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Quality of Cardiopulmonary Resuscitation During In-Hospital Cardiac Arrest

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SURVIVAL FROM CARDIAC ARREST remains low despite the introduction of cardiopulmonary resuscitation (CPR) more than 50 years ago.¹⁻³ The delivery of CPR, with correctly performed chest compressions and ventilations, exerts a significant survival benefit in both animal and human studies.⁴⁻⁸ Conversely, interruptions in CPR or failure to provide compressions during cardiac arrest ("no-flow time") have been noted to have a negative impact on survival in animal studies.⁷ Consensus guidelines clearly define how CPR is to be performed,⁹ but the parameters of CPR in actual practice are not routinely measured, nor is the quality known.

There are multiple reasons for concern regarding the quality of CPR. Even though CPR training programs are ubiquitous, a number of studies demonstrate that these learned resuscitation skills deteriorate over time.^{10,11} Furthermore, issues such as translation of skills from training environments to actual cardiac arrest settings, as well as rescuer fatigue during resuscitation,¹² may limit CPR quality. Recent investigations have revealed that patients may

See also pp 299 and 363 and Patient Page.

Context The survival benefit of well-performed cardiopulmonary resuscitation (CPR) is well-documented, but little objective data exist regarding actual CPR quality during cardiac arrest. Recent studies have challenged the notion that CPR is uniformly performed according to established international guidelines.

Objectives To measure multiple parameters of in-hospital CPR quality and to determine compliance with published American Heart Association and international guidelines.

Design and Setting A prospective observational study of 67 patients who experienced in-hospital cardiac arrest at the University of Chicago Hospitals, Chicago, Ill, between December 11, 2002, and April 5, 2004. Using a monitor/defibrillator with novel additional sensing capabilities, the parameters of CPR quality including chest compression rate, compression depth, ventilation rate, and the fraction of arrest time without chest compressions (no-flow fraction) were recorded.

Main Outcome Measure Adherence to American Heart Association and international CPR guidelines.

Results Analysis of the first 5 minutes of each resuscitation by 30-second segments revealed that chest compression rates were less than 90/min in 28.1% of segments. Compression depth was too shallow (defined as <38 mm) for 37.4% of compressions. Ventilation rates were high, with 60.9% of segments containing a rate of more than 20/min. Additionally, the mean (SD) no-flow fraction was 0.24 (0.18). A 10-second pause each minute of arrest would yield a no-flow fraction of 0.17. A total of 27 patients (40.3%) achieved return of spontaneous circulation and 7 (10.4%) were discharged from the hospital.

Conclusions In this study of in-hospital cardiac arrest, the quality of multiple parameters of CPR was inconsistent and often did not meet published guideline recommendations, even when performed by well-trained hospital staff. The importance of high-quality CPR suggests the need for rescuer feedback and monitoring of CPR quality during resuscitation efforts.

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be hyperventilated during out-of-hospital arrest,¹³ and that low chest compression rates are present during in-hospital arrest.^{14,15}

Given the proven survival benefit of high-quality CPR and the lack of data on actual performance, we sought to de-

termine whether well-trained hospital staff perform CPR compressions and ventilations according to guideline recommendations. The in-hospital environment was selected because it offers the added advantage of thorough pre-arrest documentation as well as resus-

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citation by ample numbers of highly trained personnel.

METHODS

Patient Enrollment

The study protocol and consent materials were approved by the institutional review board at the University of Chicago Hospitals, Chicago, Ill. Data collection was carefully structured to comply with all relevant Health Insurance Portability and Accountability Act of 1996 regulations. Consent was obtained from all members of the resuscitation teams via an oral consent process.

Resuscitation events were studied among inpatients at the University of Chicago Hospitals who experienced cardiac arrest, defined by the documented loss of a pulse and respirations as well as the delivery of chest compressions. Patients were excluded for analysis if they experienced arrest in the operating room or emergency department, were younger than 18 years, or if the CPR-sensing defibrillator was used without its chest compression-detecting mechanism.

Measuring Parameters of CPR Quality

During in-hospital cardiac arrests, an investigational monitor/defibrillator (IDE G020121) was used. This device is based on a commercially available monitor/defibrillator (Heartstart 4000SP, Laerdal Medical Corporation, Stavanger, Norway) with the additional investigational capabilities for capturing and recording rate and depth of chest compressions, rate and volume of ventilations, presence or absence of a pulse, as well as standard electrocardiogram and defibrillator shock event data. In addition, customized software for data analysis collected these parameters and calculated the no-flow time and no-flow fraction (NFF, fraction of cardiac arrest time without compressions being performed). These additional device features and analysis software were developed by engineers at Laerdal Medical Corporation.

