Resuscitation (2006) **71**, 137—145

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RESUSCITATION

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CLINICAL PAPER

Effects of compression depth and pre-shock pauses predict defibrillation failure during cardiac arrest☆

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Received 27 March 2006; received in revised form 8 April 2006; accepted 10 April 2006

KEYWORDS
Heart arrest;
Cardiopulmonary resuscitation;
Defibrillation;
Chest compression

Summary
Background: Cardiopulmonary resuscitation (CPR) and electrical defibrillation are the primary treatment options for ventricular fibrillation (VF). While recent studies have shown that providing CPR prior to defibrillation may improve outcomes, the effects of CPR quality remain unclear. Specifically, the clinical effects of compression depth and pauses in chest compression prior to defibrillation (pre-shock pauses) are unknown.
Methods: A prospective, multi-center, observational study of adult in-hospital and out-of-hospital cardiac resuscitations was conducted between March 2002 and December 2005. An investigational monitor/defibrillator equipped to measure compression characteristics during CPR was used.
Results: Data were analyzed from 60 consecutive resuscitations in which a first shock was administered for VF. The primary outcome was first shock success defined as removal of VF for at least 5 s following defibrillation. A logistic regression analysis

☆ A Spanish translated version of the summary of this article appears as Appendix in the online version at 10.1016/j.resuscitation.2006.04.008.

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0300-9572/$ — see front matter
doi:10.1016/j.resuscitation.2006.04.008

demonstrated that successful defibrillation was associated with shorter pre-shock pauses (adjusted odds ratio 1.86 for every 5 s decrease; 95% confidence interval 1.10—3.15) and higher mean compression depth during the 30 s of CPR preceding the pre-shock pause (adjusted odds ratio 1.99 for every 5 mm increase; 95% confidence interval 1.08—3.66).

Conclusions: The quality of CPR prior to defibrillation directly affects clinical outcomes. Specifically, longer pre-shock pauses and shallow chest compressions are associated with defibrillation failure. Strategies to correct these deficiencies should be developed and consideration should be made to replacing current-generation automated external defibrillators that require long pre-shock pauses for rhythm analysis.

Introduction

Although rapid defibrillation remains the cornerstone of treatment for ventricular fibrillation (VF), a number of studies have supported the notion that cardiopulmonary resuscitation (CPR), especially in the time preceding defibrillation, may also play a key therapeutic role.[1,2] However, the effect of CPR quality on clinical outcomes remains poorly understood.

Recent work, relying on new technology capable of sensing compression rate and depth, has shown that CPR quality is inconsistent in actual clinical practice, with frequent pauses and shallow compression depth.[3,4] Using this technology, the effects of these CPR variables on clinical outcomes can now be evaluated. Of particular interest are the duration of time from the end of chest compressions until the defibrillation shock is given (i.e., the pre-shock pause) and the measured depth of chest compressions preceding defibrillation. Both have been shown to have significant impact on outcomes in animal studies,[5—8] yet neither has been rigorously investigated in the clinical setting.

Understanding the effects of these variables has significant public health and policy implications. Pre-shock pauses are particularly important as automated external defibrillators (AEDs), that generally require long pre-shock pauses for rhythm analysis,[8—10] have gained widespread acceptance and have been implemented in a variety of settings.[11—14] Additionally, understanding the relative importance of these variables of CPR quality on outcomes will have implications for resuscitation guidelines and training. We therefore examined whether pre-shock pause and compression depth, two likely determinants of blood flow preceding defibrillation, affect the ability of a shock to terminate VF.

Methods

Study design

An international, multi-center, observational study of in-hospital and out-of-hospital cardiac arrests occurring between March 2002 and December 2005 was conducted. Approval was granted by the Institutional Review Board of the University of Chicago Hospitals and the regional ethics committee in Akershus, with mechanisms to satisfy waiver of consent provisions at both sites. Additionally, an oral consent process was used for rescuers in Chicago.

