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Compression force—depth relationship during out-of-hospital cardiopulmonary resuscitation☆

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Summary
Background: Recent clinical studies reporting the high frequency of inadequate chest compression depth (<38 mm) during CPR, have prompted the question if adult human chest characteristics render it difficult to attain the recommended compression depth in certain patients.
Material and methods: Using a specially designed monitor/defibrillator equipped with a sternal pad fitted with an accelerometer and a pressure sensor, compression force and depth was measured during CPR in 91 adult out-of-hospital cardiac arrest patients.
Results: There was a strong non-linear relationship between the force of compression and depth achieved. Mean applied force for all patients was 30.3 ± 8.2 kg and mean absolute compression depth 42 ± 8 mm. For 87 of 91 patients 38 mm compression depth was obtained with less than 50 kg. Stiffer chests were compressed more forcefully than softer chests ($p < 0.001$), but softer chests were compressed more deeply than stiffer chests ($p = 0.001$). The force needed to reach 38 mm compression depth (F_{38}) and mean compression force were higher for males than for females: 29.8 ± 14.5 kg versus 22.5 ± 10.2 kg ($p < 0.02$), and 32.0 ± 8.3 kg versus 27.0 ± 7.0 kg ($p < 0.01$), respectively. There was no significant variation in F_{38} or compression depth with age, but a significant 1.5 kg mean decrease in applied force for each 10 years increase in age ($p < 0.05$). Chest stiffness decreased significantly ($p < 0.0001$) with an increasing number of compressions performed. Average residual force during decompression was 1.7 ± 1.0 kg, corresponding to an average residual depth of 3 ± 2 mm.

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Conclusion: In most out-of-hospital cardiac arrest victims adequate chest compression depth can be achieved by a force <50 kg, indicating that an average sized and fit rescuer should be able to perform effective CPR in most adult patients.

Introduction

Animal studies show that blood flow increases with increasing compression force and/or depth during cardiopulmonary resuscitation (CPR),[1–6] and in humans end-tidal CO_2 and systolic blood pressure increases linearly with applied force from 10 to 64 kg.[5] The CPR guidelines recommend that chest compressions should be applied with the force necessary to depress the sternum 4—5 cm (38—51 mm ~ 1.5—2 in.) with each compression.[7,8] There is, however, very limited information available describing the relationship between forces applied to the sternum and the degree of displacement achieved during manual CPR on humans.[5,9–12]

Recent clinical studies have reported a high frequency of inadequate chest compression depth compared to guidelines recommendations.[13,14] In-hospital more than one-third[13] and out-of-hospital more than half[14] of the compressions were less than 38 mm deep. This raises the question if the mechanical characteristics of the adult human chest render it difficult to attain this depth in certain patients. These characteristics have only been studied in a few small cohorts of 10—16 in-hospital cardiac arrest patients,[10,11] and possible changes with time during CPR or possible gender differences have, to our knowledge, not been reported. We have therefore studied the dynamic relationship between sternal compression force and displacement during CPR in a larger number of out-of-hospital cardiac arrest patients.

Material and methods

The material was collected during the third phase of a large study of quality of CPR performed by ambulance personnel.[14] Except for the specifics on compression depth and force, this section has been presented in detail in previous reports,[14,15] and a more condensed version is therefore presented here.

Study design and recruitment

The study was performed in three ambulance services: Akershus (Norway), Stockholm (Sweden), and London (England) and approved by the respective regional ethics committees. Informed consent for inclusion in the study was waived as decided by these committees in accordance with paragraph 26 in the Helsinki Declaration.[16] In this prospective study registered at ClinicalTrials.gov (NCT00138996, Initial release 29 August 2005) patients older than 18 years suffering from out-of-hospital cardiac arrests of all causes were included. In the first phase quality of CPR was recorded from the defibrillators without feedback to the rescuers.[14] In the second phase rescuers received feedback on CPR quality via the defibrillators after training in the use and meaning of the feedback software (manuscript submitted).

