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Chest Compression Rates During Cardiopulmonary Resuscitation Are Suboptimal

A Prospective Study During In-Hospital Cardiac Arrest

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Background—Recent data highlight a vital link between well-performed cardiopulmonary resuscitation (CPR) and survival after cardiac arrest; however, the quality of CPR as actually performed by trained healthcare providers is largely unknown. We sought to measure in-hospital chest compression rates and to determine compliance with published international guidelines.

Methods and Results—We developed and validated a handheld recording device to measure chest compression rate as a surrogate for CPR quality. A prospective observational study of adult cardiac arrests was performed at 3 hospitals from April 2002 to October 2003. Resuscitations were witnessed by trained observers using a customized personal digital assistant programmed to store the exact time of each chest compression, allowing offline calculation of compression rates at serial time points. In 97 arrests, data from 813 minutes during which chest compressions were delivered were analyzed in 30-second time segments. In 36.9% of the total number of segments, compression rates were <80 compressions per minute (cpm), and 21.7% had rates <70 cpm. Higher chest compression rates were significantly correlated with initial return of spontaneous circulation (mean chest compression rates for initial survivors and nonsurvivors, 90 ± 17 and 79 ± 18 cpm, respectively; $P=0.0033$).

Conclusions—In-hospital chest compression rates were below published resuscitation recommendations, and suboptimal compression rates in our study correlated with poor return of spontaneous circulation. CPR quality is likely a critical determinant of survival after cardiac arrest, suggesting the need for routine measurement, monitoring, and feedback systems during actual resuscitation. (*Circulation*. 2005;111:428-434.)

Key Words: cardiopulmonary resuscitation ■ death, sudden ■ heart arrest

Survival rates from cardiac arrest remain poor despite the development of both cardiopulmonary resuscitation (CPR) and electrical defibrillation as treatment modalities over the past 50 years.^{1,2} Approximately 1% to 6% of patients suffering out-of-hospital cardiac arrest ultimately survive the event, and although survival rates are somewhat better for in-hospital arrest patients, a recent comprehensive report observed that only 17% of these patients were discharged alive.³⁻⁵

In an effort to improve cardiac arrest outcomes, recent investigations have focused on the timing and quality of CPR. For example, a study of in-hospital resuscitation showed that even short delays in the initiation of CPR correlated with poor outcomes.⁶ Another out-of-hospital investigation demonstrated that pauses in chest compressions reduce the chance of

subsequent defibrillation success.⁷ Although CPR is traditionally composed of chest compressions interspersed with ventilations, recent work suggests that increasing the ratio of chest compressions to ventilations may improve the probability of the return of spontaneous circulation (ROSC), ie, the return of a viable rhythm and pulse.^{8,9} One study found that chest compression without ventilation yielded improved survival over chest compression with intermittent ventilation.⁹ The notion of chest compression-only CPR (without ventilations) has begun to accumulate support from both clinical and animal investigations.¹⁰ An important challenge to the current resuscitation paradigm was issued by Wik et al,¹¹ who recently showed that out-of-hospital arrest patients who received 3 minutes of CPR before defibrillation had higher survival rates than those who were immediately defibrillated.

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This study, along with a prior investigation with similar results from Seattle,¹² suggests the paramount importance of chest compression in the framework of CPR and resuscitation. Most recently, Aufderheide et al¹³ have demonstrated that out-of-hospital arrest patients are hyperventilated during arrest, and parallel animal experiments confirmed that this hyperventilation can decrease coronary perfusion pressures during resuscitation efforts and worsen survival.

These investigations collectively support the notion that high-quality CPR is vital for survival after cardiac arrest. Chest compressions are central to the performance of CPR, yet very few data exist on how well rescuers perform this important therapy. Resuscitation guidelines published in the United States and Europe recommend that chest compressions be performed at a rate of 100 compressions per minute (cpm).¹⁴ We undertook a multicenter investigation to determine whether CPR-certified rescuers actually perform chest compressions at the guideline-specified rate during in-hospital arrest. We designed a custom-programmed data collection tool to allow observation and recording of real-time chest compression rates for the duration of resuscitation efforts. In this fashion, we studied a readily quantifiable metric (chest compression rate) as a surrogate measure for CPR quality.

