Background—Survival after prolonged ventricular fibrillation (VF) appears severely limited by 2 major factors: (1) low defibrillation success rates and (2) persistent post-countershock myocardial dysfunction. Biphasic (BP) waveforms may prove capable of favorably modifying these limitations. However, they have not been rigorously tested against monophasic (MP) waveforms in clinical models of external defibrillation, particularly where rescue from prolonged VF is the general rule.

Methods and Results—We randomized 26 dogs to external countershocks with either MP or BP waveforms. Hemodynamics were assessed after shocks applied during sinus rhythm, after brief VF (>10 seconds), and after resuscitation from prolonged VF (>10 minutes). Short-term differences in percent change in left ventricular $+dP/dt_{\text{max}}$ (MP $-16 \pm 28\%$, BP $+9.1 \pm 24\%$; $P=0.03$) and left ventricular $-dP/dt_{\text{max}}$ (MP $-37 \pm 26\%$, BP $-18 \pm 20\%$; $P=0.05$) were present after rescue from brief VF, with BP animals exhibiting less countershock-induced dysfunction. After prolonged VF, the BP group had lower mean defibrillation thresholds (107 $\pm$ 57 versus 172 $\pm$ 88 J for MP, $P=0.04$) and significantly shorter resuscitation times (397 $\pm$ 73.7 versus 488 $\pm$ 74.3 seconds for MP, $P=0.03$).

Conclusions—External defibrillation is more efficacious with BP countershocks than with MP countershocks. The lower defibrillation thresholds and shorter resuscitation times associated with BP waveform defibrillation may improve survival after prolonged VF arrest. (Circulation. 2000;101:2968-2974.)

Key Words: ventricular fibrillation • defibrillation waveform • resuscitation

Much of our experience with biphasic (BP) waveform defibrillation stems from its widespread use in implantable cardioverter-defibrillators. In the setting of brief-duration ventricular fibrillation (VF), BP waveform pulses have demonstrated significantly lower defibrillation thresholds (DFTs) than standard monophasic (MP) waveform pulses.1–3 However, they have not been tested extensively in prehospital models of external defibrillation for which prolonged cardiac arrest and severe myocardial stunning are often overriding considerations.

Time-dependent increases in DFTs have been well described for MP waveforms4 and for BP waveforms after relatively brief durations of VF.5 Little is known, however, about the energy requirements for BP defibrillation after prolonged arrest. BP waveforms may rescue victims who might otherwise have failed defibrillation with conventional MP waveforms. In addition, the lower energy BP countershocks may produce less myocardial injury and mechanical dysfunction than equally effective MP countershocks.

The present study tested the hypothesis that BP waveforms are more efficacious than MP waveform countershocks in an animal model of out-of-hospital VF arrest. The primary aim was to test for differences in DFTs and overall resuscitation outcomes between the 2 waveforms. Secondary aims were to characterize the effects of countershocks on myocardial function and to clarify the importance of coronary perfusion pressures before defibrillation on resuscitation outcomes after prolonged cardiac arrest.

Methods
All experiments were conducted in accordance with the “Position of the American Heart Association on Research Animal Use” and with the approval of the Animal Care and Use Committee at The Johns Hopkins University.

Animal Preparation
Twenty-six consecutive mongrel dogs (25 to 28 kg) were studied. Anesthesia was induced with intravenous sodium thiopental (12.5 to 15.0 mg/kg) before endotracheal intubation and maintained with 1% to 3% isoflurane delivered with an anesthesia ventilator (Narkomed,
pressures set between 225 and 235 mm Hg. The device was inflated and deflated at 60 cycles per minute with peak vest pressures of 170 J.

Maximum device outputs were achieved in 5 steps. The MP sequence was 50, 100, 200, 300, and 360 J; the BP sequence was 50, 70, 120, 150, and 170 J.

**Definitions**

Defibrillation was defined as the maintenance of a rhythm other than VF for a minimum of 30 seconds. ROSC required a perfusing rhythm in the absence of VF for at least 1 minute. Study deaths were prospectively defined as the following: (1) >19 minutes of uninterrupted VF, (2) arrest in the alternate waveform, and (3) no return of spontaneous circulation (NROSC). Study survivors were categorized as capable of self-sustaining blood pressure (SSBP) or nonsustaining blood pressure (NSBP) on the basis of their ability or inability to support LVSBP>50 mm Hg during a 10-minute washout period. Surviving animals were euthanized at 50 minutes. Necropsy was limited to animals without ROSC.