Data collection for the present investigation, the third phase in the study of CPR quality by professional rescuers outside the hospital, was conducted between October 2004 and June 2005. Before this last investigational phase was launched, results from the first phase were revealed to the participants. Information about the strengths and weaknesses concerning the quality of CPR performance was thus passed on to all personnel in each of the three participating ambulance services, and used by their CPR instructors to reinforce and tailor retraining in the ACLS guidelines[17] at each site.

All ambulances were staffed with paramedics. In Stockholm they had a two-tiered system with a nurse anesthetist in the second car attending cardiac arrests.

Equipment

Prototype defibrillators based on standard Heartstart 4000 (Philips Medical Systems, Andover, MA, USA) defibrillators were deployed in six ambulances at each site. The defibrillators were approved for investigational use in Europe (DNV; CE-mark; 2002-OSL-MDD-0009) and in the USA (FDA; IDE# G020121). The defibrillators had an extra chest pad to be mounted on the lower part of the sternum with double adhesive tape. The pad was fitted with an accelerometer (ADXL202e, Analog Devices, USA) and a force sensor (HBM DF2S-LAD from HBM, Darmstadt, Germany). The heel of the rescuer's hand should be placed on top of the chest pad and its movement was considered equal to that of the sternum during chest compressions with compression force >2 kg. A second accelerometer within the defibrillator enabled to be cancelled out the global vertical motion of both patient and defibrillator. Trans-thoracic impedance was measured by applying a near constant sinusoidal current across the standard defibrillation pads and accelerometer and impedance signals were stored in an extra data card in the defibrillators. The defibrillators gave verbal and visual feedback on CPR based on measured quality compared to a built in set of target values.

Data processing

The force and acceleration signals were imported into a mathematical software package (MATLAB®, Natick, MA, USA) and processed offline. Compression depth x was found by integration from the measured chest acceleration a and chest speed v. To avoid depth ''runoff'' due to drift in the accelerometer, minimum depth was synchronized with minimum force for each compression.

The elastic force $F_k(x) = k(x)x$ of the chest was estimated by plotting measured force against calculated depth and subtracting the velocity-dependent damping force (force hysteresis).[11] x is here compression depth and $k(x)$ is chest stiffness.

To compensate the depth curves for incomplete release, the minimum ''leaning'' force $F_k(x_{\min})$ was measured between compressions and the corresponding minimum depth $x_{\min}$ estimated by help of the measured chest stiffness, using the following formula:

$$x_{\min} = \frac{F_k(x_{\min})}{k(x_{\min})}$$

Chest stiffness and damping were then recalculated using the compensated depth curves. The results were averaged across all compressions. Based on the calculated stiffness $k(x)$ of the chest, the necessary force needed to reach 38 mm (1.5 in.) compression depth, here termed F_{38}, was calculated. A higher value of F_{38} thus means a stiffer chest. For episodes where 38 mm compression depth was not reached, F_{38} was estimated by extrapolation of chest stiffness measured at lower depths. F_{25} and F_{19}, the forces necessary to reach 25 and 19 mm compression depth, were also calculated.

To characterise changes in chest stiffness during CPR, F_{25} (force needed to compress the chest 25 mm) was calculated as a function of the number of compressions performed, in steps of 50 compressions. F_{25} was chosen as this compression depth was achieved at one point in all except two patients included in the study. In order to capture the effect of compressions at the very start of CPR and in the longer run, only episodes where no bystander CPR had been performed and a minimum of 1000 compressions were administered, were analysed. A total of 39 episodes were included.

To characterise how linear the relationship between force and depth is for each episode, we defined the *stiffness progressivity factor* γ:

$$\gamma = \frac{F_{38}}{2F_{19}}$$

For $\gamma = 1$, the stiffness $k(x)$ is the same at 19 and 38 mm compression depth. For $\gamma > 1$ the stiffness increases with increasing depth.

The applied force in an episode is defined as the average value of the maximum force of all compressions. Absolute compression depth was defined as average depth of all compressions after the depth signal had been compensated for leaning. The applied force and absolute compression depth, as well as the leaning force and depth, were calculated for each episode.