Methods

Study Design

Our study protocol was approved by the Institutional Review Boards (IRBs) of the 3 study hospitals. Waiver of consent was used for cardiac arrest patients after appropriate measures were taken to satisfy the use of waiver provisions, including community and staff notification before initiation of our study. This included several advertised meetings in the hospital and clinics at which patients and physicians were presented with the study design and given an opportunity to comment. Data collection was structured to carefully comply with all relevant Health Insurance Portability and Accountability Act of 1996 (HIPAA) regulations.

Cardiac arrests were observed by investigators at University of Chicago Hospitals (UCH), a 600-bed academic medical center; Lutheran General Hospital (LGH), a 600-bed referral hospital; and MacNeal Hospital (MNH), a 400-bed community hospital. Investigator observation teams were organized to provide coverage in their respective hospitals during equally proportioned day, evening, and overnight shift periods. In this fashion, cardiac arrests were recorded at each site from April 2002 to October 2002 (UCH) and from April 2003 to October 2003 (LGH and MNH). Trained observers were registered nurses (UCH, MNH) or respiratory therapists (LGH). All observers were previously certified in basic life support and had prior experience in cardiac resuscitation. Trained observers were linked to hospital paging systems to be alerted to each cardiac arrest, and they recorded chest compression data continuously from their arrival at the arrest scene throughout the duration of the arrest efforts. At all 3 hospitals, staff members performing CPR included nurses, resident physicians, and medical students; at a minimum, all were certified in basic life support.

Cases were excluded if the patients experiencing arrest were <18 years of age or if the arrests occurred in operating rooms or emergency departments. Arrests were also excluded if the trained observers arrived at the arrest before sufficient personnel were present, so that their direct assistance in patient care was required. True arrest cases were defined by the loss of a pulse and the delivery of chest compressions by hospital staff. On arrival at a cardiac arrest, observers made all reasonable efforts to record compressions using the data collection tool without alerting resuscitation providers to their presence.

Data Collection Tool

A novel tool was developed to record real-time chest compression rates with a personal digital assistant (PDA; Palm Pilot m500, Palm, Inc) programmed with the assistance of a Visual Basic application platform (AppForge Professional Edition 2.1.1, AppForge, Inc). The PDA application was designed to record such events as arrival at arrest, chest compression given, and end of event by pressing different buttons on the device. Investigators were trained to press the "chest compression given" button in a synchronized 1-to-1 fashion with each compression delivered. Events were automatically time stamped to the nearest 10 milliseconds and stored on a memory card (SD Card, SanDisk Inc). Clinical data such as age, sex, race, and outcome were also recorded for each event on the device. To comply with IRB and HIPAA requirements, these clinical data were collected in aggregate fashion only, with outcome (ROSC or no ROSC) as the only patient characteristic linked to the actual event. Observers were trained to indicate ROSC if a detectable pulse and perfusing rhythm were maintained for ≥ 5 minutes. Similarly, data were collected only for the cardiac arrest event; patients were not followed up to hospital discharge.

Observers received several hours of training and were tested with a simulated cardiac arrest before the study. Additionally, during the study period, observers were tested against a standard videotaped arrest simulation with variable known compression rates. This allowed us to assess correct performance and validate the recording protocol (see below).

Data Analysis

Data were analyzed with a spreadsheet application (Excel, Microsoft Corp). Arrest recordings were divided into 30-second segments for analysis, and chest compression rates were computed for each segment from this formula: rate = (compressions per 30-second segment) $\times 60 / (30 - \text{total pause time in 30-second segment})$, where pause time indicates periods of time in which ≥ 4 seconds pass without chest compressions, suggesting that some noncompression action such as a pulse check or shock is taking place. Analysis of our data using pause time thresholds from 2 to 5 seconds did not significantly change our results (data not shown). Thus, calculated compression rates are relatively unaffected by pauses for pulse checks and rescuer change or other brief times without compressions. Average chest compression rates for each arrest were also calculated. Mean chest compression rate data (to determine the significance between ROSC and non-ROSC cohort subsets) were compared by use of the 2-tailed Student *t* test, with significance set at $P < 0.05$. The frequency of ROSC was tabulated for each quartile of average chest compression rates. The quartile groups were then compared by use of the χ^2 test with Bonferroni adjustment for 6 pairwise comparisons, yielding a required significance level (α) of 0.0083.