**Data Analysis/Calculations**

An oscillograph (Gould) was used to record RA, aortic, and LV pressures. The maximal rates of the rise and fall of LV pressure were calculated as the instantaneous difference between end-diastolic aortic and RA pressures.

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**Figure 1.** Schematic of waveforms. A, Critically damped sinusoidal MP waveform. B, Truncated exponential BP waveform.

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**Figure 2.** Time line of protocol events during resuscitation from prolonged VF. Epi indicates epinephrine.
The time difference between successful defibrillation and onset of ROSC was designated as the post-arrhythmic mechanical arrest interval.

Statistics
Sample size was calculated to detect a 40-J difference in DFTs after prolonged VF; a SD of 50, a power of 80%, and \( P = 0.05 \) were assumed. Continuous and categorical variables were evaluated with the unpaired \( t \) test (2-tailed) and \( \chi^2 \) analysis, respectively. Repeated measures ANOVA was used to test for variance in LV contractile function and loading conditions; then paired \( t \) tests (2-tailed) were performed to isolate differences for our prospective end points. All results were reported as mean \( \pm \) SD. A value of \( P = 0.05 \) was considered significant.

Results
Baseline Characteristics
Baseline LV hemodynamics and loading conditions were not different between the 2 randomized groups. In addition, clinical resuscitation factors did not differ significantly between groups (Table 1).

Defibrillation Efficacy
Mean DFTs were consistently lower for the BP waveform than for the MP waveform (Figure 3). Increasing the duration of VF had the effect of raising DFTs for both waveforms. After 10 seconds of VF, there was a strong trend (\( P = 0.07 \)) toward lower mean DFTs for the BP waveform (56\( \pm \)26 versus 109\( \pm \)93 J for MP). After 10 minutes of VF, there was a significantly lower DFT for the BP waveform (107\( \pm \)57 versus 172\( \pm \)88 J for MP, \( P = 0.04 \)).

All defibrillation attempts were successful after brief VF; however, defibrillation failures occurred after prolonged VF. Notably, 3 of 13 MP animals failed countershocks to 360 J but were successfully rescued with a single BP countershock at 170 J. In contrast, only 1 of 13 BP animals failed countershocks to 170 J but proved refractory to MP rescue countershocks at 360 J. This animal represented the only death attributable to refractory VF in the present study and was excluded from calculations of mean DFT.

Countershock-Induced Myocardial Dysfunction
Greater hemodynamic impairment was consistently observed in the MP group, with larger initial drops in \( dP/dt_{\text{max}} \) and less

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**TABLE 1. Baseline Characteristics and Resuscitation Factors**

<table>
<thead>
<tr>
<th></th>
<th>MP ((n=13))</th>
<th>BP ((n=13))</th>
</tr>
</thead>
<tbody>
<tr>
<td>LSVBP, mm Hg</td>
<td>146( \pm )16</td>
<td>145( \pm )14</td>
</tr>
<tr>
<td>HR, bpm</td>
<td>144( \pm )22</td>
<td>142( \pm )26</td>
</tr>
<tr>
<td>RAP, mm Hg</td>
<td>4.8( \pm )1.7</td>
<td>4.8( \pm )2.4</td>
</tr>
<tr>
<td>LVEDP, mm Hg</td>
<td>8.6( \pm )5.7</td>
<td>9.6( \pm )6.1</td>
</tr>
<tr>
<td>(+dP/dt_{\text{max}} ), mm Hg/s</td>
<td>2100( \pm )480</td>
<td>2180( \pm )920</td>
</tr>
<tr>
<td>(-dP/dt_{\text{max}} ), mm Hg/s</td>
<td>2020( \pm )480</td>
<td>1980( \pm )520</td>
</tr>
<tr>
<td>Cumulative VF, s</td>
<td>851( \pm )290</td>
<td>905( \pm )389</td>
</tr>
<tr>
<td>Countershocks</td>
<td>12.2( \pm )3.3</td>
<td>12.5( \pm )5.4</td>
</tr>
<tr>
<td>Total epinephrine, mg</td>
<td>5.9( \pm )5.1</td>
<td>6.1( \pm )8.7</td>
</tr>
<tr>
<td>Peak CPP, mm Hg</td>
<td>32.9( \pm )25.5</td>
<td>45.4( \pm )22.3</td>
</tr>
</tbody>
</table>

Values are mean\( \pm \)SD. HR indicates heart rate; RAP, RA pressure; and LVEDP, LV end-diastolic pressure. Differences were not statistically significant.