Details of the study design and methods have been described previously.[3,4] An investigational monitor/defibrillator (FDA IDE # G020121) was used during resuscitation from cardiac arrest. This device is a modification of a standard biphasic monitor/defibrillator with additional sensing capabilities to detect chest compression rate and depth, ventilation rate and volume, and presence of a pulse. Chest compression measurements were obtained using a chest compression pad outfitted with both an accelerometer and force detector while ventilations and pulse were detected by changes in chest wall impedance. Measurements of these variables have been validated elsewhere.[15—18]

Study setting and population

Consecutive adult in-patients at the University of Chicago Hospitals between December 2002 and December 2005 and out-of-hospital patients in Akershus, Norway, between March 2002 and August 2003 were enrolled in the study if they suffered a cardiac arrest, as defined by the loss of a pulse, requiring the delivery of chest compressions. In-hospital patients were excluded if they were arrested in the emergency department or operating

room environments. Additionally a small number of patients did not receive treatment with the study defibrillator and were therefore excluded from analysis. These were rare and sporadic occurrences, related to local team response and not to specific patient characteristics. Only those patients whose first shock was received for VF were considered in this analysis.

CPR was provided by resident physicians certified in Advanced Cardiovascular Life Support (ACLS) with assistance from respiratory technicians, nurses, and medical students in Chicago and by paramedics from the emergency medical system in Akershus. The CPR-sensing monitor/defibrillator was used in manual mode in both locations and all rescuers received training in its use. In Akershus, a modified protocol required paramedics to provide 3 min of CPR prior to defibrillation. Data from the investigational devices were collected on memory cards and subsequently downloaded by study personnel.

Measurements

All arrest transcripts with shocks were analyzed and annotated manually for rhythm prior to and immediately following defibrillation attempts. The time interval of the last 30 s of CPR preceding the pre-shock pause was also annotated. The duration for CPR quality assessment was chosen to remain consistent with our earlier work evaluating CPR quality in 30 s segments[3,4,19] and in order to evaluate the immediate effect of CPR quality on shock outcomes. Further quantitative analysis was then performed to determine the pre-shock pause duration and variables of CPR quality. All rhythms and pause times were confirmed manually independently by two physician investigators (DPE, BSA).

Pre-shock pauses were measured from the end of the last chest compression to the start of defibrillation (Figure 1). Shocks were deemed successful if VF was terminated for at least 5 s, consistent with the prevailing definition in the literature.[10,20,21] Return of spontaneous circulation (ROSC) was defined by the presence of an organized rhythm with a palpable pulse and measurable blood pressure for at least 20 min, as documented in the medical record.

Three measures of CPR quality were considered in this analysis. Compression depth was the calculated mean depth of all compressions administered during the 30 s segment of CPR preceding the pre-shock pause, measured in millimeters. No flow time (NFT) was the number of seconds during that same time period in which no compressions were

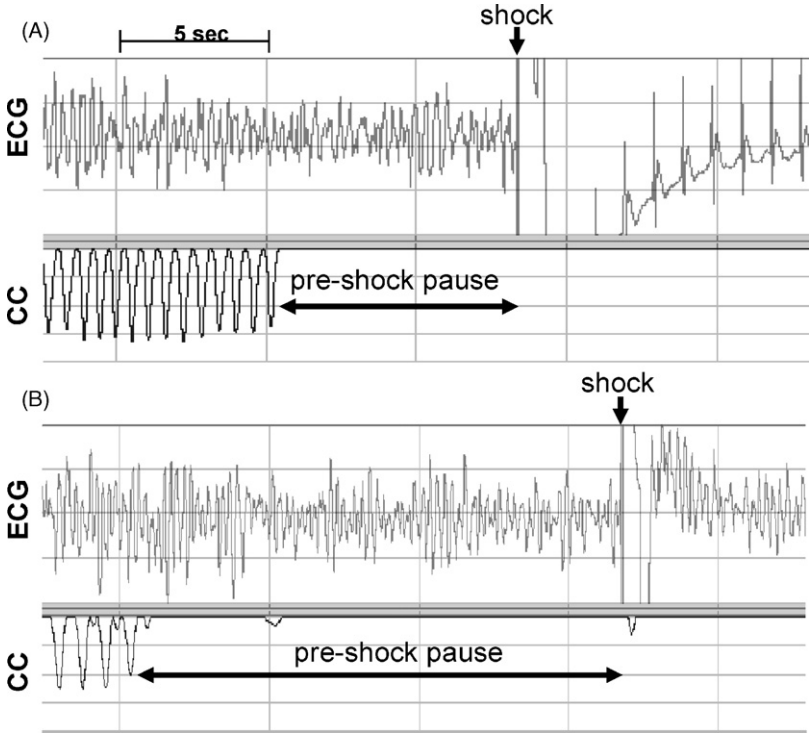

Figure 1 Examples of defibrillation attempts. (A) Successful shock preceded by an 8-s pre-shock pause and deep chest compressions. (B) Unsuccessful shock preceded by a 16 s pre-shock pause and shallower chest compressions. ECG, electrocardiogram; CC, chest compressions.

