Electrophysiology of Muscle Fatigue in Cardiopulmonary Resuscitation on Manikin Model

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Cardiopulmonary resuscitation requires the provider to adopt positions that could be dangerous for his or her spine, specifically affecting the muscles and ligaments in the lumbar zone and the scapular spinal muscles. Increased fatigue caused by muscular activity during the resuscitation could produce a loss of quality and efficacy, resulting in compromising resuscitation. The aim of this study was to evaluate the maximum time a rescuer can perform uninterrupted chest compressions correctly without muscle fatigue. This pilot study was performed at Universidad Complutense de Madrid (Spain) with the population recruited following CONSORT 2010 guidelines. From the 25 volunteers, a total of 14 students were excluded because of kyphoscoliosis (4), lumbar muscle pain (1), anti-inflammatory treatment (3), or not reaching 80% of effective chest compressions during the test (6). Muscle activity at the high spinal and lumbar (L5) muscles was assessed using electromyography while students performed continuous chest compressions on a ResusciAnne manikin. The data from force exerted were analyzed according to side and muscle groups using Student's *t* test for paired samples. The influence of time, muscle group, and side was analyzed by multivariate analyses ($p \leq .05$). At 2 minutes, high spinal muscle activity (right: 50.82 ± 9.95; left: 57.27 ± 20.85 μV/ms) reached the highest values. Activity decreased at 5 and 15 minutes. At 2 minutes, L5 activity (right: 45.82 ± 9.09; left: 48.91 ± 10.02 μV/ms) reached the highest values. After 5 minutes and at 15 minutes, activity decreased. Fatigue occurred bilaterally and time was the most important factor. Fatigue began at 2 minutes. Rescuers exert muscular countervailing forces in order to maintain effective compressions. This imbalance of forces could determine the onset of poor posture, musculoskeletal pain, and long-term injuries in the rescuer.

Key Words: Cardiopulmonary resuscitation; Muscular fatigue; Electromyography; Lumbar muscles; High spinal muscles; Emergencies.

The performance of cardiopulmonary resuscitation (CPR) is a key factor in cardiac arrest survival. For effective implementation of this activity, steady arms and trunk flexion are required in repetitive compressions and decompressions. This position allows one to reach high strength at lumbar and high spinal levels, causing pain that can trigger fatigue and compromising the quality of CPR.[1–5]

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The current protocol approved by the American Heart Association, the European Resuscitation Council, and the International Liaison Committee on Resuscitation in 2015 describes a sequence of 30 compressions and 2 ventilations as an ideal method for the successful adult cardiac arrest technique.[6] Alternatively, CPR based exclusively on compressions (without ventilations) at a rate not less than 100 compressions per minute with a depth greater than or equal to 50 mm can be maintained and minimizes rest intervals.[7,8] This sequence allows for easier learning and involves wider dissemination of CPR skills in untrained persons.[9] However, there is controversy about establishing the time after which CPR loses effectiveness because of the rescuer's fatigue depending on the technique applied.[10,11]

Effectiveness of CPR and its impact on a rescuer's fatigue have been studied by exercise testing, spirometry, and metabolic rate analysis, showing that it is a moderate-intensity exercise that requires a certain level of physical training to maintain quality of the maneuvers and technical preparation to economize on energy consumption.[10–13] Garcia and Clemente[12] correlated the electrocardiographic pattern, muscular endurance, and Borg Scale of Perceived Exertion, concluding that there is a close relationship between subjective and objective assessment of muscular fatigue. Most studies record the depth and rate of compressions to study the activity of high spinal and lumbar muscles, associating lowering effectiveness of compressions with rescuers' muscle fatigue.[3,9–20] However, there are no studies that determine muscle fatigue during CPR techniques using electromyography while the technique is performed on the manikin.

Electromyography determines the fatigue associated with muscular work. This system has been used in different models that mimic performing CPR, as in the Biering-Sørensen test (a timed test to determine endurance of trunk extensor muscles).[21] Muscular work in electromyography is measured in microvolts, and its time to reach maximum values depends on the subject. It is considered that the normal muscle potential during activity is between 20 and 50 mV. Values above 450 mV are considered harmful for muscle.