Statistical analysis

Statistical calculations were performed using either MATLAB or a statistical software package (SPSS 11.0, SPSS Inc., Chicago, IL, USA). Data are presented as mean ± S.D. when normality tests were passed and median (25, 75 percentile) when these failed.

Regression analysis was used to check for significant trends between the stiffness variable F_{38} and the applied force and absolute compression depth. To investigate whether chest stiffness changed under continued CPR, F_{25} was calculated every 50 compressions and regression analysis used to check for significant variations in F_{25} with the number of compressions. Regression analysis was also used to check for significant variations with age.

Student's t-test and Wilcoxon rank sum test were used to test for significant differences in mean and median values, respectively, of measurement variables between patient sex and size.

Results

CPR episodes were analysed from 91 patients, including 61 men and 30 women aged between 18 and 92 years. Median age was 70 (61, 81) years.

Figure 1 shows the relationship between compression force and depth (chest wall elasticity) for all the individual episodes. Mean applied force for all patients was 30.3 ± 8.2 kg and mean absolute compression depth 42 ± 8 mm.

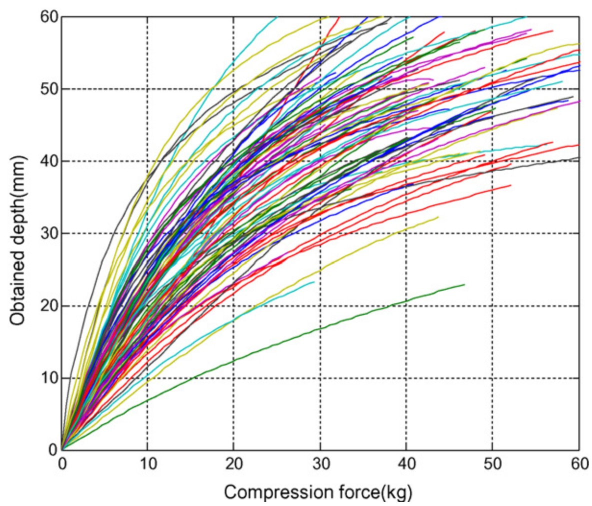

Figure 1 Compression force (kg) vs. absolute compression depth (mm) for all episodes.

For eight patients the recommended minimum compression depth of 38 mm was never reached (maximum force applied for these patients ranged from 14.7 to 37.4 kg) and for two patients a depth of 25 mm was never achieved (maximum force applied for these patients was 21.3 and 37.4 kg). For these patients F_{25} and F_{38} were estimated by extrapolation. Mean calculated F_{25} was 13.9 ± 6.6 kg and mean calculated F_{38} 27.5 ± 13.6 kg.

For 87 of 91 patients 38 mm compression depth was obtained with less than 50 kg. There was a significant trend that stiffer chests were compressed more forcefully than softer chests ($p < 0.001$), but softer chests were still compressed more deeply than stiffer chests ($p = 0.001$) as shown in Figures 2 and 3.

Average residual force during decompression was 1.7 ± 1.0 kg, corresponding to an average residual depth of 3 ± 2 mm. For all patients, the median (25, 75 percentile) percentage of compressions with a residual force above 3 kg was 6 (2, 19).

Both F_{38} and mean compression force were higher for males than for females: 29.8 ± 14.5 kg versus 22.5 ± 10.2 kg ($p < 0.02$) (Figure 4), and 32.0 ± 8.3 kg versus 27.0 ± 7.0 kg ($p < 0.01$), respectively. For 47 patients, the rescuer estimated the size of the patient's chest (small, medium or large). There were no significant differences in F_{25} or F_{38} between the three chest size groups.

There was no significant variation in F_{38} or compression depth with age, but a significant 1.5 kg mean reduction in applied force for each 10 years increase in age ($p < 0.05$, linear regression).