being administered. Compression rate was calculated as the compression count*60/(30-NFT) and represented the rate of compressions/min during the fraction of the 30 s segment in which compressions were being provided. Ventilation rate was determined by multiplying the number of ventilations provided during the 30 s by two.

Patient demographic and outcome data were extracted from a subsequent review of medical records. Time to shock was measured from the time the defibrillator was turned on until the first shock was administered. This is only a proxy for arrest time but was chosen for consistency due to lack of time synchronization between defibrillators and other clocks used for reporting arrest intervals. This dilemma has been reported by other investigators.[22]

Data analysis

All calculations were performed using a statistical software application (Stata Version 9.0, College Station, TX). Skewed data, such as times and total shocks, were reported as medians with interquartile ranges and compared using a Wilcoxon rank sum test. Means were compared with a two-sided student's *t*-test and binary variables were compared via chi-squared analysis. A logistic regression analysis was undertaken to adjust for possible confounding variables. Additionally, trends in proportions were analyzed with an ordinal trend test. Significance was set at $p < 0.05$ for all values. As this manuscript represents a post hoc study of a collected data set, there were no interim analyses and all patients who met inclusion criteria for this analysis were included.

Table 1 Baseline patient characteristics ($n = 60$)

Age (year), mean (SD)	65 (16)
Male sex, *n* (%)	38 (63)
Out-of-hospital arrest location, *n* (%)	33 (55)
Time to first shock (min), median (IQR)	3.7 (2.2—5.7)
Total shocks per patient, median (IQR)	5 (2—8)
First shock success, *n* (%)	44 (73)
Return of spontaneous circulation, *n* (%)	28 (53)
Survival to hospital discharge, *n* (%)	4 (7)

S.D., standard deviation; IQR, interquartile range.

Results

A total of 60 patients received a first electrical shock for VF during the study period. Table 1 summarizes the baseline characteristics of the entire cohort. Characteristics of successful and unsuccessful shocks are compared in Tables 2 and 3. There were no statistically significant differences

Table 2 Patient characteristics by first shock success

Characteristic	Success ($n = 44$)	Failure ($n = 16$)	*p*-Value
Age (year), mean (SD)	67 (16)	61 (16)	0.23
Male sex, *n* (%)	30 (68)	8 (50)	0.20
Out-of-hospital arrest location, *n* (%)	27 (61)	6 (38)	0.10
Time to first shock (min), median (IQR)	3.8 (2.7—5.3)	3.3 (1.7—11.2)	0.96
Outcomes			
Return of spontaneous circulation, *n* (%)	24 (55)	4 (25)	0.04
Survival to discharge, *n* (%)	4 (9)	0 (0)	0.21

S.D., standard deviation; IQR, interquartile range.

Table 3 CPR quality prior to the first shock by shock outcome

	Success	Failure	Overall	*p*-Value
Pre-shock pause (s), median (IQR) [$n = 53$]	11.9 (6.8—19.4)	22.7 (15.6—37.7)	15.3 (8.3—23.5)	0.002
[a]No flow time (s), median (IQR) [$n = 49$]	4.8 (0.6—13.8)	0.0 (0.0—9.1)	4.5 (0.0—13.3)	0.15
[a]Compression rate (min^{-1}), mean (S.D.) [$n = 49$]	114 (17)	120 (23)	116 (19)	0.31
[a]Compression depth (mm), mean (S.D.) [$n = 47$]	39 (11)	29 (10)	36 (11)	0.004
[a]Ventilation rate (min^{-1}), mean (S.D.) [$n = 39$]	16 (9)	16 (11)	16 (10)	0.99

[a] During the 30 s of CPR preceding the pre-shock pause. IQR, interquartile range.

