a constrained slab of viable tissue, and 2. a strand of surviving myocardial fibers with distal expansion. Equations are formulated to estimate activation coupling intervals, and ranges in taper and circuit dimensions, that will support functional conduction block during premature stimulation and reentrant ventricular tachycardia.
Results: For onset and maintenance of reentry, the arrhythmogenic regions forming both slab and strand circuits are in the range of 50–600 μm at their thinnest dimension. For constrained slabs, unidirectional block leading to reentry forms in the thin-to-thick direction during premature stimulation, and functional block at lateral boundaries enable formation of a double-loop circuit. The activation wavefront proceeds around the impediment and then curves in the opposite direction through the slab, reentering the previously excited tissue. For strands, unidirectional block forms at a distal expansion in response to premature stimulation. The strand reentrant circuit is bounded by infarcted tissue causing anatomical block, and can be single-loop or coaxial. For all architectures, circuit dimensions ranging from 1.6 × 1.6 mm to 3.5 × 3.5 mm support functional block when premature stimulus coupling intervals are 117–150 ms and ventricular tachycardia cycle lengths are 160–350 ms.
Conclusions: For slab and strand mid-myocardial arrhythmogenic structures, taper and circuit dimensions govern ranges in premature excitation coupling intervals and tachycardia cycle lengths necessary to support functional block.

1. Background–reentrant circuit architecture

In prior work, reentrant circuit formation at the postinfarction surface of the heart was described based upon critically convex wavefront curvature, which results in functional conduction block [1,2]. Such circuits are entirely mappable with contact electrodes, and are evident in clinical as well as canine episodes of ventricular tachycardia [3]. During tachycardia, the reentrant circuit tends to reside at the endocardial surface in clinical post-myocardial infarction [4], and at the epicardial surface in canine postinfarction hearts [5], although intramural and opposite surface reentry can also be observed [6,7]. The electrical activation wavefront typically propagates in a thin surviving layer of border zone that is adjacent to the heart surface, with the infarct at depth. The circuit is therefore maintained in part by no-flux anatomical boundaries, i.e., non-conducting zones consisting of heart surface and infarct. The central common pathway, also called the diastolic pathway or isthmus of the reentrant circuit, is coincident with the thinnest border zone [1,8,9] and is bounded laterally by functional conduction block. These arcs of block result from the presence of source–sink mismatch and critically convex wavefront curvature, when current generated from a smaller volume of previously excited myocardium at the thinnest border zone is insufficient to activate the larger volume of surviving myocardium in the distal, laterally outward direction. This has been observed to occur when the thinnest infarct border zone is $\lesssim$500 μm [8,9]. The presence of critically convex wavefront curvature, source–sink mismatch, and functional block is rate-dependent [10,11]. That conduction block is functional, not anatomic, is evident since it is only present at the

* Correspondence to: P&S 7-446, Columbia University, 630 West 168th Street, New York, NY 10032.
E-mail address: ciaccio@columbia.edu (E.J. Ciaccio).

http://dx.doi.org/10.1016/j.compbiomed.2016.02.009
0010-4825/

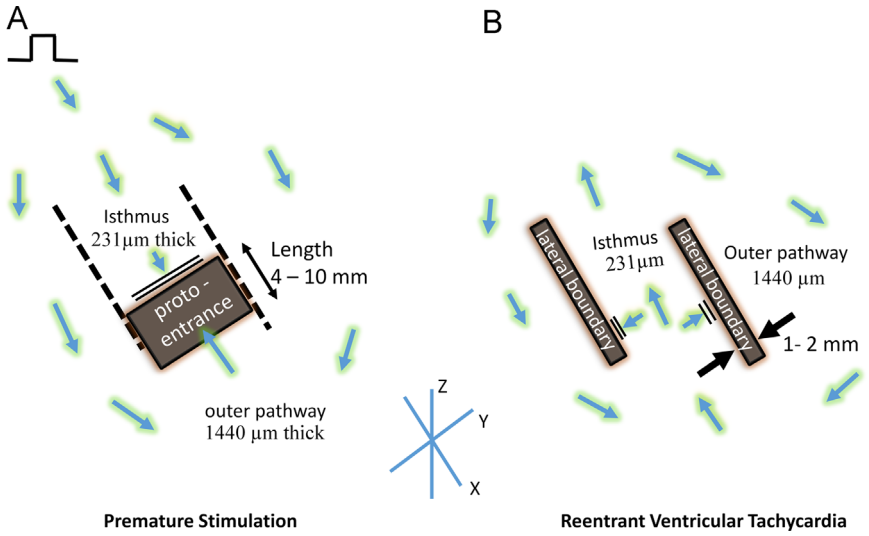

Fig. 1. Configuration of functional block lines during A. premature excitation and B. reentrant ventricular tachycardia. Coordinate axes are shown. *X* and Y represent the plane of the heart surface. The electrical activation wavefront travels in the *XY* plane. The *Z* axis represents the thickness direction of the infarct border zone. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.).

short activation coupling intervals of premature stimulation and ventricular tachycardia, not at the longer cycle lengths of normal sinus rhythm [12,13].