The average stiffness progressivity factor $\gamma = F_{38}/2F_{19}$ was 1.41 ± 0.25, significantly higher for females (1.52 ± 0.33) than males (1.35 ± 0.18)

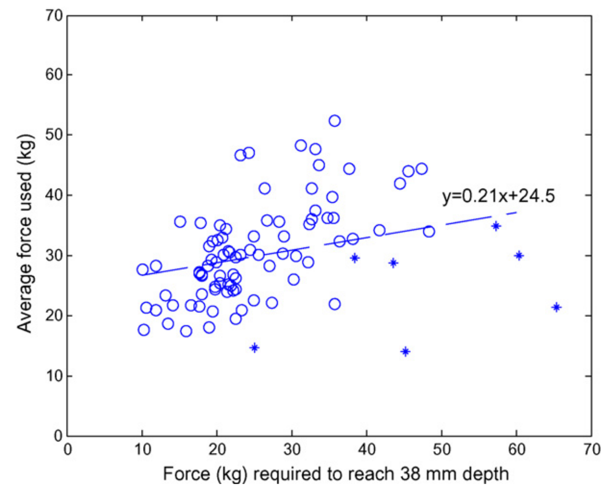

Figure 2 The relationship between average force (kg) used and force (kg) needed to reach 38 mm compression depth. Open circles represent measured values; stars extrapolated data. The dashed line represents the best linear fit to the data with extrapolated values included ($r = 0.35$, $p = 0.001$).

($p < 0.01$). There was a significant increase in γ with age ($p = 0.005$). This increase in progressivity with age is associated with non-significant trends towards decreased F_{19} and increased F_{38} with age.

There was a significant decrease ($p < 0.0001$) in the average value of F_{25} (chest stiffness) with increasing number of compressions performed (Figure 5). The decrease in stiffness was however not uniform across the patient group, with a significant decrease for only 13 of 39 patients. For 7

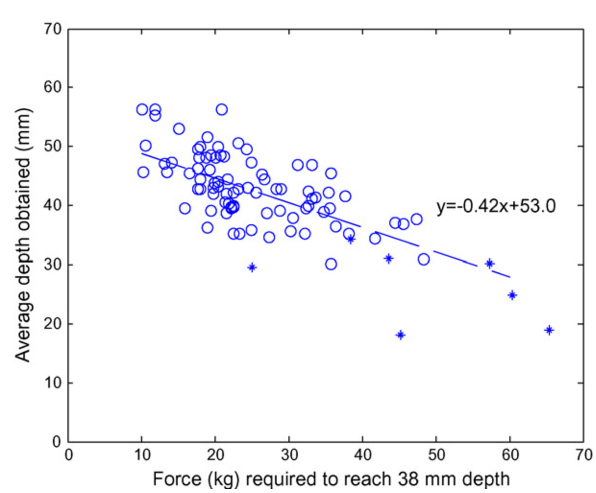

Figure 3 The relationship between average compression depth (mm) obtained and force (kg) needed to reach 38 mm compression depth. Open circles represent measured values; stars extrapolated data. The dashed line represents the best linear fit to the data with extrapolated values included ($r = -0.75$, $p < 0.0001$).

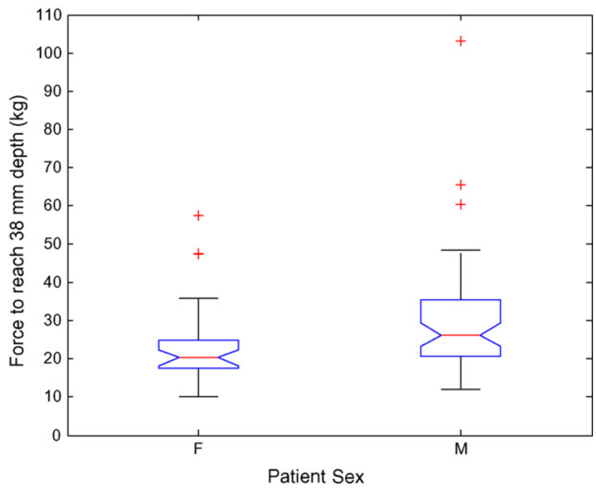

Figure 4 Box plots of the force needed to compress the chest 38 mm (minimum depth recommended in the guidelines) for females (F) and males (M).

