Disparate effects of biphasic and monophasic shocks on postshock refractory period dispersion

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Sims, J. Jason, Allison Winecoff Miller, and Michael R. Ujheldi. Disparate effects of biphasic and monophasic shocks on postshock refractory period dispersion. Am. J. Physiol. 274 (Heart Circ. Physiol. 43): H1943–H1949, 1998.—The magnitude by which a defibrillation shock extends the refractory period immediately postshock (refractory period extension, RPE) does not explain why biphasic shocks defibrillate with greater efficacy than monophasic shocks. It may be that spatial heterogeneity of RPE is a more important regulator of defibrillation efficacy. We measured RPE in 15 pentobarbital-anesthetized swine using 400-V biphasic and monophasic shocks of equal pulse duration at three discrete myocardial sites. Spatial heterogeneity of RPE was calculated as the difference between the maximum and minimum values of the three recording sites. Monophasic shocks produced greater magnitude of RPE than biphasic shocks at all sites tested (82 ± 6 to 99 ± 13 and 64 ± 6 to 68 ± 5 ms, respectively; P < 0.05). However, RPE dispersion was significantly less with biphasic shocks versus monophasic shocks (29 ± 4 and 48 ± 7 ms, respectively; P < 0.05). This suggests that one potential mechanism by which biphasic shocks defibrillate with greater efficacy is limiting postshock spatial heterogeneity of refractoriness. Thus these data support our hypothesis that RPE heterogeneity is a more likely predictor of defibrillation efficacy than magnitude of RPE.

defibrillation; electrophysiology; graded response

ELECTRICAL DEFIBRILLATION via the automatic implantable cardioverter-defibrillator is recognized as an important means of preventing sudden cardiac death (21). Nevertheless, the mechanisms of defibrillation remain elusive and are often debated. It is clear that direct excitation of a critical myocardial mass is required to achieve successful defibrillation (22, 47). However, mapping studies show that early postshock activations arise and/or continue in areas of low voltage gradients and can occur regardless of the absolute mass excited (3, 41, 42). Propagation of these early postshock activations can lead to failed defibrillation (3, 5, 6, 11, 13, 17, 25, 44). Conversely, impeding the propagation of early postshock activations should facilitate successful defibrillation. Thus refractoriness of the myocardium immediately postshock is likely to determine whether early postshock activations will propagate and lead to failed defibrillation. This has led to the theory that a shock must produce extension of action potential duration and thus refractory period extension (RPE) to achieve successful defibrillation (8, 35, 45).

In vitro, both monophasic and biphasic waveforms extend repolarization and refractoriness, with the latter waveform producing a greater response (30). Initially this was thought to explain why biphasic waveforms have lower defibrillation thresholds than monophasic waveforms. However, follow-up in vitro and in vivo studies have shown that extension of repolarization and refractoriness is larger with monophasic shocks than with biphasic shocks (7, 32, 33, 37, 45, 46). Because the magnitude of RPE does not consistently predict waveform efficacy, other mechanisms must be operative. The magnitude of RPE, regardless of waveform, has been characterized as being dependent on local voltage gradients and shock timing during cellular repolarization (31, 35). Because defibrillation shocks produce heterogeneous potential gradients across the heart (4, 7, 41) and cellular depolarizations are asynchronous throughout the myocardium during fibrillation, it can be expected that a shock would produce a heterogeneous RPE response across the myocardium. Spatial heterogeneity in myocardial refractoriness postshock may allow for conduction block and therefore enhance propagation of early postshock activations. The effects of varying voltage gradients on postshock action potential extension were assessed in an in vitro model (37). It was found that biphasic shocks produced more homogeneous action potential extension at varying voltage gradients compared with monophasic shocks. This suggests that biphasic shocks produce a more homogeneous tissue response regardless of gross heterogeneity in myocardial voltage gradients. However, this investigation was limited to studying the action potential response of a single cell.