Previously, it was shown in postinfarction canine hearts that the thinnest epicardial border zone has an average thickness of 231 μm at the reentry isthmus location, while the outer circuit pathway averages 1440 μm in thickness [1]. Fig. 1 depicts the configuration based upon prior work. There is a step change in infarct border zone thickness from 231 μm to 1440 μm across the lateral isthmus boundaries (dashed lines in Fig. 1A) but a more gradual change along the isthmus long axis. During premature stimulation from the site noted, unidirectional conduction block can occur at the region of gradual change, i.e., the proximate edge of the proto-isthmus entrance, when the wavefront results from a premature stimulus [2]. The wavefront then bifurcates, traveling as two distinct wavelets about the sides (Fig. 1A) [2]. The wavelets then curve and coalesce, and propagate as a single impulse in the opposite direction. If sufficient time for recovery of excitability has elapsed, the merged impulse can cross the unidirectional block line from the opposite side to reenter the previously excited region, initiating reentrant ventricular tachycardia, as illustrated in Fig. 1B. The circuit will be stably maintained only if there are lateral bounding lines of functional conduction block which are approximately constant in position (thick lines). Outward across these lateral boundaries, the sharp change from thinnest-to-thick border zone causes critically convex wavefront curvature and functional block. The electrical impulse thus propagates through the isthmus, but it cannot traverse outward at the lateral boundaries (as noted by small blue arrows and double lines in Fig. 1B). Since conduction block occurs at both lateral edges, a double-loop circuit configuration is initiated, and maintained during reentry [2].

Although the above model describes reentrant circuits at the heart surface, ventricular tachycardia sometimes exhibits an incompletely mappable or even an entirely unmappable circuit there, but it is evidently not focal in origin, suggesting that the circuit may either contain transmural components, or perhaps is entirely constrained to the mid-myocardium (intramural location). In this study, the model developed for reentrant circuits forming at the heart surface is extended to describe anatomical structures causing arrhythmogenicity in the mid-myocardium. Equations are formulated to express the unique structural aspects of the mid-myocardium that can lead to onset and maintenance of reentrant circuits as a source of ventricular tachycardia from this region. The equations are used to estimate the mid-myocardial geometric dimensions and characteristics leading to functional block and reentry, which is partially validated by comparing with prior work, and can be further tested in future studies.

2. Model of functional conduction block based on convex wavefront curvature

In this section, equations that describe wavefront curvature causing functional block at the postinfarction surface of the heart are first reviewed [1,2,14]. Then equations describing critically convex wavefront curvature at mid-myocardial arrhythmogenic structures are formulated.

2.1. At the heart surface

When the infarct border zone resides at the heart surface, the conduction velocity equation for thickness-induced changes in wavefront curvature can be written as [2]:

$$\theta \approx \theta_o - \frac{D}{c} \cdot \frac{\Delta T}{T} \tag{1}$$

where θ is the wavefront conduction velocity, θ_o is the velocity when the geometry of the conducting medium along a particular distance is unchanged, T is the border zone thickness, c is the spatial transition step, or space step, and D is the diffusion coefficient, with c and D both constant, and ΔT is the spatial change in thickness per unit space step c, taken as the absolute maximum ΔT in the vector field about the measurement point [1,2]. The approximation sign is used to simplify a more complex equation derived in prior work [1], and is valid when the absolute maximum $\Delta T \ll c$. For functional conduction block to occur, from Eq. (1), the following condition must therefore be met:

$$\theta_o \lesssim \frac{D}{c} \cdot \frac{\Delta T}{T} \tag{2}$$

which will occur when T is minimized and ΔT is maximized, i.e., as the activation wavefront propagates along a sharp transition from thinnest-to-thick border zone. An approximation is used in Eq. (2) because very slow conduction may effectively result in functional block if the tachycardia cycle length is shorter than the wavefront travel time across the lateral boundary. The conduction velocity