There is an association between muscle fatigue electromyographically recorded and altered muscle fiber by biopsy.[22,23] The limited information about fatigue measured by electromyography during CPR has led us to initiate this study. It might open a new option for the assessment of muscle fatigue during CPR and lead to optimizing the rotation of the CPR team members in the extrahospital and intrahospital environments.

We aimed to evaluate by electromyography the onset of muscle fatigue after continuing chest compressions, following the 2015 recommendations of the American Heart Association, the European Resuscitation Council, and the International Liaison Committee on Resuscitation. A secondary objective was to determine the maximum time without muscle fatigue that a rescuer could maintain effective chest compressions without interruption.

METHODS

Ethical approval for this study (Ethical Committee No. 15/464-E) was provided by the Ethical Committee of Hospital Clínico San Carlos, Madrid, Spain. This study was performed in accordance with the provisions of the Declaration of Helsinki (World Medical Assembly).

Figure 1. Position of electrodes.

The CONSORT 2010 guideline was followed for population recruited. The volunteers were enrolled from February 2016 to April 2016. The criteria for inclusion in the study included those subjects aged 19 to 22 who had learned and practiced CPR during a 4-hour course. Exclusion criteria included any malformation, abnormality, or history of musculoskeletal and/or neurological disease; recent use of analgesics or anti-inflammatory drug treatment; and refusal to sign the informed consent. We also excluded subjects who did not reach an effective compression rate of 80% of the guideline.

We employed an electromyography recorder (Medelec-Mistro Plus, Surrey, England), with 5 independent channels, using 2 pairs of 10-mm spoon type electrodes at the high spinal–level and lumbar-level (L5) muscles on both sides according to the method of De Nooij et al,[23] about 3 cm from the midline, and a neutral reference electrode at the midline of the seventh cervical level (see Figure 1).[24] The muscles at L5 and high spinal levels are considered the most involved in CPR, and are therefore recorded.[6,21,26,27] The recording area was performed simultaneously with a lower filter of 3 Hz and an upper filter of 10 kHz, with an acquisition of 500 μV/500 ms, considering muscle activity during the time that the maneuvers were performed. The analysis time selected was 250 ms.

The maneuvers performed on the ResusciAnne Manikin were monitored to determine the percentage of effective chest compressions. An observer reported to the rescuer the depth and rate of the compressions performed, establishing a feedback system.

A previous recording of maximum muscle strength was obtained by a forced hyperextension of the lumbar and high spine muscle fibers. Then rescuers performed compressions on the dummy continuously for 15

Table 1. Sample Data of the 11 Included Volunteers*

Volunteer No.	*Age, y*	*Height, cm*	*Weight. kg*	*BMI, kg/m²*	*Hand*
1	20	167	54	19.36	Right
2	20	183	95	28.37	Right
3	20	170	75	25.95	Left
4	20	170	70	24.22	Right
5	22	173	72	24.06	Right
6	19	173	70	20.39	Right
7	20	170	76	26.30	Right
8	21	168	70	24.28	Right
9	22	169	55	19.26	Right
10	20	167	57	20.44	Right
11	22	169	60	21.01	Right
Mean	20.55 ± 1.04	170.82 ± 4.51	68.55 ± 11.90	23.11 ± 8.98	

* BMI indicates body mass index.

minutes. Values of muscle activity at baseline and at 2, 5, and 15 minutes were recorded.

Statistical analyses were performed using SPSS 22.0 for Windows (Statistical Package for Social Science, IBM, Chicago, Ill). The force exerted by the muscle groups (spinal and lumbar) for each side (right and left) of the different times was analyzed using the analysis of variance test for paired samples. Differences between paired samples were obtained by the Student's t test for both the muscle group factor and the side factor. Multivariate contrasts were used for studying the impact of time, muscle group, and side on the recorded muscle activity. Analyses were considered statistically significant at p values $\leq$.05. Muscle activity of each area was expressed in microvolts/milliseconds (µV/ms).