Chest compression data were captured via a special chest compression pad outfitted with an accelerometer sensor (ADXL202e Analog Devices, Norwood, Mass) and a pressure sensor (22PCCFBG6, Honeywell, Morristown, NJ). The pad was placed on the mid-sternum of the patient under the hands of the rescuer performing compressions. This method has been previously validated in the laboratory setting, with compression depth data accurate to within 1.6 mm.^{16,17} Components of the sensing and recording software have also been tested, validated, and published elsewhere.^{18,19} Additional testing has demonstrated the use of impedance measurement for ventilation monitoring, in both swine²⁰ and healthy human volunteers (P. A. Steen, oral communication, 2003). This latter human study was performed as a validation pilot study to our current study and demonstrated a strong correlation between impedance and spirometry waveforms.

Ventilation and pulse data were obtained using impedance measurements captured from the defibrillation pads. All data collected by the device were stored on data cards for subsequent analysis using additional custom software that allowed for calculation of rates and other parameters. Per hospital regulation, all users of the device and CPR performers were originally certified in either basic life support (medical students and nurses), advanced cardiovascular life support (all physicians), or both. The study device was utilized by the hospital team that responds to all cardiac arrests. The study design was purely observational with no alteration in therapy or suggested change from standard resuscitation practice. Resuscitation teams were blinded to the results of defibrillator measurements during the arrest. The patients studied represented a convenience sample of all cardiac arrests during the study period, in that during some other cardiac arrests another defibrillator was used instead of the study device.

Data Analysis

To determine CPR parameters, chest compression rate, depth, ventilation rate, no-flow time, and NFF were calculated by Sister Studio software (Laerdal Medical Corporation). Correct chest compression depth was defined as between 38 and 51 mm (1.5-2.0 in). (Current CPR guidelines do not take adult patient characteristics into account in recommendations for CPR parameters; therefore, we did not perform adjustments for any of these variables.) Pauses in chest compressions of more than 1.5 seconds (for pulse checks and intubation) were excluded from rate calculations so as to not artifactually lower chest compression rate. Mean (SD) values were calculated for CPR parameters. No-flow time (time periods of cardiac arrest without compressions being performed) was mathematically defined as total time minus the time with chest compressions or spontaneous circulation, and NFF was defined as the no-flow time divided by cardiac arrest time (ie, total time minus time periods with spontaneous circulation). This measure of NFF represents the fraction of time during the resuscitation episode without cerebral or myocardial circulation.

All data were sent to the study investigator (H.M.) at Laerdal Medical Corporation, where data were processed by filtering and down sampling to 50 Hz to prepare files for annotation and review. Proprietary software designed for the study (Sister Studio) was used for processing each cardiac arrest file. Raw data from each patient were collected as 2 separate data files. One file contained impedance and chest compression data, while the second file contained elements collected by the recording defibrillator (electrocardiogram and shock times). These 2 data files were then conditioned, filtered, and merged into a single data set for each patient by the study sponsor. At this time the study sponsor did not analyze the data or perform interpretation of waveforms. The merged conditioned files were then sent back to the study site, where all data annotation,

analysis, and interpretation were conducted. This analysis involved a full annotation of the file to determine when a pulse was present vs when cardiac arrest was present; the software would then read compressions and ventilations, which were confirmed by a study investigator, before a final data file was prepared that contained the parameters of interest (compression rate, compression depth, ventilation rate, no-flow time). The study sponsor did not perform interpretation or access the data during this analysis phase. Secondary data analysis was performed using a spreadsheet application (Excel, Microsoft Corp, Redmond, Wash).

For our outcome measures of CPR quality, we analyzed the first 5 minutes of CPR, which was presumed to be both the best rescuer effort based on study of rescuer fatigue¹² and the most clinically important. Each 5-minute resuscitation episode was divided into 30-second segments, and both compression and ventilation rates were calculated. Segments in which either chest compression or ventilation signals were obscured by signal noise were excluded from analysis. Segments without compressions or ventilations were excluded from calculations of mean compression or ventilation rates, respectively. All files were manually evaluated by a physician investigator to ensure appropriate software marking of events such as compressions, ventilations, and rhythms. Similar analysis was also performed for entire cardiac arrest episodes to provide comparison with the initial 5-minute data. No-flow fraction was only calculated for the first 5-minute period.

