Initiation and propagation of ectopic waves: insights from an in vitro model of ischemia-reperfusion injury

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Arutunyan, Ara, Luther M. Swift, and Narine Sarvazyan. Initiation and propagation of ectopic waves: insights from an in vitro model of ischemia-reperfusion injury. Am J Physiol Heart Circ Physiol 283: H741–H749, 2002; 10.1152/ajpheart.00096.2002.—The objective of the present study was to directly visualize ectopic activity associated with ischemia-reperfusion and its progression to arrhythmia. To accomplish this goal, we employed a two-dimensional network of neonatal rat cardiomyocytes and a recently developed model of localized ischemia-reperfusion. Washout of the ischemia-like solution resulted in tachyarrhythmic episodes lasting 15–200 s. These episodes were preceded by the appearance of multiple ectopic sources and propagation of ectopic activity along the border of the former ischemic zone. The ectopic sources exhibited a slow rise in diastolic calcium, which disappeared upon return to the original pacing pattern. Border zone propagation of ectopic activity was followed by its escape into the surrounding control network, generating arrhythmias. Together, these observations suggest that upon reperfusion, a distinct layer, which consists of ectopically active, poorly coupled cells, is formed transiently over an injured area. Despite being neighbored by a conductive and excitable tissue, this transient functional layer is capable of sustaining autonomous waves and serving as a special conductive medium through which ectopic activity can propagate before spreading into the surrounding healthy tissue.

CULTURED MYOCYTES; CALCIUM TRANSIENTS; ISCHEMIC BORDER ZONE

Cardiac arrhythmias arise from abnormalities of either impulse propagation (reentry based) or impulse initiation (focal or ectopic). Although the development of reentry arrhythmias, which involves rotation of an excitation wave around an anatomic or functional block, is conceptually well understood (19, 34, 44), it remains unclear exactly how the excitation propagates from an ectopic cell into the surrounding cell network. Previous studies have addressed several important questions about ectopic activity associated with ischemia-reperfusion. Specifically, many electrophysiological studies have shown the ability of individual myocytes to exhibit either triggered activity or abnormal automaticity upon reperfusion and have tied such arrhythmic behavior to specific ionic currents (7, 11, 54). Studies conducted in isolated papillary muscles and Purkinje fibers have revealed the importance of electrotropic interactions across inexcitable regions of tissue in modulating the activity of ectopic foci (1) and the role of entrance block with exit conduction (protected ectopic foci) for depolarization-induced automaticity to spread (31, 41). Mapping studies conducted in intact hearts have revealed that 25% and 75% of arrhythmias occurring during ischemia and reperfusion, respectively, can be traced to ectopic sources (37), with the majority located close to the ischemic border zone (20). Finally, theoretical studies have addressed the critical size of an automatic focus, the safety factor (ratio of generated charge and that required to excite neighboring cells), and the roles of cell-to-cell coupling and anisotropic conduction in the propagation of ectopic activity (21, 43, 49). Despite these significant advancements, the actual progression of ectopic activity to arrhythmia has yet to be observed, mainly because the ischemic border of intact cardiac tissue has been inaccessible to real-time observation on a cellular scale. To visualize such a progression, we used a cellular model of ischemia-reperfusion that was recently developed in our laboratory (2). The results we obtained with this model not only have substantiated earlier theoretical estimates of the critical size of ectopic loci and the role of uncoupling in the generation of ectopic activity, but have also revealed a new phenomenon: a transient functional layer that is capable of sustaining autonomous ectopic waves.

MATERIALS AND METHODS

Myocyte cultures. Cardiomyocytes from 1- and 2-day-old Sprague-Dawley rats were obtained by an enzymatic digestion procedure described previously (2). The cells were plated on 25-mm laminin-coated glass coverslips (10⁵ cells/cm²) and kept under standard culture conditions in DMEM, supplemented with 5% fetal bovine serum (FBS), 10 U/ml penicillin, 10 μg/ml gentamicin, and 1 μg/ml streptomycin. By the third day in culture, the cells had formed interconnected confluent networks that exhibited rhythmic, spontaneous contractions. The cells were used in experiments for the next 3–4 days.