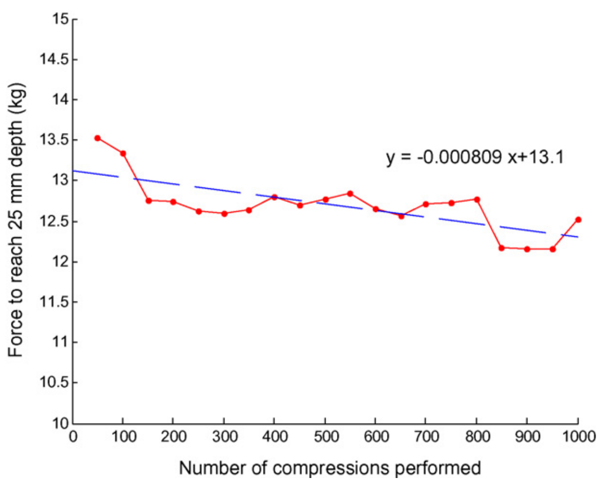

Figure 5 The average force needed to reach 25 mm compression depth (F_{25}) as a function of the number of chest compressions performed. The dashed line represents the best linear fit to the data ($r = -0.72$, $p < 0.001$).

patients stiffness increased during the 1000 compressions.

Discussion

For chest compressions to be efficient they must be executed with a force sufficient to produce adequate sternal displacement, and the present guidelines recommend 4—5 cm (38—51 mm ∼ 1.5—2 in.).[7,8] To date, there are only limited clinical data on the compression forces needed to achieve this compression depth in human cardiac arrest victims,[5,9—12] and thus there is a continuing debate concerning whether it is possible for even an average fit and sized adult rescuer to provide chest compressions with the force necessary to displace the sternum to an adequate depth.[11]

The present study provides comprehensive information concerning the elastic properties of the human chest during chest compressions and the forces needed to induce a given depth of sternal deflection in an actual cardiac arrest situation. The study contains three times as many patients as all previous published studies combined, all from Johns Hopkins with a total of 27 cardiac arrest patients[10,11] and one human volunteer.[18] The median age of 70 years old and sex distribution with two-third men among our study subjects should be representative for the average out-of-hospital cardiac arrests population.[14,19,20]

The mean 27.5 ± 13.6 kg force required for 38 mm compression depth in the present study tends to be lower than the mean 43.9 ± 4.0 kg (431 ± 40 N) reported by Gruben et al. in 16 cardiac arrest patients.[11] In their study 38 mm was not reached in 9 of the 16 patients whose values were calculated by extrapolation. Chest wall elasticity varied greatly between individuals in the present study with a range in force from 10 to 54 kg in patients where 38 mm depth was achieved. Gruben et al. also found a large range from 24.8 to estimated 81 kg (245 to estimated 800 N) for 38 mm, and estimated that >71.3 kg (>700 N) would have been required in 5 of the 16 patients. The authors were concerned that it would be difficult, let alone unrealistic, for the average rescuer to achieve even the minimum recommended 38 mm compression depth during CPR.[11] These reservations are still upheld in discussions concerning the possibility of delivering adequate chest compressions.[21] This was not a big problem in the present study where 38 mm would have been reached in 87 of 91 patients during manual out-of-hospital CPR with less than 50 kg force, although lightweight rescuers will probably not be able to compress all chests to guidelines level. More than half the patients were at some point compressed to the maximum recommended depth of 51 mm[8] in the present study, while this was not reached in any patient in Gruben et al.'s study.[11]

Our finding that there is a strong non-linear relationship between the force of compression and sternal displacement achieved, corroborate the observations from the Johns Hopkins group. In their three studies[10,11,18] the relationship between compression force and depth also behaved non-linearly. This is different from commonly used CPR training manikins which usually have spring loaded chests with a linear relationship between force and depth.[10,11,22] This means that the elastic force in manikins is higher than in humans at the onset of compression and lower at higher depths of compression. If it is important that CPR is performed to a certain depth as recommended in the guidelines, trainees should learn to assess the correct depth of compression. It is probably advantageous that they practise on manikins mimicking more closely the elastic properties of the human chest with a non-linear force—depth relationship during compressions, and while the mean compression force required in the present study fits relatively well with the chest stiffness in commonly used training manikins,[10,22] an adjustable stiffness is desirable to account for the great variation in human chest properties.