Validation of Data Recording

To determine whether trained observers could accurately record chest compressions using our handheld device, we performed validation testing on each of the observers at the 3 hospital sites (18 total observers). A carefully simulated cardiac arrest with realistic chest compression rates and rate variation was videotaped. Each observer recorded this arrest using the handheld device, and data were analyzed against the "true" chest compression data for the same event derived by study authors by freeze-frame analysis of the simulation video with millisecond time stamping. Validation data were evaluated with Pearson correlation coefficient analysis.

Results

Observer Validation

Each observer was tested with a videotaped cardiac arrest simulation during the study period to ensure correct data recording performance (see Methods). This validation of our data collection tool and trained observers is shown in Figure 1. The mean correlation coefficient calculation for our 18

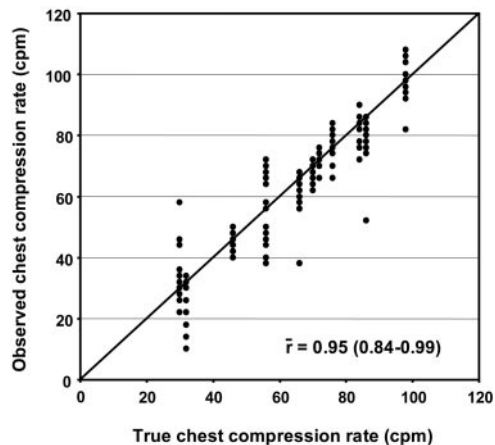


Figure 1. Validation of observer chest compression recording method with Pearson correlation coefficient analysis. Observers were tested against videotaped simulated cardiac arrest, and chest compression rates were compared with known rates of simulation derived by digital time stamping. Mean correlation coefficient for all data points is shown, with range of coefficients in parentheses.

observers revealed $r=0.95$, demonstrating that observers could collect chest compression data reproducibly and reliably.

Study Population

Over the study period, 813 minutes of resuscitation was observed at the 3 hospitals during 97 cardiac arrest events.

IRB-approved aggregate demographic data are shown in the Table. The average age of the patients was 73.1 years; 49 of 97 (51%) were female. Cardiac arrests occurred in intensive care settings (53 of 97, 55%), hospital ward beds (31 of 97, 32%), or other locations such as radiology areas (13 of 97, 13%). Initial survival (ROSC) was attained in 61 of 97 patients (63%). Differences in demographic data between the 3 hospitals reflected their different patient populations. Age, setting of cardiac arrest, and survival data are generally consistent with other reports of in-hospital arrest.^{15,16}

Chest Compression Rate Analysis

An example cardiac arrest data set is shown in Figure 2A. Chest compression rates were calculated for each 30-second segment (see Methods) and are shown in the figure. In this arrest record, as in other arrests in our cohort, chest compression rates often fell to <100 cpm, the rate recommended during standard CPR by the American Heart Association and European Resuscitation Council.¹⁴ Many arrest records demonstrated significant time intervals during which no chest compressions were performed, representing interventions such as intubation or periods when compressions were held because a pulse may have been detected. Shorter pauses, for pulse checks or change of rescuer, were excluded in the calculation of 30-second compression rates because these pauses would artificially lower the true rates when compressions were actually being delivered. The average chest compression rates over resuscitation time are shown in Figure 2B.