Intracellular calcium measurements. Cells were loaded for 1 h with 5 μM fluo 4-AM in Tyrode solution at room temperature. The superfusion solutions contained 0.25 μM fluo 4-AM to maintain the intracellular dye concentration during extended experiments. Each spontaneous or stimulated ac-
The C- and I-solutions. Specifically, flow from a 5-ml syringe was added in parallel to flow from the control 30-ml syringe. This increased the flow of C-solution from 75 to 90 μl/min (while inflow of the I-solution remained the same) and effectively reduced the size of the I-zone.

**Injury solution.** The terms “ischemic” or “injury” environment in our study refer to a solution that reproduces certain elements of the extracellular milieu of ischemic cells (2, 48). It consisted of (in mM) 136 NaCl, 0.8 MgCl2, 8 KCl, 1.2 CaCl2, 20 deoxyglucose, 2 heptanol, 5 HEPEs, and 5 MES; pH 6.5. Inclusion of the gap junction uncoupler heptanol allowed us to mimic the uncoupling effects of free fatty acids, e.g., arachidonic and palmitoleic acids, which have been shown to accumulate in the extracellular milieu of ischemic tissue (12, 38). In neonatal rat cardiomyocytes, 2 mM heptanol reversibly inhibits gap junction permeability (6, 46), whereas it's effect on Ca2+ and spontaneous contractions is negligible (4, 23).

**Acquisition systems.** Fluo 4-loaded cells were imaged with low power magnification objectives (Olympus; PlanApo x/2, 0.08 numerical aperture and UPlanFl ×10/0.3 numerical aperture) to capture the I- and C-zones simultaneously. For the experiments shown in Figs. 1, 2, 4, and 5, the BioRad MRC 1024 confocal system was used. Experiments presented in Fig. 3 were acquired with a Metafluor Imaging System equipped with an intensified charge-coupled device camera (Pentamax, Princeton Instruments).

**Data analysis.** Unless specified otherwise, the conclusions of this study were based on the analysis of over 300 injury/reperfusion episodes (yield from a single litter was sufficient to plate 20–40 coverslips, which were then used for individual experiments). Specifically, in 190 experiments with the I-solution containing heptanol, the following responses were obtained: 1) no changes (immediate return to the original frequency), 46 cases (24%); and 2) tachyarrhythmias, 144 cases (76%). Tachyarrhythmias, in turn, included 1) tachycardia (monotonic increase in frequency), 57 cases (30%); 2) arrhythmia (irregular increase in frequency with observable ectopic beats), 63 cases (33%); and 3) tachyarrhythmia associated with the formation of spiral waves, 24 cases (13%). Spreads and other spatiotemporal patterns, which formed as a result of colliding ectopic waves, will be the subject of a follow-up paper and thus are not discussed here. In the 120 experiments that employed heptanol-free I-solution, tachycardia was observed 13 times (11%) and arrhythmia with the ectopic extra beats was observed 6 times (5%). The presented figures are typical results of corresponding scenarios. Quantitative results are expressed as means ± SD. Data and images were plotted using Microcal Origin 6.0 and Scion (NIH) Image software.

**Chemicals.** Collagenase type II was obtained from Worthington (Freehold, NJ). Media and porcine trypsin were obtained from GIBCO-BRL (Grand Island, NY). Fluo 4-AM was purchased from Molecular Probes (Eugene, OR). FBS and all other chemicals were purchased from Sigma (St. Louis, MO).