RESULTS

From the 25 volunteers recruited, a total of 14 participants were excluded from the sample because of kyphoscoliosis (4), prior lumbar muscle pain (1), anti-inflammatory treatment (3) or not reaching 80% of effective chest compressions during the test (6). The electromyography results from 11 volunteer students, aged between 19 and 22 years (mean age 20.55 ± 1.45 years), were analyzed. The sample included 7 men and 4 women, in a 10:1 right-handed to left-handed proportion. The body mass index of the study subjects was 23.11 ± 8.98 kg/m^2. The sample had a suitable body mass related to height and age for performing physical activities efficiently (Table 1).

The maximum values of area activity for high spinal muscles were 45.00 ± 11.38 µV/ms and 41.55 ± 14.00 µV/ms on the right and left sides respectively. At rest, before commencing resuscitation, there was a muscular silence activity of 8.91 ± 2.30 µV/ms and 7.73 ± 1.73 µV/ms on the right and left sides respectively. At 2 minutes, muscle activity reached 50.82 ± 9.95 and 57.27 ± 20.85 µV/ms, higher than the maximum values recorded for this muscle group. This activity decreased at 5 minutes to 41.55 ± 8.43 and 35.73 ± 6.90 µV/ms. Muscle activity decreased again at 15 minutes to 30.00 ± 11.59 and 28.64 ± 6.77 µV/ms (Table 2 and Figure 2).

The area activity of the lumbar muscles showed a maximum value of 43.00 ± 12.94 for the right side and 39.55 ± 11.77 µV/ms for the left side. The recordings of the right and left lumbar muscles obtained at rest were

Table 2. Muscular Force Exerted During CPR†

	Muscular Group			
	High Spinal		*Lumbar (L5)*	
Recording	*Right, µV/ms*	*Left, µV/ms*	*Right, µV/ms*	*Left, µV/ms*
Maximum	45.00 ± 11.38 (p = .001)*	41.55 ± 14.00 (p = .001)*	43.00 ± 12.94 (p = .001)*	39.55 ± 11.77 (p = .001)*
Rest	8.91 ± 2.30	7.73 ± 1.73	7.64 ± 3.53	8.30 ± 3.47
2 min	50.82 ± 9.95 (p = .001)*	57.27 ± 20.85 (p = .001)*	45.82 ± 9.09 (p = .001)*	48.91 ± 10.02 (p = .001)*
5 min	41.55 ± 8.43 (p = .002)*	35.73 ± 6.90 (p = .003)*	41.27 ± 8.28 (p = .001)*	39.45 ± 6.17 (p = .002)*
15 min	30.00 ± 11.59 (p = .004)*	28.64 ± 6.77 (p = .003)*	32.55 ± 11.23 (p = .003)*	31.00 ± 12.01 (p = .003)*

* Statistically significant, $p \leq .05$.

† Data recorded of area muscular activity of high spinal and fifth lumbar muscles on each side during CPR at rest; at 2, 5, and 15 minutes; and at maximum activity. CPR indicates cardiopulmonary resuscitation.

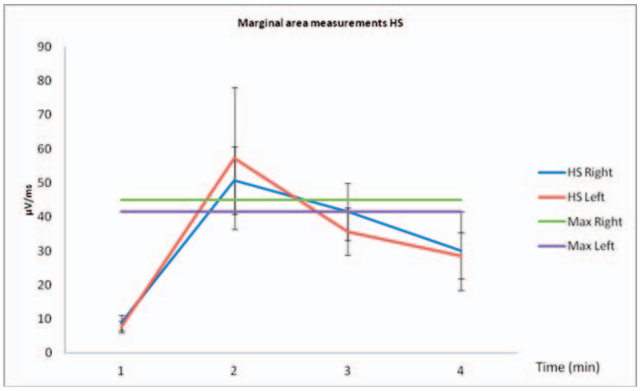

Figure 2. Muscular activity of high spinal muscles. The muscular activity at rest is near zero for both sides. At 2 minutes the muscular activity increases to 50–60 µV/ms but with a high standard deviation. At 5 minutes the activity decreases to below the maximum potential activity of high spinal muscles. At 15 minutes the muscular activity is about 30 µV/ms.