Characteristics of Patient Cohort

	All Sites	Hospital		
		UCH	LGH	MNH
Cohort size				
Time recorded, min	813	638	109	66
Events recorded, n	97	71	14	12
Age (mean), y	73.1*	72.4*	75.7±18.9	74.2±13.6
Gender, n (%)				
Female	49/97 (51)	38/71 (56)	6/14 (43)	5/12 (42)
Male	48/97 (49)	33/71 (44)	8/14 (57)	7/12 (58)
Race, n (%)				
Black	38/97 (39)	35/71 (52)	1/14 (7)	2/12 (17)
White	48/97 (49)	29/71 (46)	12/14 (86)	7/12 (58)
Other	11/97 (11)	7/71 (2)	1/14 (7)	3/12 (25)
Location, n (%)				
Intensive care	53/97 (55)	40/71 (64)	8/14 (57)	5/12 (42)
Ward	31/97 (32)	23/71 (26)	4/14 (29)	4/12 (33)
Other	13/97 (13)	8/71 (10)	2/14 (14)	3/12 (25)
Arrest characteristics				
Initial ROSC, n (%)	61/97 (63)	46/71 (65)	8/14 (57)	7/12 (58)
Event duration (mean), min	8:23±6:42	9:00±6:34	7:48±8:35	5:33±4:15
Event duration, range, min	0:08–26:11	0:40–23:56	0:08–26:11	0:52–14:32

*“Other” locations included cardiac catheterization and radiology areas. “Other” race included patients of Hispanic or Asian descent. “Event duration” refers to time duration of recorded resuscitation efforts.

*Given IRB requirements at this hospital to aggregate demographic data, we cannot calculate an SD for this data set.

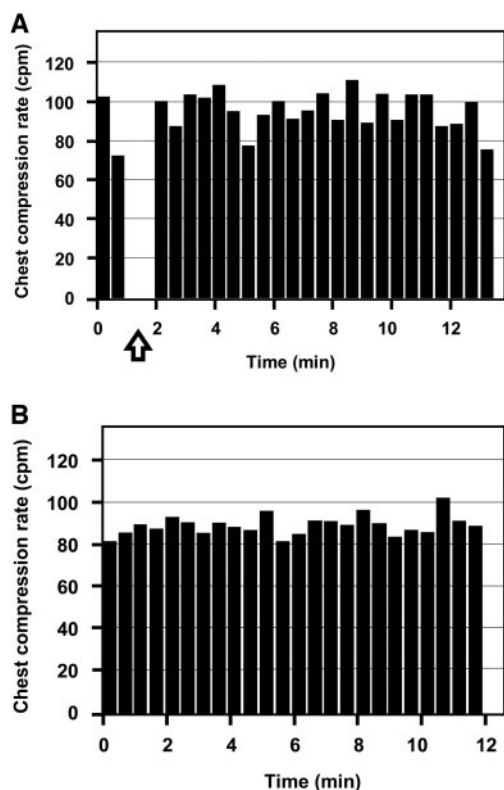


Figure 2. A, Example of chest compression rate data from one cardiac arrest event. Each bar represents average chest compression rate for 30-second time segment. Note the pause during first 2 minutes of resuscitation marked by arrow; during this time, intubation was performed. B, Average chest compression rates for entire cohort during each time segment. Each bar represents average of all chest compression rates at that point in time for entire cohort. First 12 minutes of arrest time is shown. Because some resuscitation efforts ended before 12 minutes, number of arrests included in each average declines over time. Similarly, some resuscitations lasted >12 minutes; for simplicity, data from beyond 12 minutes are not shown. It does not appear that chest compression rates decay significantly over this time interval in the resuscitation cohort.

Chest compression rates in our cohort showed great variation and often fell well below 100 cpm (Figure 3). In fact, rates were at 100 ± 10 cpm in only 31.4% of segments and were <80 cpm in 36.9% of segments. When data from each individual hospital were compared, similar distributions of chest compression rates were seen, supporting the notion that poor rate compliance is not a hospital-specific issue (data not shown). A variety of medical staff, specifically nurses, residents, and medical students, performed chest compressions at each study hospital, and all were CPR-certified via basic life support or advanced cardiopulmonary life support training courses.