**RESULTS**

**Appearance of ectopic clusters.** During “ischemia,” the amplitude of CaT-s within the I-zone declined progressively and was followed by cessation of cell beating. Although changes in CaT frequency inside and outside the I-zone were not detected during perfusion with I-solution, tachyarrhythmic episodes lasting 15–200 s were recorded in both the C- and I-zones immediately upon restoration of control flow in ~76% of the exper-
iments. When these tachyarrhythmic episodes occurred, we observed ectopic CaTs within the former I-zone, predominantly within or close to the border (Fig. 1). Such ectopic activity appeared as a local increase in $\text{Ca}^{2+}$ with the amplitude and duration similar to pacing-elicited CaTs (Figs. 1 and 2). The average distance from the center of the functional border (defined in Ref. 2) to an ectopic cluster was $232 \pm 113$ μm. The linear sizes of the observed ectopic clusters varied from 180 to 300 μm (236 ± 57 μm), encompassing $\sim 2$–$9 \times 10^4$ μm$^2$ (shape of ectopic clusters depended on particular cellular arrangement, see examples in Figs. 1 and 2). This area corresponds to $\sim 8$–50 cells, which is in agreement with theoretical studies that estimate the minimum size of the ectopic region as $8$–10 cells (52). It is possible, however, that these numbers are overestimates, because high binning, which was used to acquire the images, lowers spatial resolution of images to 44 μm/pixel ($\times 2$ objective) and makes clusters smaller than $\sim 100$ μm indistinguishable from noise.

The fate of ectopic clusters was threefold: 1) activity remained confined to the ectopic cluster and, after 1–3 ectopic beats, this area was “swept” by a CaT wave from another source; 2) the cluster slowly expanded, encompassing a larger area of border or I-zone cells (Fig. 2, B and C) but failed to propagate into the control network; and 3) slow (0.1–0.4 cm/s) expansion of the ectopic cluster caused excitation of the surrounding network with fast propagation velocities (Fig. 2, C and D). As a result of the above events, a complex pattern of colliding ectopic waves spread through the entire field, including the former I- and C-zones. The exact patterns varied between experiments.

**Ectopic activity is associated with changes in CaT shape.** To understand the basis of the elevated excitability of ectopic regions, we examined CaTs in more detail using the MetaFluor imaging system (Fig. 3). Specifically, recordings were obtained from the border area and included CaTs from both ectopic and control regions. An immediate increase of baseline $\text{Ca}^{2+}$ was observed in myocytes from the ectopic regions upon reperfusion (Fig. 3, red trace). In this particular experiment, the first ectopic beat (black arrow) failed to propagate to neighboring myocytes, but the next CaT from the same ectopic locus drove the cell network for at least 140 s, until the pace approached the initial frequency of the layer. The slowing of ectopic pacing during the later stages of reperfusion revealed an important feature of the ectopic cells’ CaT, a prominent rise in diastolic $\text{Ca}^{2+}$ (Fig. 3, red arrows), which resem-

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**Fig. 1. Generation of ectopic beats in the border zone.** A: diagram on the left shows the experimental field and the injury zone (I-zone). The I-zone (shown in gray) was created by flows of control and ischemia-like solutions using a custom-designed superfusion chamber (2). Recordings of calcium transients (CaTs) were obtained from the border zone, inside the blue box shown on the left. The pseudocolor reflects increasing calcium concentrations as measured by fluo 4 fluorescence. a, Image was obtained during application of injury (I) solution. It shows a propagating wave of CaTs (CaT wave) that travels through the control area but does not penetrate into the I-zone. Black arrows point in the direction of CaT wave propagation. b, Appearance of ectopic clusters upon initiation of reperfusion. Three large clusters and a small one can be seen in this frame. c, Spreading of ectopic activity into surrounding network. Black arrows point in the direction of CaT wave propagation. B: A, b was used to plot the intensity profiles for regions where ectopic activity was observed. Two rectangular regions with their corresponding profiles are shown on the left. The position of these regions relative to the rest of the field can be seen on the right. The white dotted line marks the border of the I-zone.
bled the diastolic depolarization of a pacemaker cell. Although only an estimate of Ca$^{2+}$ can be obtained from nonratiometric calcium probes, such as fluo 4, we calculated slope values for the control and ectopic CaTs using the $K_d$ value of 345 nM (15, 17). The slope in ectopic regions ranged from 7 to 40 nM/s and was significantly higher than in control traces (Fig. 3C). This slope disappeared upon return of the original
pacing pattern, suggesting its direct involvement in ectopic activity.