On the basis of these observations, we postulate that biphasic shocks produce a more uniform postshock state of refractoriness across the myocardium than monophasic shocks. Moreover, this difference between waveforms may be a mechanism by which biphasic shocks defibrillate with greater efficacy. The present study was designed to test the hypothesis that transcardiac biphasic shocks produce less dispersion of shock-induced RPE than monophasic shocks in the intact porcine heart.

METHODS

Animal preparation and surgical instrumentation. All procedures were approved by the Medical College of Georgia and Augusta Veterans Affairs Medical Center Animal Care and Use Committees before this investigation was conducted. Fifteen domestic farm swine weighing between 25 and 30 kg were used in this investigation. After an overnight fast, the animals were sedated with ketamine (15 mg/kg) administered intramuscularly. Subsequently, pentobarbital sodium (25 mg/kg) was administered intravenously for initial anesthesia induction. After intubation with a cuffed endotracheal tube, the animals were mechanically ventilated using a large-animal Harvard pump ventilator with 5 cmH2O positive end-expiratory pressure and supplemental oxygen as needed. A level plane of anesthesia was subsequently main-
tained throughout the study period with the use of pentobarbital as a continuous infusion of 150–300 mg/h. The external jugular vein, internal carotid artery, and femoral artery were cannulated for catheterization, drug infusion, and blood collection. Guided by fluoroscopy, we placed a combination of pacing and contact monophasic action potential catheter (EP Technologies, Mountain View, CA) into the right ventricular apex via the external jugular vein, and a second catheter was placed into the left ventricle against the left lateral wall via the internal carotid artery. These catheters recorded local monophasic action potentials from the right and left ventricular endocardium and paced the ventricles. A pigtail 5-Fr Millar pressure-sensing catheter was placed via the femoral artery for blood pressure monitoring. Surface electrocardiographic leads were placed on four limbs for monitoring of lead II. The chest was opened using a median sternotomy. A monophasic action potential probe (Franz Spring Cantilever Epicardial Probe, EP Technologies) was placed on the left ventricular apex of the epicardium; a second probe was placed on the right ventricular base of the epicardium. An arterial catheter was delivered at a coupling interval equal to the local ARP. An S2 stimulus (5 mA) was inserted after the shock. A monophasic action potential recording at the stimulation site was used to assess whether the S2 stimulus resulted in ventricular capture postshock. A 2-min rest phase ensued, allowing blood pressure to return within 10% of preshock values. This algorithm continued by decreasing the S2 stimulus by 5 ms every 2 min until the stimulus failed to produce ventricular capture. Six to eight shocks are required per waveform at each site to determine RPE. Thus three myocardial sites were tested to confirm the number of shocks to 50 and to limit myocardial damage. All parameters were randomly measured according to myocardial site and shock waveform to ensure that shock-induced myocardial damage did not affect the results. Figure 1A depicts the postshock refractory period protocol, and Fig. 1B shows capture of an S2 stimulus after a defibrillation shock.

Single-axis voltage gradients. Single-axis voltage gradients were measured at each epicardial site using two poles (5-mm interpole spacing) of the four-pole silver-silver chloride electrode array. Endocardial voltage gradient was measured using the intercardiac pacing electrode that had an interpole spacing of 2 mm. A differential probe (model P5200, Tektronics, Beaverton, OR) coupled to a storage oscilloscope (model TDS310, Tektronics) was used to measure the differential of the leading-edge peak voltage produced by the biphasic and monophasic shocks. The differential leading-edge peak voltage was measured at each site was divided by the distance between the poles, yielding the single-axis voltage gradient. To minimize intrasubject variability, careful attention was paid to keeping the same heart rate and the same epicardial location during each measurement.
given to consistently place the defibrillation electrodes and the recording electrodes in the same angular orientation.