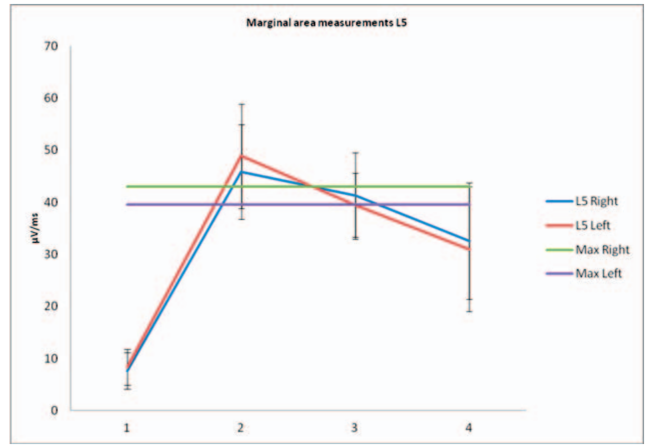

Figure 3. Muscular activity of fifth lumbar muscles. The muscular activity at rest is near zero for both sides. At 2 minutes the muscular activity increases to near 50 µV/ms. At 5 minutes the activity is about 40 µV/ms. At 15 minutes the muscular activity decreases to below the maximum potential activity of fifth lumbar.

7.64 ± 3.53 and 8.30 ± 3.47 µV/ms respectively. At 2 minutes, muscle activity reached values higher than maximum activity (45.82 ± 9.09 and 48.91 ± 10.02 µV/ms). After 5 minutes of maneuvers, the average activity of the lumbar musculature decreased to 41.27 ± 8.28 and 39.45 ± 6.17 µV/ms. After 15 minutes, the activity decreased to 32.55 ± 11.23 and 31.00 ± 12.01 µV/ms (Figure 3). Activity logged at 2, 5, and 15 minutes showed statistically significant differences among the same muscle groups at all time points and compared with the activity at rest ($p \leq .05$). No statistically significant differences were found in muscle activity between left and right in the lumbar spinal musculature.

The influence of time as a factor in muscle activity was demonstrated as muscular work improved significantly at 2 minutes. After 5 minutes, muscle activity was significantly increased compared with 15 minutes. No significant differences were observed between muscle groups (high spinal vs L5) or working sides (right vs left) in muscle activity althoug,h there was a significant effect of the interaction between muscular side and time at minute 2 and 5. This effect disappeared after 15 minutes (Figure 4).

DISCUSSION

The 2015 CPR protocol consisting of a sequence of 30 compressions and 2 ventilations has been an accepted method for the improving survival of adult cardiac arrest victims. However, the American Heart Association, the European Resuscitation Council, and the International Liaison Committee on Resuscitation emphasize the importance of compression quality for a successful resuscitation. Several researchers have concluded that a greater depth and/or higher frequency of chest compressions may contribute to the return of spontaneous circulation.[9,15,16,25,28] It has also been observed that during the first 2 minutes of resuscitation maneuvers without ventilation, adequate compressions increase by 29% and a greater number of total compressions is performed.[29]

There is no agreement on the percentage of compressions that determines appropriate performance of high-quality CPR. We consider, as do other authors,[1,3,4,25,30] that 80% of the recommended 100 compressions per minute is the performance that determines good-quality CPR. Several studies have been carried out with a technique to reach a greater number of compressions per minute, and they corroborate that these resuscitation protocols (without ventilation) are favorable.[10,13,31] However, there is concern over time with rescuer fatigue.

We have shown that there is a time-dependent muscle fatigue increase bilaterally in both high spinal and lumbar muscles. However, the results obtained showed that muscle fatigue affected all muscle groups after 2 minutes, considering time as the only significantly influential factor in rescuer fatigue.

Some authors determined the onset of fatigue after the first minute of CPR without ventilations, with a subsequent decreasing percentage of effective chest compressions from 93 to 67%.[3,32] However, the appearance of the rescuer's fatigue causes a decrease in the depth of compressions but not as much in their frequency.[19,33] Most authors consider 2 minutes the time the rescuer is able to maintain at least 80% of effective

