Optimising

basic skills in adult

cardiopulmonary resuscitation

Thesis for the degree PhD

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This thesis is dedicated
to the memory of my father
Kolbjørn Bjørshol
(1928-2009)

Table of contents

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Conrad Arnfinn Bjørshol

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2. Abbreviations

AED	automated external defibrillator
AHA	American Heart Association
ALS	advanced life support
BC	before Christ
BLS	basic life support
CCC	continuous chest compressions
CPR	cardiopulmonary resuscitation
CRM	crisis resource management
C:V ratio	compression:ventilation ratio
EMS	emergency medical services
ERC	European Resuscitation Council
ICD	implantable cardioverter defibrillator
ICU	intensive care unit
IHCA	in-hospital cardiac arrest
ILCOR	the International Liaison Committee on Resuscitation
IV	intravenous
MTM	mouth-to-mouth
NASA TLX	the National Aeronautics and Space Administration Task Load Index
NFR	no-flow ratio
NRC	Norwegian Resuscitation Council
OHCA	out-of-hospital cardiac arrest
PEA	pulseless electrical activity
ROC	Resuscitation Outcome Consortium
ROSC	return of spontaneous circulation
SAFER	Stavanger Acute Medicine Foundation for Education and Research
SUH	Stavanger University Hospital
VAS	visual analogue scale
VF	ventricular fibrillation
VT	ventricular tachycardia

3. List of papers

This thesis is based on the following papers.

Paper I

Bjørshol CA, Lindner TW, Søreide E, Moen L, Sunde K. Hospital employees improve basic life support skills and confidence with a personal resuscitation manikin and a 24-min video instruction. *Resuscitation* 2009;80:898-902.

Paper II

Bjørshol CA, Søreide E, Torsteinbø TH, Lexow K, Nilsen OB, Sunde K. Quality of chest compressions during 10 min of single-rescuer basic life support with different compression: ventilation ratios in a manikin model. *Resuscitation* 2008;77:95-100.

Paper III

Bjørshol CA, Myklebust H, Nilsen KL, Hoff T, Bjørkli C, Illguth E, Søreide E, Sunde K. Effect of socioemotional stress on the quality of cardiopulmonary resuscitation during advanced life support in a randomized manikin study. *Crit Care Med* 2011;39:300-4.

Paper IV

Bjørshol CA, Sunde K, Myklebust H, Assmus J, Søreide E. Decay in chest compression quality due to fatigue is rare during prolonged advanced life support in a manikin model. *Scand J Trauma Resusc Emerg Med* 2011;19:46.

Conrad Arnfinn Bjørshol

4. Introduction

"Anyone, anywhere, can now initiate cardiac resuscitative
procedures. All that is needed is two hands."
William Kouwenhoven, James Jude & Guy Knickerbocker, 1960.[1]

Sudden cardiac arrest is defined as "*cessation of cardiac mechanical activity, confirmed by the absence of a detectable pulse, unresponsiveness and apnoea (or agonal, gasping respirations)*".[2] The incidence of sudden out-of-hospital cardiac arrest (OHCA) varies between different regions of the world.[3] It is one of the leading causes of death in the Western World with an annual incidence of approximately 80 per 100,000 inhabitants[3] or 700,000 cases in Europe each year. The incidence in Norway is uncertain. There is no national cardiac arrest registry, and cardiac arrest is not an accepted cause of death in the national death registry. Calculations indicate that the annual number of OHCA is close to 2,500.[4]

Two thirds of cardiac arrests occur outside hospital, with slightly different aetiologies between out-of-hospital and in-hospital cardiac arrests (IHCA).[5] In OHCA, 70-80% are presumably caused by cardiac disease,[6,7] with myocardial infarction as the single most frequent direct cause.[8] Initial rhythms in cardiac arrest are asystole, ventricular fibrillation (VF), ventricular tachycardia (VT) and pulseless electrical activity (PEA), with some variations in frequency between OHCA and IHCA.[7,9,10]

Survival from cardiac arrest varies greatly between sites, from 2 to 25%,[11-13] depending on local infrastructure, quality of treatment and differences in inclusion criteria. This variation means that there is still a long way before we can reach the mission statement of the European Resuscitation Council (ERC) which is to "*preserve human life by making high quality resuscitation available to all.*"[14] To reach this goal, resuscitation quality needs to be substantially improved both when performed by lay people and professionals. This includes cardiopulmonary resuscitation (CPR) skills, here defined as chest compressions with or without ventilations.