Chest Compression Rate and Outcome

The distribution of chest compression rates was plotted separately for the patients who attained ROSC and for those who did not survive initial resuscitation efforts (Figure 4). The data show that patients who attained ROSC were given chest compressions at higher rates. Mean chest compression rate for initial survivors was 90 ± 17 cpm; for nonsurvivors,

79 ± 18 cpm ($P=0.0033$). Average total resuscitation times for the 2 groups were 450 ± 403 and 595 ± 390 seconds, respectively, suggesting that poor compression rate may not reflect performer bias against patients thought to have little chance of resuscitation (see Discussion). Two additional analyses also revealed better compression rates for initial survivors than nonsurvivors. First, when average chest compression rates were calculated for the 2 groups at each time segment during resuscitation (ie, at segment 1, segment 2), average chest compression rates among the ROSC group were higher than among the nonsurviving group during the vast majority of time segments (data not shown). Second, a quartile analysis was performed in which all arrests were grouped into 4 groups ranked by chest compression rate (Figure 5). ROSC was scored for each of these groups. The quartile of arrests with the lowest chest compression rates had a ROSC rate of 42%, whereas the quartile with the highest chest compression rates had a ROSC rate of 75% ($P=0.0083$). Given the small number of arrests with average chest compression rates >100 cpm, we could not discern a significant drop in ROSC rate for overly high compression rates in separate analysis (data not shown).

Discussion

Using a custom-designed data collection system, we have performed the first comprehensive evaluation of chest compression rates during cardiac arrest. After observing 97 cardiac arrests, we have concluded that chest compressions are often delivered at rates much lower than recommended. The frequency of suboptimal compression rates was similar in all 3 hospitals, suggesting that poor chest compression rates may be a widespread problem. Our work confirms and extends a small pilot study that found low chest compression rates when manually counted for 45 seconds during a convenience sample of 12 in-hospital arrests for a total of 8 minutes of observation time at one hospital site.¹⁷

When resuscitation outcomes were evaluated, we found that higher average chest compression rates correlated with higher rates of ROSC. Perhaps most interesting is the quartile analysis in Figure 5, which demonstrates that the group of arrests with the lowest chest compression rates had a greatly reduced rate of initial survival compared with the group of arrests with the highest chest compression rates. The 2 upper quartiles have similar ROSC rates, suggesting that a “threshold” effect may be evident; ie, survival may be diminished only if the chest compression rate falls below a certain critical value. Our analysis suggests that such a threshold may exist at a rate between 80 and 90 cpm. We did not design our study with the expected power necessary to detect differences in ROSC rates, yet these differences are statistically significant by both direct comparison and quartile analysis.

There are 2 possible explanations for this intriguing finding. Low rates of chest compression may contribute to resuscitation failure; therefore, our findings may reveal an important aspect of CPR performance by trained personnel. This would suggest that improvements in chest compression rates might improve outcomes. This hypothesis is consistent with animal data on CPR quality. Alternatively, low chest compression rates may reflect bias of the resuscitation team