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**Figure 3.** Comparison of MP and BP DFTs after brief and prolonged VF. A BP animal with refractory VF was excluded from calculations of mean DFTs after prolonged arrest.

**Figure 4.** Effect of countershock waveform on percent change versus baseline in LV \(+dP/dt_{\text{max}} \) (A) and LV \(-dP/dt_{\text{max}} \) (B). Post-sync indicates post-synchronous countershock. \(^*P = 0.05\).
complete recovery after countershocks than in the BP group (Figure 4). Percent change versus baseline suggested significant intergroup differences in +dP/dt\textsubscript{max} (MP \( -16\pm 28\% \), BP +9.1\pm 24\%; \( P=0.03 \)) and \(-dP/dt\textsubscript{max} \) (MP \( -37\pm 26\% \), BP \(-18\pm 20\% ; P=0.05 \)) after termination of brief VF, with more pronounced effects on \(-dP/dt\textsubscript{max} \) than on +dP/dt\textsubscript{max} for both waveforms.

LV loading conditions were serially assessed during each phase of the experimental protocol. No significant differences in RA pressure, heart rate, LVSBP, and LV end-diastolic pressure were appreciated at baseline, after synchronized countershocks, or after brief VF (repeated measures ANOVA, \( F=0.29; P=NS \)).

Resuscitation Outcomes After Prolonged Arrest
Although 19 of 26 animals were defibrillated within the first round of stacked countershocks, 6 remained in VF until a subsequent round of defibrillation. Rhythms after defibrillation were pulseless electrical activity in 19 animals, asystole in 4, and sinus rhythm in 2. Refractory VF was observed in 1 animal.

Significant differences in resuscitation times were noted between randomized groups (Figure 5). Mean ROSC occurred at 488\pm 74.3 and 397\pm 73.7 seconds for MP and BP animals, respectively (\( P=0.03 \)). This was associated with longer periods of contractile arrest after successful MP countershocks, with postarrhythmic mechanical arrest intervals of 429\pm 86 seconds for the MP group versus 271\pm 168 seconds for the BP group (\( P=0.02 \)). In 1 MP animal, supervening VF interrupted ROSC and delayed resuscitation substantially (ROSC time 1254 seconds). This MP outlier was excluded to provide the most conservative estimate of group differences.

Study death occurred in 7 of 13 MP animals (Table 2): 4 remained pulseless (NROSC), 1 required BP rescue but remained pulseless after defibrillation (crossover death), and 2 were resuscitated only after BP rescue (crossover death/ROSC). In contrast, only 3 of 13 BP animals were study deaths: 1 remained pulseless (NROSC), 1 exhibited refractory VF, and 1 remained pulseless because of a catheter-based hemorrhage confirmed on necropsy. A strong trend toward reduced mortality in the BP group was demonstrated by use of intention-to-treat analysis (\( \chi^2 2.6, P<0.11 \)). The difference reached statistical significance, however, when the fatal complication was excluded (\( \chi^2 3.7, P=0.05 \)).

Post-Resuscitation Myocardial Dysfunction
Although more BP animals were resuscitated, the percentage of animals exhibiting SSBP in the BP group (5 of 10) and the MP group (3 of 6) was not different. More quantitative statements could not be made regarding relative degrees of postresuscitation myocardial dysfunction, because steady-state measurements could not be established in animals that were often dependent on inotropic support and subject to variable postresuscitation loading conditions.