Evaluation of Clinical Outcomes

Our study was not designed or powered to find CPR quality differences between survivors and nonsurvivors; however, we undertook this evaluation as a secondary analysis. Of the 67 arrest episodes, 60 had complete data sets for comparison of all parameters. Cardiopulmonary resuscitation parameters were compared between the cohort of patients that achieved return of

spontaneous circulation (ROSC) vs those who died during resuscitation. This analysis was only conducted on data from the first 5 minutes of resuscitation efforts.

Statistical Analysis

All means (SDs) were calculated using a spreadsheet application (Excel). Differences in CPR parameters for outcome evaluation were assessed using a 2-tailed *t* test. Statistical evaluation of data was performed independent of the study sponsor in consultation with a biostatistician at our institution. *P* < .05 was considered statistically significant.

RESULTS

A total of 67 patients with cardiac arrest were treated using the study defibrillator with data collection from December 11, 2002, to April 5, 2004. Data analyzed from this cohort included 1073 segments (536.5 minutes) with chest compression and ventilation data. Patient demographic and cardiac arrest data are shown in TABLE 1. Mean (SD) patient age was 62.2 (17.4) years, and 34.3% of patients were women. Patient race included black (65.7%), white (23.9%), and other/unknown (10.5%) individuals. Cardiac arrest events took place in intensive care settings (52.2%), general wards (44.8%), or other locations (3.0%, radiology [n=1] and cardiac catheterization laboratory [n=1]). Frequencies of the presenting rhythm were 14.9% ventricular fibrillation/ventricular tachycardia, 59.7% pulseless electrical activity, 10.4% asystole, and 14.9% other (indeterminate). Return of spontaneous circulation was achieved in 40.3% of patients. Baseline characteristics and rate of ROSC are similar to data reported in other studies of in-hospital cardiac arrest.²¹

Cardiopulmonary resuscitation characteristics for the entire patient cohort are shown in TABLE 2. During the first 5 minutes of resuscitation, mean chest compression rate was less than 90/min 28.1% of the time and less than 80/min 12.8% of the time. Chest compression depth data revealed that chest

Table 1. Demographic and Descriptive Clinical Data of Cardiac Arrest Cohort (N = 67)*

| | Total Patient Cohort, No. (%) |
|--|-------------------------------|
| Demographics | |
| Age, mean (SD) [range], y | 62.2 (17.4) [21-94] |
| Race† | |
| Black | 44 (65.7) |
| White | 16 (23.9) |
| Other/unknown | 7 (10.5) |
| Sex | |
| Men | 44 (65.7) |
| Women | 23 (34.3) |
| Descriptive clinical data | |
| Cardiac arrest location | |
| Intensive care setting | 35 (52.2) |
| Hospital general ward setting | 30 (44.8) |
| Other‡ | 2 (3.0) |
| Time of cardiac arrest | |
| Morning (6:00 AM-12:00 PM) | 17 (25.4) |
| Afternoon (12:00 PM-6:00 PM) | 14 (20.9) |
| Evening (6:00 PM-12:00 AM) | 19 (28.4) |
| Night (12:00 AM-6:00 AM) | 17 (25.4) |
| Initial rhythm | |
| Ventricular fibrillation/ventricular tachycardia | 10 (14.9) |
| Pulseless electrical activity | 40 (59.7) |
| Asystole | 7 (10.4) |
| Perfusing rhythm | 0 |
| Other§ | 10 (14.9) |
| Return of spontaneous circulation | |
| Yes | 27 (40.3) |
| No | 40 (59.7) |
| Survival to hospital discharge | |
| Yes | 7 (10.4) |
| No | 60 (89.6) |

*Percentages may not all total 100 due to rounding.

†Race was extracted from chart demographic data.

‡Includes radiology (n = 1) and cardiac catheterization laboratory (n = 1).