**Role of cell-to-cell coupling and the number of injury events.** Omission of heptanol from the I-solution sharply reduced the incidence of reperfusion arrhythmias (from 76% to 16%). Thus a 10-min superfusion with uncoupler-free I-solution resulted in the return of CaTs and restoration of rhythmicity across the entire field in a majority of the experiments. However, if the 10-min ischemia/10-min reperfusion cycle was repeated, the occurrence of reperfusion arrhythmias increased in proportion to the number of injury events (Fig. 4A). Typical traces from the C- and I-zones during the repetitive injury protocol are shown in Fig. 4B, and tachyarrhythmic episodes are marked with an asterisk. The lower traces in Fig. 4 reveal that tachyarrhythmic episodes in the C-zone occurred when cells inside the I-zone failed to exhibit CaTs upon reperfusion.

**Role of border zone propagation.** Upon reperfusion, ectopic CaT often propagated along small areas of the border and then spread into the C- and recovering I-zones. In one series of experiments, we blocked the propagation of such activity into the inner area of the I-zone by continuing to superfuse it with I-solution (see MATERIALS AND METHODS and Fig. 5). Such “microreperfusion” allowed us to confine ectopic activity to the large segments of the border zone (Fig. 5A). Border zone propagation was followed by the escape of ectopic activity from the border zone into the surrounding control network, resulting in the generation of arrhythmias (Fig. 5B).

**DISCUSSION**

Despite recent advances in mapping electrical activity in the heart (35, 45, 47, 55), cellular events within the border zone of an ischemic area have not been observed in situ. Thus until now the initial stages of...
ectopic activity and its propagation have been addressed mainly by computational approaches (16, 21, 52, 53). In contrast, this study provides insights from direct observation of ectopic activity, resulting from a new experimental approach developed in our laboratory (2). It employs a multicellular network of myocytes and fluo 4 fluorescence to visualize propagating ectopic waves of CaTs. Despite the absence of electrophysiological measurements, the results are highly relevant to cardiac arrhythmias. First, ultimately it is the disorganized contraction (as a result of CaT), not electrical activity, that renders the heart unable to pump blood efficiently. Second, monitoring CaTs as a means to measure beat rates and the velocity of impulse propagation has been used successfully both in vitro and in vivo (5, 14, 24). Third, CaTs measured in our experiments were direct indications of propagating action potentials, because the velocity of CaT wave propagation exceeded by at least two orders of magnitude the velocity of diffusion-based Ca waves (25, 27) and was similar to the velocity of action potentials measured by others in neonatal myocyte cultures (13, 29). In addition, the magnitude and velocity of ectopic CaTs that spread from the I-zone to the C-zone were identical to these elicited by the external pacing electrodes.