Subgroup analysis was performed on the 6 animals that initially failed defibrillation (Table 3). Despite longer mean arrest intervals (immediate defibrillation 615\pm 13 seconds, delayed defibrillation 1152\pm 270 seconds; \( P=0.002 \)), ROSC occurred in 5 of 6 animals. All 3 BP animals had SSBP, 2 MP crossover death animals had NSBP, and 1 MP crossover death animal had NROSC. A longer mean ROSC time in the delayed defibrillation group was not significant, having been offset by a marked decrease in the mean postarrhythmic mechanical arrest interval (immediate defibrillation 409\pm 67 seconds, delayed defibrillation 72\pm 93 seconds; \( P=0.0002 \)). Interestingly, the only 2 animals to be defibrillated directly into perfusing rhythms were BP animals in this delayed defibrillation subgroup.

TABLE 3. Clinical Resuscitation Factors and Outcomes

<table>
<thead>
<tr>
<th></th>
<th>Immediate Defibrillation ( (N=19) )</th>
<th>Delayed Defibrillation ( (N=6) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>VF time, s</td>
<td>615\pm 13</td>
<td>1152\pm 270*</td>
</tr>
<tr>
<td>Countershocks, n</td>
<td>11.5\pm 4.0</td>
<td>13.2\pm 3.1</td>
</tr>
<tr>
<td>Total epinephrine, mg</td>
<td>6.74\pm 7.9</td>
<td>4.33\pm 3.9</td>
</tr>
<tr>
<td>Peak CPP, mm Hg</td>
<td>39.3\pm 26</td>
<td>38.3\pm 19</td>
</tr>
<tr>
<td>ROSC animals, n</td>
<td>13</td>
<td>5†</td>
</tr>
<tr>
<td>Time to ROSC, s</td>
<td>424\pm 63</td>
<td>626\pm 372</td>
</tr>
<tr>
<td>Postarrhythmic mechanical arrest, s</td>
<td>409\pm 67</td>
<td>72.4\pm 93‡</td>
</tr>
<tr>
<td>SSBP animals, n</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td>NSBP animals, n</td>
<td>8</td>
<td>2†</td>
</tr>
<tr>
<td>Survivors, n</td>
<td>13</td>
<td>3</td>
</tr>
</tbody>
</table>

Values are number of animals or procedures \( (n) \) from group \( (N) \). *\( P<0.005 \). †Two animals achieving ROSC/NSBP were study crossover deaths. ‡\( P<0.0005 \).
Discussion
To the best of our knowledge, the present study is the first to describe the following: (1) lower biphasic DFTs after 10 minutes of unsupported VF, (2) milder degrees of countershock-induced contractile dysfunction with biphasic pulses, and (3) shorter postarrhythmic mechanical arrest intervals resulting in earlier resuscitation after biphasic defibrillation. These findings suggest that certain BP waveforms may have a significant impact on resuscitation from prolonged VF and that their continued development in external defibrillators will result in improved survival.

Defibrillation Efficacy of MP and BP Waveforms
Lower BP waveform DFTs have been reported versus MP waveforms for internal defibrillation of brief VF. Available evidence suggests that BP pulses are similarly efficacious in external defibrillators. Although our data demonstrated only a strong trend toward lower BP energy requirements after brief VF (P=0.07), our lowest energy countershock (50 J) likely exceeded the actual DFT recently reported in a similar experimental model (20.3±4.4 J). 8

DFTs and first-shock efficacy rates have been reported as superior for BP waveforms despite increasing VF durations. However, arrest intervals have seldom been >30 seconds. Walcott et al recently reported the external DFTs of MP and BP waves after 15 seconds of VF and then 3 minutes of unsupported VF. They reported a 2-fold increase in mean DFTs over time for the MP waveform but no increase in mean DFTs for the BP waveform. Our BP data, however, documented significant increases in DFTs after 10 seconds and then 10 minutes of unsupported VF (56±26 and 107±57 J, respectively; P=0.02). Nevertheless, the available data suggest that certain BP waveforms are less susceptible to time-dependent increases in DFTs than are MP waveforms.

External DFTs proved significantly lower for the BP group than the MP group despite >10 minutes of VF. No other studies have compared DFTs under such extreme conditions of global ischemia after prolonged arrest. Furthermore, 3 of 4 arrhythmic deaths that failed multiple defibrillation attempts with their assigned waveform were salvaged after crossover to the BP waveform. The remaining arrhythmic death failed to defibrillate with either waveform. Collectively, this suggests that lower energy BP countershocks may prove capable of rescuing sudden-death victims who might otherwise have failed defibrillation with conventional MP devices.