§Patients presenting with an indeterminate rhythm.

compressions were too shallow (<38 mm depth) 37.4% of the time. Ventilation rates were calculated in a similar fashion to chest compression rates. In contrast with compressions, ventilation rates tended to be high; during 60.9% of segments, ventilations were performed at a rate of more than 20/min. Ventilation volumes did not appear to deviate greatly from physiological ranges and are not reported herein. Analysis of the time with cardiac arrest but without compressions (NFF) yielded a mean (SD) of 0.24 (0.18) with 40.3% of the segments having an NFF of more than 0.20.

Although the intent of this investigation was only to objectively describe multiple parameters of CPR during cardiac arrest, we considered whether ROSC was associated with better CPR quality. We did not find any statistically significant differences in chest compression rate, depth, ventilation rate, or NFF between patients who achieved ROSC vs those who did not (TABLE 3). A trend toward lower NFF was observed for patients with ROSC compared with nonsurvivors. We did not expect to find clinical outcome differences given our small patient cohort and the nonrandomized nature of the study; therefore, we cannot draw any conclusions regarding the di-

rect clinical impact of the quality of CPR on survival.

COMMENT

Our study represents, to our knowledge, the first multiparameter, quantitative recordings of actual CPR during in-hospital cardiac arrest. Using impedance measurement techniques, we found that quality of CPR was often deficient from guideline recommendations⁹ in several specific parameters, including chest compression rate, compression depth, ventilation rate, and NFF. Specifically, chest compression rates were often less than the recommended 100/min, compression depth was often more shallow than the mini-

mum 38 mm, ventilation rate was higher than the recommended 12 to 16/min, and NFF was longer than adherence to recommendations might allow (although not clearly specified in the guidelines, a 10-second pulse check every minute of CPR would yield an NFF of 0.17).

These data confirm other recent investigations¹³⁻¹⁵ suggesting that CPR quality may be highly variable in actual practice. Just as we observed frequent overventilation, Aufderheide et al¹³ recently showed that paramedics hyperventilate patients during out-of-hospital cardiac arrest, and parallel animal experiments confirmed that this degree of hyperventilation led to decreased survival. We recently documented low chest compression rates during in-hospital cardiac arrest in a multicenter study when recorded by observers equipped with a handheld device to record compression rate.¹⁵ A smaller observer-based study found low chest compression rates during in-hospital arrest.¹⁴

Cardiopulmonary resuscitation performance in our study may have been affected by the knowledge that rescuers were being studied. This "Hawthorne effect"²² would likely have led to improved CPR quality and would minimize our findings of significant deviations from recommended practice. In addition, due to institutional review board requirements, we did not link individuals performing CPR with CPR-quality data. However, resuscitation teams change each month (with resident rotations), with completely new rescuers. Therefore, it is unlikely that an individual rescuer performed CPR in more than approximately 4 to 5 cardiac arrests.

The paramount importance of CPR has been confirmed in both animal and human studies. In 2 clinical studies, survival from ventricular fibrillation arrest was improved if CPR was performed before defibrillation attempts.^{23,24} In animal studies, coronary perfusion pressure, hemodynamic function, and survival were adversely affected by even short pauses

Table 2. CPR Parameters During Cardiac Arrest Episodes*

| | First 5 Minutes of Cardiac Arrest Episode (N = 67) | Complete Cardiac Arrest Episode (N = 67) |
|--------------------------------|--|--|
| Chest compression data | | |
| Compression rate, /min | | |
| Mean (SD) | 102 (19) | 105 (21) |
| <80 | 12.8 | 10.8 |
| <90 | 28.1 | 23.7 |
| >110 | 36.5 | 38.7 |
| Compression depth, mm | | |
| Mean (SD) | 42 (13) | 43 (14) |
| <38 | 37.4 | 36.3 |
| Ventilation data | | |
| Ventilation rate, /min | | |
| Mean (SD) | 21 (12) | 20 (13) |
| <10 | 7.3 | 7.5 |
| >20 | 60.9 | 58.9 |
| Chest compression interruption | | |
| NFF, mean (SD) | 0.24 (0.18) | |
| 30-s segments with NFF >0.20 | 40.3 | |

Abbreviations: CPR, cardiopulmonary resuscitation; NFF, no-flow fraction.

*Data are presented as percentages unless otherwise specified. Percentages refer to portion of time from respective episode (either 5 minutes or whole episode) that include the criteria as described. NFF is defined as the cumulative no-flow time for a given cardiac arrest divided by the total time without a pulse during that same episode.