Although there was a difference between sexes in chest stiffness, the mean force needed for 38 mm compression in the current study was well below 40 kg for males with stiffer chests as well as for females. The ribs form the main elastic component and surround the internal organs that may cause damping. Women are generally more delicately built than men, and this may result in a more elastic ribcage and a softer chest. Given that soft chests were compressed more deeply than stiff chests in this study, one would also expect that females were compressed more deeply than males. The fact that this was not the case may partly be explained by the smaller size of women: the rescuer may feel that it is not appropriate to compress so deep on a small individual. In addition the progressivity factor was higher for females, the force required per mm increased more rapidly with depth for females, possibly due to their smaller size. On the other hand we could not find any relationship between different chest sizes and chest elasticity. This could relate to the rather simplistic procedure for estimating chest size, which was left to the subjective judgment of the rescuers. On the other hand, Tsitlik et al.[10] did a thorough registration of chest morphometric data in their study and came to the same conclusion.

One of the more intriguing findings in this study was that rescuers seemed to hold back force and accept compression depths below 38 mm when confronted with a stiff chest, while softer chests most commonly were compressed within guidelines limits, or even too deeply (>51 mm). It is tempting to speculate that rescuers control compressions by a combination of perceived adequate force and depth, and that the perception of adequate force is important for stopping further compression. This occurred despite the fact that rescuers were continuously given visual feedback and voice prompts to guide the depth of chest compressions and other CPR elements. Even most of the stiffer chests could be compressed 38 mm using forces <50 kg, but rescuers often seemed to avoid following the voice prompt for deeper compressions under these circumstances. On the other end of the spectrum rescuers frequently ignored voice prompts telling that compressions were too deep (>51 mm) on softer chests. It could be speculated that rescuers are afraid of rapidly tiring[23] or causing damage with high force on a stiff chest, while they feel that they are not brutal when compressing a soft chest deeply without much effort and are ''getting the circulation going''. In both cases they might choose to ignore the feedback. It is also possible that frequent training on manikins where a set ''average'' force is required to give 38—51 mm compressions, give them a feel of what is the ''correct'' force-independent on the force required on a specific patient.

We were also interested in how chest elasticity would change over time, or more precisely with the number of compressions performed. In experiments on healthy young pigs the chest configuration changes considerably during the initial phase of CPR.[24] We therefore chose to analyse this effect only in cardiac arrest episodes where bystander CPR had not been performed and where less than 1 min of unrecorded professional rescuer CPR had been carried out. The significant decrease in chest stiffness with time could be due to rib or sternal fractures which commonly occur during CPR.[25] As mentioned above, the rib cage represents the main elastic component of the chest. Broken ribs will most certainly influence the elastic properties of the chest.

An important limitation to our study is that chest compression depth as studied was calibrated for the presence of a firm compression surface. Although most out-of-hospital cardiac arrest patients receive CPR on the floor or ground, chest compression depth may be overestimated in some if the patient rests on a compressible underlay.

The patient stiffness may also be underestimated if some of the force is delivered outside the sternal pad area during compressions, but this is probably not very important as the pad is 25 mm thick, and our experience is that the force is concentrated much more than without a sternal pad.

Conclusion

In most out-of-hospital cardiac arrest victims adequate chest compression depth can be achieved by applying 50 kg force to the sternum. This means that average sized and fit rescuers should be capable of performing effective CPR in adult patients.

Conflict of interest statement

Authors Elizabeth Dorph, Ann-Elin Tomlinson and Jo Kramer-Johansen have no conflicts of interest to declare. Jon Nysaether is a full time employee on a fixed salary at Laerdal Medical, Stavanger. Petter Andreas Steen is a member of the board of directors for Laerdal Medical and The Norwegian Air Ambulance.

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