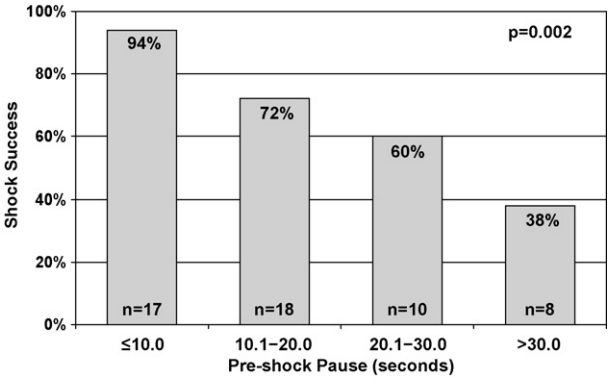

Figure 2 Association between pre-shock pause and shock success. Cases are grouped by pre-shock pause in 10 s intervals. Note that longer pre-shock pauses are significantly associated with a smaller probability of shock success.

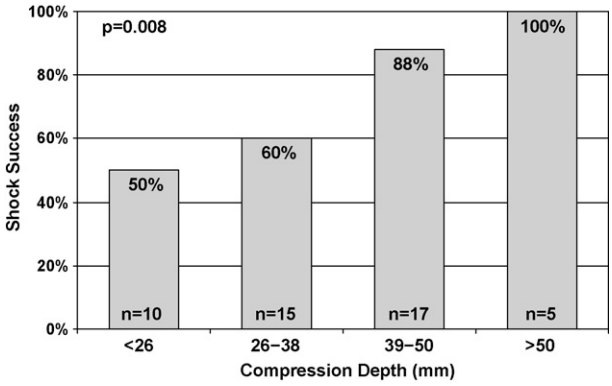

Figure 3 Association between chest compression depth and shock success. Cases are grouped by 30 s average compression depth in approximately 11 mm (0.5 in.) intervals. Chest compression depth of 38—50 mm (1.5—2 in.) represents current CPR guidelines recommendations. Deeper chest compressions are significantly associated with increased probability of shock success.

in age, sex, arrest location or time to shock by first shock success. However, successful shocks were associated with a shorter median pre-shock pause duration (11.9 s versus 22.7 s; $p = 0.002$) and higher mean chest compression depth in the 30 s of CPR preceding the pre-shock pause (39 ± 11 mm versus 29 ± 10 mm, $p = 0.004$). The other features of CPR quality, including ventilation rate, chest compression rate and no flow time, were similar between the two groups.

When pre-shock pause time and compression depth were divided into categories, a statistically significant dose-response effect for each was seen on first shock success. Figure 2 shows the relationship between increasing pre-shock pause and probability of shock success. In this model, 10-s increments were chosen for simplicity and comparability to an established animal model.[6] A similar relationship was seen between compression depth in the 30 s preceding the pre-shock pause and the probability of shock success (Figure 3). For compression depth evaluation, half-inch increments (converted into millimeters) were assessed to allow those patients who received the ACLS recommended compression depth of 1.5—2 in. (38—50 mm) to fall into one category.[23]

The effects of pre-shock pause and compression depth on shock success were seen independently in both the in-hospital and the out-of-hospital setting (data not shown). However, in order to account for this possible confounder (as well as age, sex, and time to shock), a logistic regression model was used. The results are shown in Table 4. After adjusting for these factors, a 5 s decrease in pre-shock pause was associated with an 86% increase in the odds of shock success ($p = 0.02$) while a 5 mm increase in compression depth was associated with a 99% increase in the odds of shock success ($p = 0.03$).

While there was no statistically significant effect of either pre-shock pause or compression depth on ROSC or survival to hospital discharge, patients with first-shock success were more likely to achieve ROSC at some point during the resuscitation (55% versus 25%; $p = 0.04$) and trended toward a higher survival to hospital discharge rate (9% versus 0%, $p = 0.21$), as shown in Table 2.