Study design. A 30-min equilibration phase followed surgical preparation. Subsequently, ARP measurements were quantified at each myocardial site in a random fashion. This was followed by the postshock refractory period protocol. The postshock refractory period protocol was performed at a specific myocardial site using either shock waveform. Subsequent sites and shock waveforms were then assessed, using a random testing order, until all six site and shock waveform combinations were completed. Next, ARP measurements were repeated at each myocardial site to confirm model stability. The ARP measured at the beginning and end of the experiment were averaged for analysis purposes.

Data analysis. The difference between the ARP measured with an intervening shock and the ARP without a shock represented shock-induced RPE. Spatial heterogeneity (i.e., dispersion of refractoriness and potential gradients) was calculated as the difference between the maximum and minimum values measured at the three discrete myocardial sites. A paired t-test was used to test differences in RPE and potential gradient between waveforms at a single site. A paired t-test was also used to test differences between ARP measurements made at the beginning and end of the postshock refractory period protocol. A two-way ANOVA was used to test differences in ARP between myocardial sites within a waveform. Significant differences were evaluated post hoc between the three sites using the Tukey test. The nonparametric Kruskal-Wallis ANOVA on ranks was used to test differences between dispersion values calculated at baseline and during monophasic and biphasic shocks and to test differences in RPE between myocardial sites within a waveform. Significant differences were evaluated post hoc between the three testing phases using the Student-Newman-Keuls test. All data and statistical analysis was performed with a personal computer using Microsoft Excel 7.0 (Microsoft, Redmond, WA) and SigmaStat 2.0 (Jandel Scientific, San Rafael, CA). Statistical significance was set at a P value < 0.05 using a two-tailed test. Data are presented as means ± SE.

RESULTS

Refractory periods. ARP measured at the beginning and end of the protocol did not significantly differ, indicating the stability of the model over time. This is illustrated in Fig. 2. Thus the two measurements were averaged for the remaining data analyses. The RV epicardial site had the largest average ARP (171 ± 4 ms), which was significantly longer than both the LVE and LVA sites (P < 0.05). This resulted in a mean ARP dispersion of 18 ± 2 ms, which is similar to that seen with effective refractory period dispersion (26).

The refractory period following a biphasic shock was 64 ± 6 to 68 ± 5 ms longer than the ARP (P < 0.05), whereas the refractory period following a monophasic shock was 82 ± 6 to 99 ± 13 ms longer than the ARP (P < 0.05). The difference between refractory periods with and without a biphasic or monophasic shock is depicted in Fig. 3 as RPE. Monophasic shocks produced the greatest RPE at the LVE site, which was ~18% greater than the lowest extension seen at the RV epicardial site (P = 0.183). Biphasic shocks produced the greatest RPE at the LVE site, which was ~3% greater than the lowest extension seen at the LVA site.

(P = 0.532). These data clearly show that monophasic waveforms produced significantly greater RPE at each site compared with biphasic shocks. It is interesting to note that basal ARP negatively influenced the magnitude of RPE with monophasic shocks (R² = 0.285, P < 0.001; i.e., the greater the basal ARP, the lower the magnitude of RPE) but not biphasic shocks (R² = 0.059, P = 0.108).

Both biphasic and monophasic shocks produced a significant increase in RPE dispersion that exceeded ARP dispersion by 11 ± 2 (P < 0.05) and 30 ± 5 (P < 0.05) ms, respectively (Fig. 4). The disparity between ARP and RPE dispersion is demonstrated by the fact that these parameters were not correlated (biphasic shocks: R² = 0.164, P = 0.135; monophasic shocks: R² = 0.087, P = 0.285). More importantly, these data show that biphasic shocks produced significantly less RPE dispersion than monophasic shocks (29 ± 4 and 48 ± 7 ms, respectively, P < 0.05; Fig. 4). This effect was consistent between animals in that RPE dispersion values were less with biphasic shocks in all but two animals. It is interesting to note that these two animals...
monophasic shocks (2, 23, 29, 40). However, the mecha-

biphasic shocks defibrillate with greater efficacy than

Local voltage gradients

DISCUSSION

had at least one myocardial site that produced greater
or equal RPE with biphasic shocks compared with
monophasic shocks, suggesting an exaggerated re-