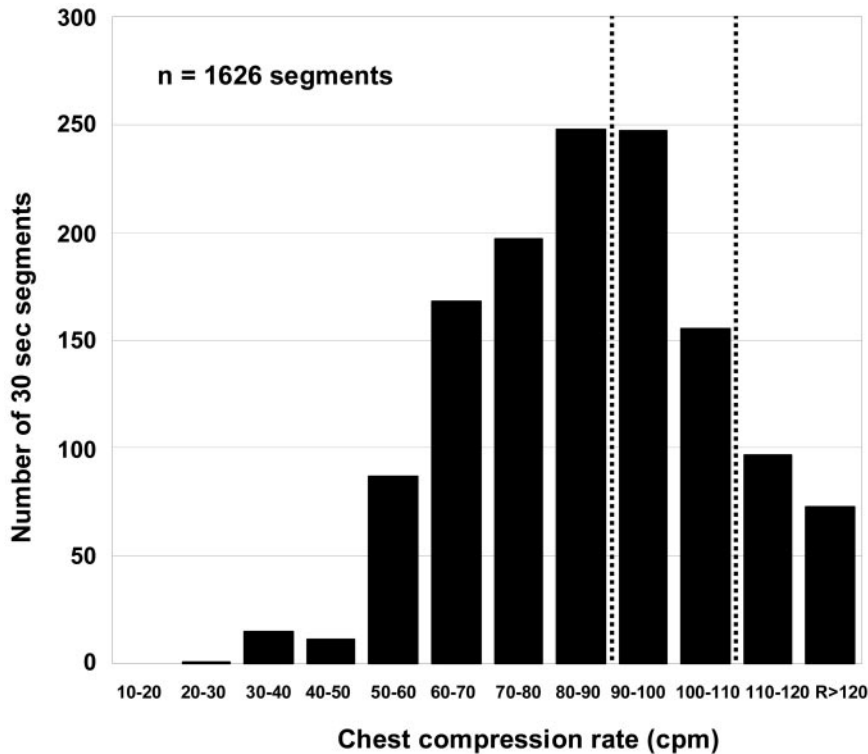


Figure 3. Distribution of chest compression rates at 3 study hospitals. Aggregated data for all 30-second segments during which compressions were delivered show wide distribution of rates. Note that standard guidelines for CPR recommend a rate of 100 cpm. Percentage of segments within 10 cpm of guideline recommendations is shown, with dotted lines on histogram representing this range.

toward probable outcome. That is, patients thought to have little chance of recovery may receive poor resuscitation efforts, intentionally or not. A surrogate marker for team effort during arrest, namely duration of resuscitation efforts, suggests that bias may not play a role because patients who died received longer resuscitation efforts than patients who lived (Figure 4). If a team correctly identifies patients who will not survive despite resuscitation, one might expect shorter resuscitation durations in the population that did not attain ROSC. This is by no means conclusive, however. Given IRB constraints on linking patient data such as age or

morbidities to our compression data (see Methods), a careful analysis comparing ROSC and non-ROSC cohorts is limited.

Effectiveness of chest compressions depends on several components and certainly includes variables that go beyond simple rate such as depth, pressure, and technique.^{18,19} Prior laboratory investigations have shown that slow rates of compression do not generate sufficient flow to sustain resuscitation²⁰ and that higher chest compression rates are associated with improved measures of perfusion.²¹ In this preliminary study, we have not considered depth of compressions or rate and depth of ventilation. Effectiveness of CPR is most

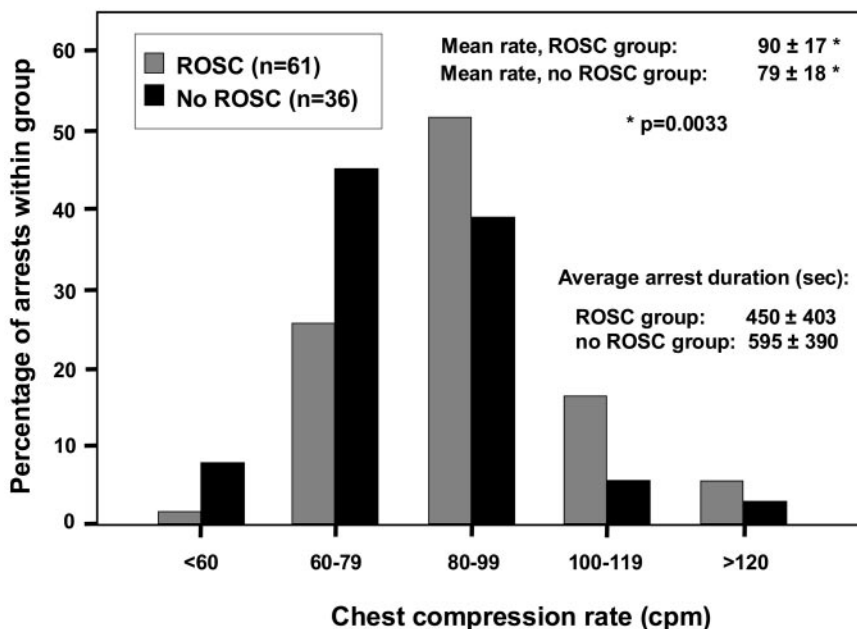


Figure 4. Chest compression rates correlate with initial resuscitation outcome. Subgroup of patients attaining ROSC is shown in gray; subgroup that did not, in black. Note 2 overlapping but distinct distributions, with mean rates for each group shown. Also note mean durations of resuscitation for 2 groups, demonstrating that the group that expired received longer resuscitation efforts on average, arguing against a “slow-code” bias (see Discussion). Asterisk denotes statistical significance from 2-tailed *t* test as shown.