4.1. History of CPR

Modern CPR consists of recognising the cardiac arrest, calling for help, initiating chest compressions and ventilations (for lay people mouth-to-mouth (MTM) ventilations).[15] With slight modifications, the concept of CPR has existed for slightly more than half a century, but before that various more or less successful lifesaving methods have been attempted for many centuries.

4.1.1. Ventilatory support

The earliest written sources of what can be considered as CPR efforts are from Egypt about 4000 years ago, when Isis restored her husband Osiris by "*breathing into his mouth*".[16] In the 11th and 12th centuries BC Hebrew midwives would revive infants with their own respiration when the child was thought to be dead. In the second Book of Kings the prophet Elisha (about 8th century BC) "*put his mouth upon his mouth … and the child opened his eyes.*" Paracelsus introduced equipment for artificial ventilation and tried in 1530 to revive an apnoeic patient by inserting a fireside bellows into the nostril.[17] With refinements, this remained the recommended method for resuscitating drowned victims until 1837. MTM ventilation of an adult was first described by Tossach in 1744, who rescued a pulseless victim of coal steam inhalation.[18] A Society for the Recovery of Drowned Victims was founded in Amsterdam in 1767, and MTM resuscitation was one of their initiatives. Similar societies followed shortly thereafter in Hamburg, London and St. Petersburg. In 1857 in London, external compression of the chest was used outside hospital to achieve some kind of artificial ventilation.[19] Endotracheal intubation (inserting a tube into the trachea to secure the airways and facilitate ventilation), described by several authors almost simultaneously by the end of the nineteenth century, was not used in resuscitation until the late 1960's. The Holger Nielsen method for artificial ventilation, compressing the chest and lifting the arms in the prone position, was developed in the 1930's and rapidly spread through Europe and to the United States. This was the preferred method for artificial ventilation until MTM took over in the late 1950's.[20] James Elam discovered that exhaled air could sustain arterial oxygen saturation in postoperative patients,[21] and Peter Safar and colleagues demonstrated the effectiveness of MTM and manual opening of the airways and the ineffectiveness of the Holger Nielsen method in 1958.[22]

4.1.2. Circulatory support

External chest compressions for circulatory support was first done by the English surgeon John Hill in 1868. Three patients with cardiac arrest during chloroform anaesthesia were given three forceful sternal compressions every 15 seconds followed by a rapid inspiration of inhaled ammonia (now known to be a vasoconstrictor). All three survived.[18] The next report of external chest compressions in a human was by Friedrich Maas in Goettingen, Germany, in 1892, when a 9-year old encountered chloroform-induced cardiac arrest during surgical correction of his hare-lip.[23,24] Maas performed chest compressions, which he described very precisely, and achieved spontaneous pulse after about 50 minutes. For unknown reasons, external chest compressions were then abandoned for a long time, but rediscovered by William Kouwenhoven, James Jude and Guy Knickerbocker in 1960. They reported that 14 out of 20 patients with cardiac arrest were discharged alive. They stated that "*anyone, anywhere, can now initiate cardiac resuscitative procedures. All that is needed is two hands.*"[1]

Open-chest cardiac massage was first described by Moritz Schiff in 1874,[18] and the first successful open-chest CPR was performed by Kristian Igelsrud in Tromsø in 1900.[24] It failed to become widely applied, but is used today during open chest surgery and in special circumstances.[24]

4.1.3. CPR

Until 1958, ventilatory and circulatory support were considered separate entities. In a symposium held in Ocean City, USA in September 1960, Peter Safar stated that the two techniques *"cannot be considered any longer as separate units, but as parts of a whole and complete approach to resuscitation"*.[18] The concept of modern CPR was born, combining steps A (head-tilt and jaw-thrust), B (positive pressure ventilation) and C (external cardiac compressions).[25] In 1976, Ivar Lund and Andreas Skulberg from Oslo described, for the first time, that CPR performed by lay people before ambulance arrival increases survival after cardiac arrest.[26] Since then, widespread CPR training has been recommended for both lay people and health care providers to improve survival after cardiac arrest.