Voltage gradients. Means ± SE of the single-axis
voltage gradients are listed in Table 1. Voltage gradi-
teins were highest at the LVE for both biphasic and
monophasic waveforms, whereas the RV had the lowest
gradient, as expected (4). Voltage gradients did not

differ between biphasic and monophasic waveforms at
any site. Moreover, voltage gradient dispersion was
similar between biphasic and monophasic waveforms (19 ±
5 and 22 ± 3 V/cm, respectively) and thus cannot

explained the disparity in RPE dispersion between wave-
forms. Because single-axis voltage gradients cannot

quantitate absolute epicardial potential gradient, we
could not evaluate the relationship between shock

intensity and electrophysiological response (RPE). How-
ever, comparisons between waveforms reveal that bipo-

hasic and monophasic shocks produce similar epicardial
voltage gradients and that waveform differences in
RPE or RPE dispersion are not caused by differences in

shock intensity.

Table 1. Local voltage gradients

<table>
<thead>
<tr>
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<th>LVE</th>
<th>LVA</th>
<th>RV</th>
<th>Dispersion</th>
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<tbody>
<tr>
<td>Biphasic, V/cm</td>
<td>22 ± 6</td>
<td>10 ± 2</td>
<td>9 ± 1</td>
<td>19 ± 5</td>
</tr>
<tr>
<td>Monophasic, V/cm</td>
<td>25 ± 4</td>
<td>9 ± 9</td>
<td>8 ± 1</td>
<td>22 ± 3</td>
</tr>
</tbody>
</table>

Values are means ± SE. LVE, left ventricular endocardium; LVA, left ventricular epicardial apex; RV, right ventricular epicardial base.

DISCUSSION

Both animal and human studies have shown that
biphasic shocks defibrillate with greater efficacy than
monophasic shocks (2, 23, 29, 40). However, the mecha-

nisms by which biphasic shocks defibrillate with greater

efficacy are not well understood. The magnitude of the

postshock refractory period has been proposed to facil-
tate defibrillation. However, this study and others (7,
32, 33, 37, 45, 46) demonstrate that monophasic shocks
produce greater RPE than biphasic shocks. It may be

that the homogeneity of postshock repolarization and
refractoriness is a more important regulator of defibril-
lation outcomes than the absolute magnitude of post-

shock refractoriness. The findings of this study show

that biphasic shocks produce less RPE dispersion than
monophasic shocks of equal peak voltage. This suggests

that by limiting RPE dispersion, biphasic shocks defi-

brillate with greater efficacy than monophasic shocks.

Model considerations. The current protocol used three

myocardial sites to measure RPE dispersion. The num-
er of sites tested was limited to confine the number of

shocks to <50, thereby limiting myocardial damage
(see METHODS for further explanation). The myocardial
sites were chosen to illustrate transmural (endocardial
vs. epicardial) and ventricular (right vs. left) differ-

ences in myocardial electrical activity. Moreover, the
two-epicardial sites were at locations that usually have
the highest (left ventricular apex) and lowest (right
ventricular base) potential gradients (4). Thus the
electrode positions were expected to be sensitive enough
to detect global differences in regional heterogeneity.

This is consistent with other investigations that have

shown that electrical heterogeneity can be assessed
with two or three myocardial electrodes located very
distant from one another (13, 18, 24, 39, 43).

The current protocol was also designed to produce a large
RPE response and RPE dispersion by maximizing the
timing of the shock and the shock voltage, respectively.