Of the 60 patients, CPR quality could not be collected in 11 patients who received a shock without first receiving at least 30 s of monitored CPR. Seven

Table 4 Logistic regression of factors affecting first shock success ($n = 47$)

Factor	OR	95%CI	*p*-Value
Pre-shock pause (5 s decrease)	1.86	1.10—3.15	0.021
Compression depth (5 mm increase)	1.99	1.08—3.66	0.028
Out-of-hospital location	7.47	0.90—62.41	0.063
Male sex	1.10	0.17—7.12	0.919
Age (1 year increase)	1.01	0.96—1.07	0.616
Time to shock (1 min increase)	0.88	0.76—1.02	0.095

of those 11 patients received no compressions prior to defibrillation and therefore a pre-shock pause could not be calculated. Additionally, two patients were excluded from compression depth analysis due to technical difficulties with the compression pad. Of the seven patients who did not have measurable pre-shock pauses, two had a perfusing rhythm within 20 s of the shock while the other five were shocked soon after pad placement. In the latter cases a pre-shock pause could be estimated to be at least as long as the pads were in place prior to defibrillation. We performed a revised analysis including these estimated values, and the results did not change significantly (data not shown).

Discussion

Using technology that measures multiple variables of CPR quality accurately, our international study group has gathered data that demonstrate a significant association between termination of VF and two variables that have received little formal evaluation during human cardiac arrest, pre-shock pause duration and compression depth. Specifically, we have shown that each 5 mm increase in compression depth and each 5 s decrease in pre-shock pause portend an approximate two-fold increase in the likelihood of shock success after adjusting for arrest location, age, sex and time to shock. Given that both pre-shock pause and compression depth affect blood flow during cardiac arrest, these new data provide additional insight into the importance of high-quality CPR during attempted resuscitation.

Our findings on the inverse relationship between the duration of pre-shock pause and shock success have not been reported previously in the clinical setting, although increasing pre-shock pause intervals have been correlated with decreased survival in several animal studies.[6–8] Additionally, Eftestøl et al. demonstrated that VF waveforms in human subjects deteriorated during pre-shock pauses, correlating with a predicted decrease in the likelihood of achieving ROSC.[24] Pre-shock pauses are especially relevant to the use of AEDs. Several studies have shown improved outcomes with the use of these devices in VF.[11–13] However, the required pre-shock pause needed for an AED to perform rhythm analysis is quite variable among different models.[8–10] For example, one study of seven popular AEDs demonstrated pre-shock pauses ranging from 5.2 to 28.4 s, with only one of the devices achieving an interval of less than 10 s.[9] In light of our findings, the duration of pre-shock pause mandated by AEDs on the market may have important consequences.

While compression rate has previously been shown to correlate with outcomes in humans,[19] compression depth has not. ACLS guidelines currently specify a target compression depth of 1.5–2 in. or 4–5 cm.[23] However, scant experimental data support this recommendation. In 1960, Kouwenhoven et al. described in detail what are now recognized as modern-day chest compressions and recommended a compression depth of 3–4 cm.[25] Subsequently, Babbs et al. demonstrated in a canine model that cardiac output increases linearly with chest compression depth between 2.5 and 6 cm.[5] To our knowledge, the current study represents the first objective evidence relating compression depth to clinical outcomes from defibrillation. The 100% shock success rate seen in the five patients who received a mean chest compression depth greater than 50 mm in the 30 s preceding defibrillation (Figure 3) raises interesting questions about the upper limit of appropriate depth. While the segments evaluated in the current study reflected only short periods of CPR, these five patients had comparable rates of ROSC and survival to hospital discharge compared to the group as a whole (data not shown). However, it is too few patients to draw any conclusions and future work should seek to improve the definition of the ideal chest compression depth in humans.

It is interesting to note that shallow chest compressions may be physiologically indistinguishable from a pause in CPR if the compressions are too shallow to generate a functional cardiac output. Thus, compressions preceding the pre-shock pause that are below a certain threshold (i.e., the 2.5 cm threshold noted by Babbs et al.[5]) are likely to have the same clinical effects as a longer pre-shock pause.