4.1.4.   Defibrillation

Already in 1774 in London a successful defibrillation in a human was described. A child appeared dead after falling out of a window and was given electrical shocks to various parts of the body in vain, but some shocks to the thorax achieved a small pulsation, and the child soon thereafter began to breathe.[18] The following year, the Danish veterinarian Abildgaard conducted repeated shocks to hens with cardiac arrest demonstrating the efficacy of external defibrillation on a non-beating heart. In 1804, Aldini in Bologna, Italy, declared that artificial ventilation should be *"accompanied by the application of Galvanic power externally to the diaphragm and to the region of the heart."*[18] However, it took another fifty years before VF was described as an arrhythmia, and in 1899 Jean Louis Prevost and Frederic Battelli, Geneva, Switzerland, showed in dogs that it was possible to terminate VF with electricity.[18] In 1947, Claude Beck, Cleveland, USA, was the first to successfully shock a patient during surgery for pectus excavatum with electrode paddles placed directly on the heart. A young boy had not responded to 45 minutes of internal heart massage, but regained myocardial contractions after a series of electrical shocks and recovered well without signs of cardiac or neurological impairment.[27] Eight years later, Beck's defibrillator added 28 years of life to someone whose heart "*was too good to die*".[28] This quote has later been used for motivating people to learn and perform CPR and defibrillation.

The major limitation of defibrillators until the 1960's was their lack of portability. They needed alternate current from the mains and heavy transformers to step up the voltage to approximately 1.000 Volts that was necessary to defibrillate the heart. This problem was solved around 1960 when Bernard Lown, Boston, USA, switched from alternate to direct current in his defibrillators. Direct current also made battery operation possible,[29] and Pantridge reported successful use by a physician-manned ambulance for OHCA in 1967.[30] Today, anyone can perform defibrillation, and early defibrillation by lay rescuers or first responders improves survival after OHCA.[31-34]

4.2.   International CPR guidelines

Clinical guidelines are defined by the Institute of Medicine as "*systematically developed statements to assist practitioner and patient decisions about appropriate health care for specific clinical circumstances*".[35] In 1953, Karpovich listed 105 published methods for adults and 12 for infants to achieve artificial ventilation.[18] As a consequence, confusion and controversy existed. An international Symposium on Emergency Resuscitation – Rescue

Breathing and Closed Chest Cardiac Massage held in Stavanger in August 1961 made the first official recommendations for resuscitation.[36,37] The symposium proceedings helped spread the knowledge of CPR, which was formally endorsed by American Heart Association (AHA) in 1963.[18] Three years later the National Research Council of the National Academy of Sciences arranged a conference to establish standards for CPR.[18] Over 30 organisations were represented, and their recommendations were published in JAMA.[38] International awareness was further enhanced the following year when an International Symposium on Emergency Resuscitation was held in Oslo. AHA sponsored subsequent conferences in 1973 and 1979.[39,40] To address the challenge of variations in resuscitation technique, particularly internationally, AHA invited in 1985 resuscitation leaders from many countries to initiate an international collaboration,[41] and at the 1992 AHA conference more than 40% of the participants were from outside the USA.[42] The ERC had its first international conference in Brighton in 1992. At the end of the conference, the International Liaison Committee on Resuscitation (ILCOR) was founded and held its first meeting. ILCOR coordinate members of guideline-producing organisations worldwide and has become the authoritative voice on the consensus on science behind national and international guidelines on resuscitation.[43] For the 2005 International Consensus on CPR and ECC Science, 281 international experts were assigned to evaluate specific cardiac arrest-related questions,[44] resulting in 403 worksheets, all reviewed through a comprehensive scientific process. The last 2010 International Consensus Conference in Dallas involved 313 experts from 30 countries,[45] culminating in the 2010 ILCOR recommendations[45] and subsequent 2010 AHA[46] and ERC guidelines.[47]

Despite efforts to syncronise guidelines worldwide, partly due to political and economic reasons, slightly different guidelines are published in different parts of the world (e.g. from the ERC and AHA). For pedagogical and practical reasons, mainly due to arguments based on timing of drugs, the Norwegian Resuscitation Council (NRC) introduced a modified ALS algorithm that included three minute cycles instead of two.[48] The effect of this slight difference in guidelines have not been tested, but recent Norwegian studies with improved quality of ALS[49] and survival[7,12,50] would seem to indicate that this variation is at least not harmful.