In our experimental protocol, the generation and propagation of ectopic activity occurred only during washout of the I-solution, i.e., during reperfusion (Figs. 1–3). What are the factors that promoted the generation of ectopic beats in these experiments? In the presence of I-solution, the gap junction conductance of myocyte within the I-zone is decreased due to the uncoupling effects of low pH (32, 51) and heptanol (4, 23, 46). Although upon reperfusion heptanol is rapidly removed from the cell surroundings (<15 s), intercellular coupling was restored only gradually. For example, Bastide et al. (4) found that gap junction conduc-
derence in neonatal rat myocyte pairs was restored to 90% of its control value ~90 s after withdrawal of heptanol. Therefore, during the first 100 s of reperfusion, a range of coupling conductances is superimposed upon rapidly recovering cell excitability, which passes through abnormally high values during the initial phase of reperfusion (7, 11, 33). Thus the combination of high excitability and decreased intercellular coupling creates conditions that favor the generation and propagation of ectopic activity from an individual myocyte or myocyte cluster (42). By decreasing cell-to-cell coupling, one effectively reduces a current “sink” leading to improvement of impulse propagation from an active focus (21, 50, 52). A similar phenomenon, a paradoxical improvement in the safety factor of conduction, was observed when cell-to-cell coupling was reduced in branching strands of cardiomyocytes (39). Our experiments provided two lines of evidence that decreased cell-to-cell coupling is essential for the successful progression of ectopic activity. First, omission of heptanol from the I-solution reduced the occurrence of reperfusion arrhythmias by more than fourfold (from 76% to 16%), suggesting that elevated excitability, alone, is insufficient for ectopic activity to proceed. Importantly, heptanol-containing control Tyrode solution failed to cause reperfusion arrhythmias (data not shown). The second line of evidence comes from our repetitive injury experiments (Fig. 4). Although CaTs recovered after a single exposure to heptanol-free I-solution, repetitive injury progressively diminished CaT amplitudes (Fig. 4B) and eventually led to cell death within the I-zone, as assessed with trypan blue (data not shown). At the same time, a strong correlation was observed between the incidence of reperfusion arrhythmias and the absence of CaTs in the I-zone upon reperfusion (Fig. 4A). Thus we hypothesize that the irreversible injury of I-zone myocytes, which is induced
by repetitive ischemia-reperfusion cycles, removed the I-zone as an effective current “sink” and increased the probability of ectopic beat generation from the border zone. In other words, repetitive injury creates a unidirectional block for border zone cells, thereby increasing the safety factor for successful propagation of ectopic beats (49).

Whereas diminished coupling appears to be essential for both the generation and propagation of ectopic activity, an additional factor, increased cell excitability, is required for an ectopic cell or cluster to emerge. Direct visualization of ectopic sources in our cellular model of reperfusion-ischemia injury allowed us to simultaneously observe CaTs in ectopic and control regions. The distinguishing characteristic of the ectopic regions was a slow increase in diastolic Ca\(^{2+}\), which preceded the CaT and resembled the diastolic depolarization typical of pacemaker cells (Fig. 3). The basis of such an increase in diastolic Ca\(^{2+}\) is unknown. It could be the consequence of reperfusion-induced alterations of ion channels and transporters or from reperfusion-induced Ca\(^{2+}\) overload (7, 9). The latter is known to occur in cardiac myocytes upon recovery from ischemia or acidosis and can cause triggered activity as a result of the inward sodium current generated by the Na\(^{+}/\)Ca\(^{2+}\) exchanger or Ca\(^{2+}\)-activated nonselective cation channels, facilitating myocyte depolarization. Ca\(^{2+}\) overload also enhances the probability of Ca\(^{2+}\) efflux from the sarcoplasmic reticulum (SR) during diastole, thereby increasing the likelihood of automaticity in latent pacemaker cells as well as ventricular and atrial myocytes (3). Through a positive feedback loop, which involves low-voltage-activated T-type Ca\(^{2+}\) channels and Ca\(^{2+}\)-induced Ca\(^{2+}\) release from the SR, subsarcolemmal Ca\(^{2+}\) also may induce pacemaker activity in atrial cells (18, 26). Any of these mechanisms could be involved in the slow rise of diastolic Ca\(^{2+}\) observed in our experiments.