Maximum RPE response is achieved by delivering the

shock at the ARP (~71–82% of repolarization; Ref. 26).
A shock delivered later in repolarization would likely

produce a new, shock-induced action potential. Maxi-
mum RPE dispersion likely occurs at voltages at which
the probability of successful defibrillation is between 20
and 80%. This is based on mapping studies that show
that early postshock activations are prevalent at these
voltage, regardless of the fact that the shock has

excited and/or depolarized a critical myocardial mass
(3, 41, 42). Thus a 400-V shock was used because it is
usually below the level at which defibrillation always
succeeds for monophasic and biphasic shocks. Although
we did not determine defibrillation threshold in this
study, to limit shock damage, our previous experiments
have shown that a 400-V monophasic and biphasic

shock falls along the 20–80% response curve (40).
Regardless of these limitations (limited sites, one shock
intensity and coupling interval), the data from the
current study provide evidence that defibrillation wave-
forms affect postshock spatial electrical heterogeneity
differently. However, further study is required to allow
broad application of the RPE dispersion theory.

Comparison with other works. Others have shown
that biphasic shocks consistently produce less RPE
than monophasic shocks (32, 33). These data are also
consistent with in vitro studies that showed that bipha-
Biphasic shocks produce less action potential extension than monophasic shocks (37). The magnitude of RPE produced by biphasic and monophasic shocks in the present study was similar to that seen by others using a sheep and rabbit model (27, 38) but different from that seen in canine models (31, 33, 35). In addition to species differences, the timing of the shock in relation to the refractory period also differed among studies.

Our data are in agreement with an in vitro report that assessed dispersion of action potential duration extension produced by biphasic and monophasic shocks (37). This single-cell model demonstrated that biphasic shocks produce homogeneous extension in action potential duration at different local voltage gradients, whereas monophasic shocks produce varying levels of action potential extension dependent on the local voltage gradient. Computer models have also shown similar results such that the cellular response to biphasic shocks is more synchronous than monophasic shocks (28). These studies are limited because they do not assess the effect of the shock on tissue refractoriness. The magnitude and heterogeneity of action potential duration extension may not predict refractory period extension, especially if there is postrepolarization refactoriness after a high-energy shock. Moreover, postshock refactoriness is a better determinant of tissue excitability and impulse propagation than is the action potential response to a shock. Also, it may be that a heterogeneous response in a single cell does not equate to a spatial heterogeneous response across intact myocardium. The current study extends this area of investigation to an in vivo model that can assess spatial heterogeneity in postshock refractoriness across the myocardium. This report confirms the in vitro and computer modeling data showing that biphasic shocks limit postshock electrical heterogeneity.

Postshock refractory period dispersion and defibrillation efficacy. The RPE hypothesis states that extension of refractoriness postshock facilitates defibrillation by blocking propagation of postshock activation fronts (8, 25, 30, 35, 38, 39, 46). Although RPE may be a mechanism of defibrillation, it cannot explain why biphasic shocks defibrillate with greater efficacy than monophasic shocks. Another potential mechanism suggested by the current study is that biphasic shocks defibrillate with greater efficacy because biphasic shocks limit postshock RPE dispersion. Reducing postshock electrical dispersion may prevent unidirectional conduction and reentry and thus nonuniform propagation (9). Hence, the postshock electrophysiological milieu produced by biphasic shocks may be less arrhythmogenic. This was exemplified when biphasic T-wave shocks were associated with less dispersion in postshock repolarization time and a smaller area of vulnerability to ventricular fibrillation than monophasic shocks (1).

Dispersion in postshock repolarization and perhaps refractoriness decreases as a shock nears the upper limit of vulnerability, a surrogate for defibrillation threshold (16, 31). This is an expected finding, because RPE reaches a maximum when the voltage gradient exceeds 15–20 V/cm (31). Thus RPE dispersion will be minimized regardless of voltage gradient heterogeneity when the minimum voltage gradient across the myocardium exceeds 15–20 V/cm. The RPE hypothesis predicts that this will occur as the shock intensity approaches the point where defibrillation is always successful. Hence, RPE dispersion should be equivalent between waveforms at a voltage intensity that exceeds the 100% successful threshold for both waveforms (>550 V). On the other hand, shock intensities of <20% success would not excite a critical mass and never halt and/or alter the original fibrillation front. This scenario would make RPE and RPE dispersion immeasurable parameters at subthreshold shocks. Future studies must address these possibilities.