Countershock-Induced Contractile Dysfunction
Although there is growing evidence that countershocks can induce myocardial injury, the extent to which they contribute to contractile dysfunction independently of VF and global ischemia remains unclear. Several lines of evidence support the hypothesis that countershocks at clinically relevant current dosages are harmful to myocardium. Transient ECG changes consistent with myocardial damage have been reported after transthoracic countershocks and appear to be corroborated by the release of myocardium-specific enzymes and ultrastructural damage to cardiac myocytes. These indirect markers of countershock-induced injury, however, have proven difficult to correlate with surprisingly variable effects on myocardial function.

Studies using MP waveforms have demonstrated either no effect or relatively minor effects on contractile function after brief cycles of fibrillation and defibrillation. Contractile abnormalities were originally described by Kerber et al. who used repeated high-energy epicardial countershocks and implanta-ble subepicardial sonomicrometers in an open-chest dog model. Subsequent work in a dog model of epicardial defibrillation and in human subjects undergoing transthoracic defibrillation revealed inconsistent effects on systolic function but significant impairments in diastolic function. Waveform characteristics, current dosage, and lead configuration varied significantly between studies. Furthermore, the impact of pericardotomy on myocardial function and the relative sensitivities of various noninvasive methods for detecting subtle functional impairments were difficult to assess. Differences in experimental design may be responsible for perceived inconsistencies in the study literature.

Previous work comparing MP with BP waveforms has largely ignored postcountershock sequelae. However, significantly less ST-segment elevation has been reported after transthoracic defibrillation with BP waveforms than with MP waveforms of equal efficacy. Similarly, less harmful effects on mitochondrial function and oxidative metabolism have been documented after epicardial defibrillation with BP countershocks than after energy-matched MP countershocks. In spite of these findings, differential effects on actual myocardial function by particular electrical waveforms have not previously been described.

Countershocks delivered in sinus rhythm had inconsequential effects on myocardial function; however, significant effects were apparent after countershock termination of brief VF. In the present study, BP defibrillation resulted in less severe functional consequences than did MP defibrillation. Diastolic function was more impaired than systolic function for both waveform types, with more prominent filling impairments after MP countershocks persisting for up to 15 minutes. A self-limited decrease in systolic function after MP defibrillation and an unexpected increase in systolic function after BP defibrillation were also noted. Because these transient effects on systolic performance were seldom present for >1 to 2 minutes, we speculated that differential effects on adrenergic tone might be contributory. Although it is not entirely clear whether these effects were the result of an interaction between arrhythmia and waveform or carryover effects from repeated countershocks, the potential impact of defibrillatory waveforms could not be dismissed. The present study provides compelling evidence that transthoracic countershocks may exert unintended effects upon contractile function and that the choice of defibrillation waveform may have important clinical consequences on myocardial function.

Effect of Defibrillation Waveform on Resuscitation Outcomes After Prolonged Arrest
Perhaps our most intriguing study finding is that BP countershocks significantly reduced overall resuscitation times. After prolonged VF, a difference of >90 seconds in mean resuscitation time was evident between randomized groups.
Quicker resuscitation could only in small part be attributed to more efficient defibrillation and trivially shorter delays in charging lower energy BP capacitors. Improvements were largely due to shorter periods of contractile arrest after successful BP countershocks. This observation suggests a clear advantage of BP over MP countershocks in the treatment of VF arrest, for which differences of seconds to minutes often prove critical to recovery.

Jones and Jones\(^2\) described significantly shorter durations of contractile arrest after electrical field stimulation with BP pulses in a cell culture model of defibrillation. Exposure to equivalent energy MP pulses resulted in longer contractile arrest intervals on photocell mechanogram tracings and prolongation of myocyte depolarization.\(^2\) These investigators suggested that intrinsic properties of the MP waveform predisposed to membrane electroporation and that subsequent derangements of ion homeostasis were responsible for diminished cellular excitability and contractile arrest. These studies loosely corroborate our in vivo work with intact fibrillating hearts and support our contention that lower energy BP countershocks exert less harmful effects on excitation-contraction coupling. Furthermore, our results suggest that direct effects of electrical waveforms are not simply masked by the myocardial depressant effects of prolonged fibrillation and ischemia but appear fully capable of potentiating post-resuscitation myocardial dysfunction.