	ROSC	No ROSC	
Quartile 1 (n=24) 95.5-138.7 cpm	75%	25%	*
Quartile 2 (n=25) 87.1-94.8 cpm	76%	24%	*
Quartile 3 (n=24) 72.4-87.1 cpm	58%	42%	
Quartile 4 (n=24) 40.3-72.0 cpm	42%	58%	*

* $p < 0.0083$

Figure 5. Quartile analysis of chest compression rate and survival. Arrest cohort was divided into 4 groups based on mean chest compression rates (ie, quartile 1 had highest compression rates, quartile 4 had lowest compression rates). ROSC was then compared among these groups. Asterisks denote statistical significance comparing either first or second quartile with last quartile ($P=0.000925$ and $P=0.000371$, respectively); comparison of third and fourth quartiles was not statistically significant ($P=0.0997$). We used χ^2 analysis with Bonferroni adjustment for 6 pairwise comparisons to calculate significance.

likely limited by poor performance in any of its components; thus, inadequate rate, even in the presence of sufficient depth and technique, likely reduces the effectiveness of compressions.

Current research into CPR methodology suggests that ventilations may require less priority than assumed previously.⁸⁻¹¹ Concentrating on compressions alone (especially in the out-of-hospital CPR context where the lay public and paramedics serve as rescuers) may improve both the rate of participation in rescue attempts²² and the quality of compressions.¹⁰ Animal investigation has shown that even brief pauses in chest compressions adversely affect hemodynamics during resuscitation efforts.²³ If our data are also considered, it is also possible that chest compression rates (and therefore rates of ROSC) might improve if ventilation rates were reduced during CPR.

One limitation of our study is that data were collected via an observer, so human error might affect our findings. We have attempted to address this concern in several ways. First, observers undertook several hours of training with the recording device and were tested before the study began. Second, we validated our data collection via testing of each observer during the study period using a videotaped arrest simulation (Figure 1) that provided evidence that accurate data could be collected. These arguments notwithstanding, a more objective measurement of CPR quality would be a welcome advancement. After all, it is possible that some overcounting or undercounting of chest compressions might have occurred in our study despite observer training.

Another possible study limitation in the generalizability of our findings is the small number of hospital sites. We chose 3 contrasting hospitals with different philosophies of care, patient mix, and staff composition to achieve a representative sample of in-hospital CPR performance. We suspect that a variety of universal human factors contribute to poor CPR

quality. These include the difficulty of performing CPR during stressful and chaotic cardiac arrest conditions, the lack of an internal sense of chest compression rate, rescuer fatigue,²⁴ and infrequent CPR recertification. Therefore, we believe that our results are likely to reflect an endemic problem among healthcare providers.

There are at least 2 possible solutions to the problem of poor CPR quality. The first involves mechanical devices that can provide chest compressions reliably at a set rate and depth.²⁵ These devices have the potential to generate better hemodynamic characteristics than manual chest compressions.²⁶ Nevertheless, they have remained unpopular in the clinical arena because they are often cumbersome to use and awkward to work around if other patient instrumentation is required. The other solution is to improve monitoring and feedback to reduce human error during manual CPR. Our data support the importance of additional instrumentation such as end-tidal CO₂ monitors²⁷ and “smart defibrillators,” which can sense CPR characteristics and alert rescuers to errors such as incorrect chest compression rate or depth.²⁸

Our results suggest that relatively highly trained hospital personnel often fall short of CPR guidelines during resuscitation efforts. Most cardiac arrests take place in the out-of-hospital setting, where bystanders and paramedics are the primary providers of CPR.²⁹ It is possible that the quality of community CPR may be even more variable than what we have found in the present study of trained providers.

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Disclosures

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