Mechanisms of RPE dispersion. Dispersion of RPE may be caused by a diverse voltage gradient or by asynchronous timing of the shock to the action potential (4, 7, 31, 41). Because timing of the shock during the action potential was controlled, RPE dispersion in the current study was likely caused by diverse voltage gradients. This was confirmed by demonstrating that a 400-V transcardiac shock, known to cause up to a 10-fold difference between maximum and minimum voltage gradient, increased the basal level of spatial refractory period dispersion for monophasic and biphasic shocks.

Data from the current study suggest that another mechanism regulating RPE dispersion may be the basal level of refractoriness. We found an inverse correlation between ARP and RPE for monophasic shocks but not biphasic shocks. This suggests that monophasic shocks produce a graded response from the myocardium based on multiple variables including, but not limited to, tissue refractoriness and voltage gradients. Thus, as characterized in a computer model (10), a monophasic shock would be more likely to elicit different magnitudes of response from the myocardium, creating dispersion. Conversely, a biphasic shock, although producing less magnitude of response, would have a more homogeneous effect on the myocardium and thus would limit shock-induced dispersion. Why these variables affect biphasic shocks to a lesser extent than monophasic shocks cannot be elucidated in the current study. However, this may relate to how a shock waveform activates ion channels and/or charges the cell membrane (14, 15, 19, 21, 30, 36, 37). Theoretically, this could affect the homogeneity of tissue response to a shock.

Limitations. Refractory period measurements in this study were made during rapid pacing and not during fibrillation. Ionic and ischemic changes occur during fibrillation that could alter our results. However, the technical aspects of determining RPE require a known cycle length to time the shock and postshock stimulus appropriately. Rapid ventricular pacing in our model causes hemodynamic collapse and will likely mimic ischemia occurring during fibrillation. Others have shown that RPE occurs at rates of 200–600 beats/min and that RPE is still a function of coupling interval and local voltage gradients at these rates (12). Moreover, it has been demonstrated that RPE occurs after a shock is
delivered to fibrillating myocardium (34). Thus it is likely that assessing postshock refractoriness during rapid pacing is predictive of fibrillation and may provide valuable insight into defibrillation.

Absolute refractory periods were measured with a 3-s delay between 
S1 drive trains, whereas RPE measurements used a 2-min delay. The 3-s delay between determinations may result in an ARP measurement that is lower than determinations made using a 2-min delay (31). Hence, shocks separated with a 2-min delay are likely delivered at a coupling interval less than the ARP. This may decrease the magnitude of RPE, because the shock would be delivered earlier in repolarization. However, this is not likely to affect RPE dispersion, because the shorter shock coupling interval is uniformly applied to each myocardial site.

Accurate assessment of epicardial voltage gradients requires a differential voltage measurement in two dimensions (x- and y-axes). Because we were only interested in determining whether relative differences occurred between waveforms at a given site, we only measured potential gradient in one dimension. This method should be able to accurately measure relative differences in voltage gradients between waveforms if the current vector remains constant. We believe that this was the case, because defibrillation lead placement and polarity of the monophasic and biphasic shocks were fixed throughout the study, exemplified by the fact that there was little within-animal variability.

In summary, extension of refractoriness postshock is a proposed mechanism of defibrillation. It has been shown that biphasic shocks produce less refractory period extension than monophasic shocks. However, biphasic shocks consistently produce lower defibrillation thresholds. This report confirms that shock-induced refractory period extension is less with biphasic shocks compared with monophasic shocks. In contrast, heterogeneity in postshock refractoriness was significantly less with biphasic shocks. These data suggest that biphasic shocks defibrillate with greater efficacy because they produce a more homogeneous state of refractoriness postshock than monophasic shocks. Thus dispersion of refractory period extension is more predictive of waveform efficacy than the magnitude of extension.

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REFERENCES