Table 3. CPR Parameters and Resuscitation Outcomes*

| | Return of Spontaneous Circulation, Mean (SD) | | P Value |
|------------------------|--|-------------|---------|
| | Yes (n = 27) | No (n = 33) | |
| Compression rate, /min | 98 (18) | 107 (18) | .07 |
| Compression depth, mm | 42 (13) | 41 (12) | .82 |
| Ventilation rate, /min | 20 (7) | 22 (9) | .17 |
| NFF, first 5 min | 0.20 (0.14) | 0.27 (0.21) | .16 |

Abbreviations: CPR, cardiopulmonary resuscitation; NFF, no-flow fraction.

*Data for the first 5 minutes are shown for the 60 patients with complete data in all parameters. None of the differences between patients who achieved return of spontaneous circulation (ROSC) and those who did not were statistically significant, although patients with ROSC had a trend toward fewer interruptions in chest compression as observed by the NFF.

in chest compressions.^{25,26} Moreover, pauses in chest compression just before defibrillation worsened outcomes in a swine model.²⁷ Additionally, laboratory study has shown that physiological and survival outcomes are sensitive to CPR quality.^{28,29} Mechanical devices that provide chest compressions at consistent rate and depth have shown promise toward improving survival.³⁰

There are several limitations to our study. A primary limitation is that the precise contribution to survival of the specific parameters that were measured is unknown. Although an isolated compression rate of less than 100/min can be considered a failure to adhere to a published recommendation of the American Heart Association, we cannot determine whether this "deficiency" is directly linked to worsened survival. Support for objective CPR quality monitoring lies in the fact that this technology will allow future studies to carefully examine the effects of CPR parameters on survival.

Additional limitations are that filtered electrocardiogram and ventilation signals were occasionally overcome by artifact, which caused us to exclude some segments. Chest compression depth as studied was calibrated for presence of a backboard and therefore depth may be overestimated if a backboard was not used during the resuscitation. For this reason, we describe in our analysis only compressions that are too shallow. Although our study is limited by use of a single site for data collection, we believe these results are likely generalizable to other hospitals, just as our prior results demonstrated chest compression rate deficiencies when studied at 3 hospitals.¹⁵ Performance difficulties during stressful and disorganized cardiac arrest settings, the lack of reliable internal timing to pace chest compressions, rescuer fatigue,¹² and infrequent recertification in CPR³¹ may all contribute to the observed deficiencies. It is therefore likely that our findings are representative of a more general dilemma in resuscitation. Human factors in CPR perfor-

mance are important and at this point underinvestigated areas of research.³²

Our study has implications for the conduct and design of future clinical CPR studies. Cardiopulmonary resuscitation quality is currently an unmeasured but potentially important confounder in most published clinical studies involving cardiac arrest outcomes. The importance of this variable given the current ability to measure these parameters should be considered by researchers attempting to study methods for improving survival from cardiac arrest.

There are several potential practical solutions for helping to improve poor CPR quality. The first involves mechanical devices that can provide chest compressions reliably at a set rate and depth.³³ These devices may generate better hemodynamic characteristics than manual chest compressions.^{34,35} Another solution is to improve monitoring and feedback to reduce human error during manual CPR, by using devices such as end-tidal CO₂ monitors³⁶ and "smart defibrillators," which can measure CPR characteristics and provide audio feedback to alert the rescuers to errors such as incorrect chest compression or ventilation rate.^{18,19}

Author Contributions: Dr Becker had full access to all of the data in the study and takes responsibility for the integrity of the data and the accuracy of the data analysis.

Study concept and design: Abella, Myklebust, Vanden Hoek, Becker.

Acquisition of data: Abella, Alvarado, Myklebust, Barry, O'Hearn, Becker.

Analysis and interpretation of data: Abella, Myklebust, Edelson, Barry, O'Hearn, Vanden Hoek, Becker.

Drafting of the manuscript: Abella, Barry, O'Hearn, Vanden Hoek, Becker.

Critical revision of the manuscript for important intellectual content: Abella, Alvarado, Myklebust, Edelson, Vanden Hoek, Becker.

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Study supervision: Abella, Vanden Hoek, Becker.

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Do not let yourselves be discouraged or embittered by the smallness of the success you are likely to achieve in trying to make life better. You certainly would not be able, in a single generation, to create an earthly paradise. Who could expect that? But, if you make life ever so little better, you will have done splendidly, and your lives will have been worthwhile.

—Arnold Toynbee (1889-1975)