The first shock success rate of 73% in this study is lower than that reported in other studies of biphasic defibrillation.[21,26–28] However, those studies included only out-of-hospital cardiac arrests and our current investigation includes both in-hospital and out-of-hospital arrests. Our logistic regression analysis suggests that out-of-hospital location may be an independent predictor of shock success. This may be due to underlying differences in patient population or more specifically to the different resuscitation protocols between the two groups in our work, as the out-of-hospital group received 3 min of CPR prior to defibrillation. Since this protocol was unique to the out-of-hospital subgroup, it is not possible to separate the effects of the CPR prior to defibrillation from other differences between the two groups but other work has suggested a threshold value for duration of chest compressions to improve chances for successful defibrillation.[29]

A key feature of our study was the use of new technology for objective recording of multiple CPR quality variables. This is important since few of the individual variables that comprise CPR have yet been subjected to rigorous evaluation. As CPR represents a complicated set of actions, particularly for lay rescuers, many important questions remain about what specific components to prioritize. Accurate data on the relationship between CPR quality variables and outcomes will be required to address these issues. Now that CPR-sensing technology is available, it will allow the evaluation of CPR quality as an independent and potentially confounding variable in future clinical studies of cardiac arrest. As this technology becomes more widespread and available on many devices, we believe that important insights are likely to be gained from actual human cardiac arrest data. These will include methods to optimize the practice of CPR itself as well as to evaluate drugs and devices that are unlikely to work if CPR is deficient.

There are several important limitations to our study. The primary limitation is that we do not have sufficient numbers of patients to demonstrate whether pre-shock pause and compression depth correlate with survival. While shock success has been a commonly reported outcome,[10,20,21] the termination of VF does not necessarily translate into survival to hospital discharge or neurological recovery. However, our data do show a significant correlation between first-shock success and ROSC, as well as a trend towards survival to discharge. And, although shock success is less definitive than survival, it remains a crucial outcome measure since the absence of shock success invariably portends death.

An additional limitation is that our study was not a randomized, controlled trial of pre-shock pauses or compression depth. However, such a trial would not be ethically feasible. Although it is not possible to prove that there were no systematic biases in compression depth and pre-shock pause (such as delivery of suboptimal CPR in a patient whose prognosis is deemed poor), we believe such bias to be unlikely since all the patients in this study had VF, a rhythm which often portends a better chance of resuscitation than other rhythms such as asystole. Additionally, our evaluation of only first shocks further reduces the risk of this bias, as only the first brief period of CPR was analyzed, before the resuscitation prognosis may have become evident to the resuscitation team.

Future studies of pre-shock pause and compression depth need to be performed with larger sample sizes to better define the relationship between these variables and survival. Additionally, methods to minimize pre-shock pause and optimize compression depth should be developed and investigated. Potential technological solutions that are being pursued already involve the use of mechanical compression devices that can provide consistent full-force compressions throughout shock delivery without fear of electrical injury to CPR providers[30–32] as well as software that can filter out compression artifact for analysis of underlying rhythm without a requirement for pauses in chest compressions.[33] Other possibilities include audio feedback during CPR[34] and stand-alone chest compression monitoring devices.[35]

Conclusions

Using objective measurements of CPR quality during actual cardiac arrest, we have found that longer pre-shock pauses and shallower chest compressions are correlated significantly with decreased shock success. The opportunity to improve the quality of CPR in clinical practice is now practically available and may significantly improve resuscitation success. Approaches to minimize (or eliminate) pre-shock pauses and optimize compression depth should be made and consideration should be given to the use of newer-generation AEDs with shorter (<10 s) analysis times.

Conflict of interest

The sponsor had no role in data collection, interpretation of results or drafting of the manuscript. One author at the study sponsor (Mr. Myklebust) was involved in study conception and design. Drs. Abella and Becker have received honoraria and research support from Philips Medical Systems (Andover, MA) and Laerdal Medical Corporation (Stavanger, Norway) while Drs. Steen, Wik and Kramer-Johansen have received research support from Laerdal Medical Corporation (Stavanger, Norway).

Acknowledgements

We thank Jason Alvarado, Nicholas O'Hearn, Kuang-Ning Huang, Salem Kim, Nate Teisman and David Snyder, PhD for assistance during data collection and manuscript preparation; Ronald Thisted, MD for advice and statistical expertise; and Lynne Harnish for administrative assistance. We also thank the paramedics and instructors in the Akershus Ambulance Service and the members of the cardiac arrest

resuscitation team at the University of Chicago. This work was supported by a grant from the Laerdal Medical Corporation (Stavanger, Norway).

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