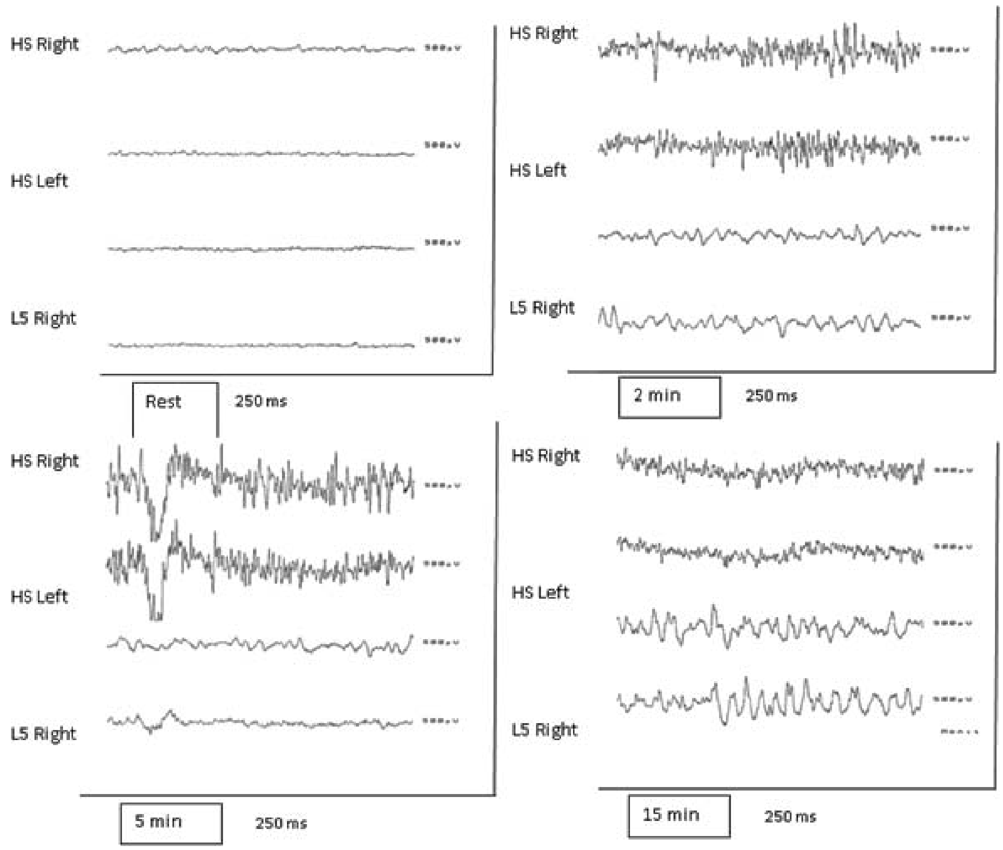

Figure 4. Electromyography recording at rest, 2 minutes, 5 minutes and 15 minutes. Sample of electromyography recording of 250 ms.

chest compressions.[1,3,17,18,28,30] In our study, the absence of muscular rest that involved ventilations showed that fatigue occurred earlier, as other authors have determined.[4,13,17,27] In our study, 24% of the rescuers were not able to complete the 80% of effective compressions for 15 minutes. This may have been due to insufficient experience in CPR maneuvers, inadequate physical fitness, or other factors. This failure rate is markedly higher than the 12% of rescuers who did not complete the maneuvers during the 9 minutes of CPR duration in one study.[30] According to these data, the physical condition of the rescuer may limit the effectiveness of CPR to 1–2 minutes.[28] However, we consider that given the great importance of compression, it is preferable to provide a greater number of compressions and change the rescuer if necessary to maintain the effectiveness of compressions.[15–17,25,28]

On the other hand, authors such as Miles,[34] Shultz,[35] and Bjørshol et al[11] claim that effective CPR can be maintained for 10 minutes. Bjørshol et al[36] found that fatigue during CPR is a rare problem and that there are wide individual differences between paramedics. They found a decline in the depth of compressions for only 26% of the rescuers, of which only 1 case occurred during the first 2 minutes of maneuvers. Moreover, they recorded a decrease in the rate of compressions for 32% of rescuers, with only 1 case in the first 5 minutes.[11]

Our study showed that fatigue affected all muscles after 2 minutes of CPR, more markedly on the left high spinal level, although the differences were not statistically significant. The increased load on the left side observed at 2 minutes was probably due to the fact that the exercise was done by a sample of mostly right-handed subjects and the lumbar musculature limited activity because of posture and resuscitation technique. However, differences based on muscle side are not significant, so it can be considered that the technique of resuscitation was properly performed. After 2 minutes, the decreased muscle activity was more evident on the left side than on the right, causing muscle imbalance.