4.3. Current CPR guidelines

4.3.1. Recognition of cardiac arrest

Early identification of cardiac arrest is essential as survival depends on early initiation of CPR and early defibrillation.[51,52] In the early phase of cardiac arrest defibrillation is especially important,[9,10,53,54] while the importance of CPR increases as time to shock increases.[55]

Traditionally, cardiac arrest was identified by the absence of a pulse. However, palpating for a pulse in a comatose patient is both time consuming and unreliable. Among 206 participants trying to identify a carotid pulse in patients undergoing coronary artery bypass surgery, either on or off cardiopulmonary bypass, thus without or with pulsatile blood flow, only 15% made a correct diagnosis within 10 seconds, and only one out of 59 identified pulselessness correctly within 10 seconds.[56] ERC therefore de-emphasised the pulse check in 1998, and stated that lay rescuers should "*look for signs of a circulation*" which included looking for movements as well as checking for a pulse.[57] In 2000 pulse checks were permanently removed from the guidelines for lay rescuers, who were trained to "*look, listen and feel for normal breathing, coughing or movement for no more than 10 seconds*".[58] This was simplified in the 2005 guidelines by recommending CPR if the patient did not respond and did not breathe normally.[59] Pulse checks were still recommended for health care providers who were "*experienced in clinical assessment*".[60]

4.3.2. Basic life support

Basic life support (BLS) consists of chest compressions with or without interposed MTM ventilations. For every minute without CPR, survival for witnessed VF decreases by 6-7%.[53] With CPR provided by bystanders, the decline is more gradual at 3-4% per minute.[54] Overall, the provision of bystander CPR increases survival by two to three times.[61]

Chest compressions

Chest compressions are performed to achieve vital organ perfusion.[62,63] While not sufficient to uphold normal conditions for the brain and heart, the coronary perfusion sustains an initial VF longer.[64-66] Their depth and rate must be optimised, and incomplete chest wall decompression (leaning) and too long pauses avoided.

Chest compressions have previously been recommended to be 38-51 mm (1.5-2.0 inches) deep,[59] although this has never been based on randomised trials. Recent studies have indicated increased shock success rate with increasing compression depth[67] as well as increased short-term survival.[68,69] As a consequence, the 2010 guidelines now recommend a compression depth of at least 50 mm.[15,70] There is currently insufficient evidence to recommend a specific upper limit on compression depth,[3] but too deep compressions might result in severe internal organ damage.[71]

Chest compression rates above 80 per minute are associated with increased return of spontaneous circulation (ROSC) rates, but without improved long-term survival.[72] Increasing chest compression rates improves cardiac output,[73,74] but too high compression rates will reduce the diastolic filling time and thereby reduce coronary perfusion.[74,75] As a consequence, current guidelines recommend compression rates of at least 100 per minute, but not exceeding 120 per minute.[15]

Leaning, which is frequent during CPR,[76] can cause continuous positive intrathoracic pressure with reduced venous return to the heart and should be avoided,[77] but its impact on survival in humans is not determined. Finally, the no-flow ratio (NFR), defined as the time fraction without chest compressions divided by the total time of the resuscitation attempt, should be as low as possible.[15] This still remains a huge challenge for CPR providers.[78,79]

Ventilations

Evidence from drowning victims and patients undergoing general anaesthesia have shown that the head tilt-chin lift manoeuvre is feasible, safe and effective in opening the airways.[3] MTM ventilation is now the preferred method for artificial ventilation for BLS, and can be supported by protective devices such as a face shield or a pocket mask. Tidal volumes as low as 400-600 ml are sufficient to maintain adequate oxygenation and carbon dioxide elimination.[80] Current guidelines recommend blowing steadily into the mouth while watching the chest to rise, taking about one second as in normal breathing.[15] Several studies, however, indicate that ventilations take longer time, thereby increasing the NFR.[81,82]

In recent years, continuous chest compressions (CCC) without ventilations have been suggested as an alternative to BLS, especially for adult cardiac arrest patients of presumed cardiac origin.[83,84] The difficulty in learning MTM ventilations could be an argument for teaching CCC to lay people. There is still a huge controversy regarding this topic,[85,86] and especially in all kinds of asphyctical cardiac arrests, ventilations are essential.[87,88] The ERC

still recommend BLS with MTM ventilations to be taught to all citizens.[89] Since the present studies were based on 2000 and 2005 guidelines, I have omitted any further discussion of this topic.