In addition to the ionic basis of ectopic foci, it is important to understand how such activity is propagated. The fact that every myocyte within the recovering border zone was subjected to similar conditions in our experimental setup, and that multiple ectopic sites emerged upon reperfusion, suggest, that many, if not all, border cells are capable to exhibit ectopic activity. Thus assuming that the entire border zone area gains automaticity or triggered activity, we hypothesize that impulse propagation within such an area should follow the principles known for the sinoatrial (SA) node. In fact, theoretical studies have shown that thousands of pacemaker cells generate synchronized outgoing action potentials by an entrainment process in the SA node: after leading cell fires, an activation front propagates through the rest of the already entrained pacemakers with an apparent, slow conduction velocity (30). If such a tissue has homogeneous physiological properties, waves of action potentials generated from an ectopic source would be spread spherically. However, if the tissue surrounding the leading cell is not homogeneous with regard to either junction conductance or diastolic depolarization rate, the activation of neighboring cells would be asymmetric. Diastolic depolarization then acts as a “pulling” force, yielding in the extreme case a linear propagation. We observed such “linear” propagation along small (200–400 \(\mu\)m) regions of the border zone. The microreperfusion protocol allowed as to effectively “focus” ectopic activity in a narrow layer around the I-zone (Fig. 5).

Although we failed to observe ectopic activity during in vitro “ischemia,” 25% of the arrhythmias that occur during ischemia in vivo can be attributed to ectopic sources (36). How can one explain this apparent paradox? We suggest that ischemic process in vivo could be associated with conditions, which are similar to those in the microreperfusion protocol. Specifically, it could be due to the dynamic conditions associated with an infarct area, when metabolic vasodilatation of adjacent coronary beds transiently relieves ischemic conditions in small areas of the infarct’s border. Myocytes within such areas might then act as a source of ectopic arrhythmias, as we observed in our study. In other words, a microreperfusion-like process could be responsible for arrhythmias that occur during ischemia.

Whether initial development of ectopic activity occurred in small ectopic clusters during the original ischemia-reperfusion protocol or in an extended borderline pattern (microreperfusion protocol, Fig. 5), at this stage CaT spread with an apparent low velocity (0.1–0.4 cm/s). Such low velocities, nevertheless, exceed by at least order of magnitude the speed of Ca\(^{2+}\) waves caused by Ca\(^{2+}\)-induced Ca\(^{2+}\) release (22). On the other hand, the apparent velocities of CaTs in ectopic clusters were an order of magnitude slower than the propagation of CaTs through the control network (6–9 and 14–18 cm/s at 25 and 37°C, respectively). Thus we suggest that the slow velocities we observed in ectopic clusters were due to the entrainment mechanisms of conduction in a network of ectopically active cells, where the activation propagates with a slow apparent velocity (30).

On the basis of the results of the present study, one can extrapolate the concept of “border zone” propagation in a two-dimensional myocyte network to the three-dimensional myocardium by incorporating the following scenario of events. At the onset of global or partial reperfusion, reversibly injured cardiomyocytes form a transient functional layer over an infarcted, irreversibly injured area. Such a layer might consist of ectopically active but poorly coupled myocytes (“pacemaker-like layer”) that are capable of sustaining autonomous ectopic waves. Upon restoration of cell-to-cell coupling, these ectopic waves would escape into the healthy network, generating arrhythmias. Given the significant differences in the electrical properties of cultured neonatal rat cardiomyocytes and adult human ventricular myocardium, additional experiments will be required to confirm occurrence and clinical relevance of such a scenario in vivo.

In summary, direct observation of reperfusion-induced ectopic activity in a two-dimensional network of neonatal rat cardiac myocytes corroborated theoretical predictions regarding the interplay between excitabil-
ity and cell-to-cell coupling required for ectopic beat propagation. We have shown that an ectopic focus has to expand to a cell cluster of certain dimensions to activate the surrounding network. The experiments also revealed that CaTs in ectopic regions exhibit a slow rise during diastole and suggested that activity within an ectopic cluster propagates via a slow, entrainment-like process, similar to the propagation of action potentials in the SA node. Our results also suggest that, upon reperfusion, a functional ectopically active layer can be formed transiently over an injured area. Despite being surrounded by a normally conductive and excitable tissue, this layer, itself, can exhibit transient autonomous activity. These results may provide further insights into the mechanisms that underlie arrhythmias in the human myocardium.

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