Several studies establish that the kneeling-on-the-floor position of the rescuer results in a significantly higher average force measured in newtons (1169 ± 89 N) and next to the maximum one for each compression-decompression cycle, reaching greater depth despite being the position that most limits lumbar movements and in which musculature accumulates the greatest load.[1,27] This posture has proven to be the most favorable for patient survival, although less favorable for the rescuer.[1] Some authors have found through surveys that approximately 90% of nurses and 60% of ambulance staff present discomfort during or after CPR. Fully 21% of nurses and 23.8% of ambulance staff who gave positive reports had injuries at the lumbar level of musculature attributed to these maneuvers, although it is not known how many years they had been pursuing this activity. Among rescuers, 51.6% associated their back pain with the position taken during CPR, and 79.1% associated it with duration as the factor.[36] The results indicate that adopting compromised postures during periods exceeding 10 minutes can produce muscular injuries.[22,36]

Differences also exist among the subjects performing CPR that should be taken into account when analyzing the onset of fatigue. The decrease in the rate and depth of compressions may be due to many factors, such as the rescuer's maximum strength, age, sex, body mass index, or level of preparation and training.[13,26,28,37] Some studies show greater resistance to fatigue in females.[26,37] Others, by contrast, determine a greater resistance in men, resulting in deeper compressions for a longer time.[13,28] Although there is controversy about the influence of sex, the influence of rescuer's age and physical training on muscle fatigue seems to be more clear, with greater muscle fatigue in subjects older than 60 years old and untrained rescuers.[13,22,26,28,36] Most studies agree that a higher body mass index is associated with an earlier onset of fatigue in the rescuer.[22,26,28,36] However, there are a few studies that conclude that these individuals are more resistant to fatigue and make deeper compressions.[13] In our study rescuers had an average age of 20.55 ± 1.04 years and were predominantly male (ratio 1:0.7), and had an appropriate body mass index in line with their age.

Although our study does not assess the time required for recovery of the rescuer after the maneuvers or the effects caused by posture and activity duration, other studies have shown that rescuers recover completely within 3 days.[1] They also describe that the maintenance of these maneuvers for more than 10 minutes leads to difficulty doing usual activities, working normally, or walking for the next 24–48 hours after the exercise.[1] Our subjects did not report any difficulty in their usual activities.

The study presents some limitations. We omitted factors such as different consistency of the human thorax, preparation before the maneuvers, ambient noise, the sense of urgency, the plight of the victim, and the number of people watching the maneuvers, which results in anxiety for the rescuer. These factors could significantly affect the effectiveness of the compressions and the onset of fatigue in the rescuer. We also omitted factors that might influence the onset of fatigue that have not been clarified, such as sex and dominant hand of the subject. Furthermore, our study had no control group to perform resuscitation maneuvers following a 30:2 sequence, so we cannot determine the differences in the onset of muscle fatigue in this method. Finally, the sample of participants included in our study was limited in order to generalize the results; therefore, further studies are necessary to reach conclusions of greater significance.

In conclusion, fatigue of the spinal and lumbar musculature involved in CPR occurred after 2 minutes of activity. Time was the only influential factor. Although there are no differences in fatigue based on the side of muscles involved, there was an increase in activity in the nondominant side relative to pretreatment rest levels after 2 minutes of maneuvers in this mainly right-handed group. This would appear to indicate that high lumbar and spinal muscles of both sides worked synergistically, introducing imbalances due to accumulated fatigue. Muscle fatigue after 2 minutes of work affects the whole musculature, decreasing the force that it is capable of performing and hence producing discomfort. Current recommendations to change rescuers every 2 minutes are confirmed by this study. Further studies should be conducted with a larger sample, including a group of left-handed rescuers, in order to establish an international rotation formula for rescuers on teams. The decrease in rescuer fatigue will likely benefit victims of cardiac arrest, especially in those situations where CPR needs to be extended.

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