More efficient defibrillation and prompter hemodynamic recovery translated predictably into fewer BP study deaths after prolonged VF. The relatively few BP deaths (3 of 13 animals) included the only animal that proved refractory to defibrillation with either waveform, as well as the only fatal technical complication encountered in the study. No such extenuating circumstances were noted among the MP deaths (7 of 13 animals). Consideration of longer-term end points and neurological death would likely have favored additional survival benefits for the BP group.

**Postresuscitation Myocardial Stunning After Prolonged Arrest**

Postresuscitation myocardial stunning is generally thought to be mediated by global no-flow myocardial ischemia. However, experimental work using isolated-perfused hearts induced into VF suggests that the electrochemical activity of the arrhythmia itself may, in the absence of ischemia, contribute to excitation-contraction uncoupling via intracellular calcium overload.\(^2\) Electrical countershocks may potentiate this effect and have furthermore been linked to the dose-dependent release of free radicals\(^2\) and to waveform-specific effects on mitochondrial function and oxidative metabolism.\(^\) Therefore, it seems reasonable to speculate that high-energy MP countershocks might contribute to more profound myocardial stunning through one of the above mechanisms.

A spectrum of progressive myocardial stunning was assumed in our experimental model. Resuscitated animals capable of SSBP were considered less severely stunned than animals with NSBP. However, the present study lacked sufficient power to detect a significant difference with the use of such crude qualitative assessments of stunning severity. Furthermore, the greater number of study deaths in the MP group likely resulted in significant statistical censoring.

**Predefibrillation CPR After Prolonged Arrest**

Prompt restoration of CPP has long been considered critical to the success of resuscitation from VF.\(^2\) Whether immediate defibrillation is always the best strategy remains controversial. Work by Niemann et al\(^2\) suggests that pretreatment with CPR and epinephrine before defibrillation will improve resuscitation after prolonged arrest. It remains unclear, however, whether the study effect was due to an order dependence of treatment or to differences in epinephrine utilization.

Delays to defibrillation were encountered in 6 animals that failed immediate defibrillation. Subgroup analysis suggested favorable outcomes for this cohort despite significantly longer arrest intervals. Our delayed defibrillation subgroup exhibited a surprising trend toward overall improved resuscitation rates and less severe myocardial dysfunction versus the immediate defibrillation subgroup despite comparable CPP during CPR. These data suggest that CPR prior to BP defibrillation may prove to be a superior resuscitation strategy for prolonged VF arrest and that countershock waveforms are indeed capable of modifying the course of post-resuscitation myocardial dysfunction.

**Study Limitations**

We prospectively chose to standardize peak vest pressures rather than clamp measured CPP during chest compressions. As a result, there was a nonsignificant difference in CPP after randomization. Lack of rigorous control of ventricular loading conditions presented another limitation. Because much of the data resulted from paired comparisons both before and after electrical countershocks, it seems reasonable to assume that loading conditions did not change appreciably except for very transient effects immediately after shock administration. Finally, the present study was neither capable of elucidating the underlying mechanisms of improved BP defibrillation efficacy nor of assessing the relative contributions of ischemia, VF, electrical waveform, or cumulative current dosage on post-arrest myocardial function.

**Clinical Implications**

BP waveforms may prove more effective than standard MP waveform countershocks in rescuing patients with out-of-hospital VF arrest. They may prove to have an impact on immediate arrest survival by (1) rescuing patients who might otherwise have failed defibrillation with standard MP pulses, (2) minimizing post-countershock myocardial dysfunction, and (3) reducing overall resuscitation times. Perhaps the most significant improvements in overall arrest survival will be attributable to the evolution of smaller, less expensive, and more widely available automated external BP defibrillators.

**References**


Resuscitation After Prolonged Ventricular Fibrillation With Use of Monophasic and Biphasic Waveform Pulses for External Defibrillation


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