Compression:ventilation ratio

There is insufficient evidence to conclude which compression:ventilation (C:V) ratio is optimal in adult CPR.[90] No randomised clinical studies have compared survival for different C:V ratios. For two-rescuer BLS performed by health care professionals, a C:V ratio of 5:1 was recommended until 1992,[91] when 15:2 was recommended for adult BLS.[92] In the 2005 guidelines it was replaced by 30:2.[59,93] The main reason for this change was observational studies in humans showing that CPR providers gave fewer compressions than recommended.[72,94,95] It has also been shown in swine that the 30:2 ratio gave sufficient oxygenation,[96] and theoretical analysis suggested that 30:2 would provide the best blood flow and oxygen delivery.[97] This change should lead to a greater number of chest compressions being performed each minute, and it has been suggested that this is one reason for increased survival after 2005 guidelines implementation in some sites.[98-101] Noteworthy, not all sites have shown improved survival after implementing the 2005 guidelines.[49,102,103]

4.3.3.   Defibrillation

Traditionally, BLS refers to maintaining airway patency and supporting breathing and circulation, without the use of equipment other than protective devices.[2] Defibrillation was previously a task reserved for doctors and specially trained health care providers, and defibrillators were not readily available. With the development of small, portable, automated external defibrillators (AED's) of relatively low cost and long battery life, defibrillation is available far outside the hospital environment and considered integrated in BLS.[93] The ability to deliver early defibrillation is one of the most important factors in determining survival from cardiac arrest, and the probability for successful defibrillation and subsequent survival to hospital discharge declines rapidly with time.[53,54] Trained first responders or volunteers with AED access have yielded improved survival rates,[32,33,104-106] also for IHCA[9] although results are conflicting.[107]

Until 2005, stacks of up to three consecutive shocks were recommended in cases of sustained VF.[108] If this was done every minute, with considerable time without compressions required for rhythm analysis, charging and defibrillation, it could partly explain NFR that approached 50% even for professional rescuers.[95,109] This was therefore changed in the 2005 guidelines process, and since then a one-shock algorithm was recommended.[59] It appears that minimising the NFR immediately before and after a shock increases the likelihood for successful resuscitation.[67,110-114]

4.3.4. Advanced life support

Early recognition of cardiac arrest, good quality BLS and defibrillation are the the most important elements for successful outcome after cardiac arrest. When sufficient trained personnel and equipment are present, ALS allows for additional tasks to be performed, although to date, none have been proven in randomised controlled studies to improve long-term patient outcome. These consist of:

- *Securing the airways:* Traditionally, the airways have been secured by endotracheal intubation. This procedure requires skilled personnel, and the pause in chest compressions during the passage of the tube between the vocal cords should not exceed 10 seconds.[60] An endotracheal tube allows for continuous chest compressions without pauses during ventilations, thereby reducing NFR.[79] Moreover, it will protect against aspiration if regurgitation occurs. Advanced airways have been shown to increase ROSC rate and intensive care unit (ICU) admission,[115] but so far no studies have shown that intubation increases survival. For personnel not trained in endotracheal intubation there are numerous alternative supraglottic devices, but good survival studies are lacking.

- *Medication:* Controversy still exists regarding the administration of intravenous (IV) drugs during CPR. Adrenaline is most frequently used and still recommended in the guidelines.[60] In a recent randomised study from Oslo, IV access and administration of drugs according to guidelines (adrenaline, atropine, amiodarone) showed improved rate of ROSC without significant difference in survival to discharge or 1-year survival versus no IV access or drugs.[116] A post hoc analysis of the same dataset showed that actually receiving adrenaline was associated with increased short-term survival but decreased survival to hospital discharge and unfavourable neurological outcome.[117] A recent randomised Australian study, comparing IV adrenaline with placebo, showed a similar increase in ROSC but no significant difference in survival to discharge. Amiodarone might be considered for

refractory or recurrent VF/VT cardiac arrests,[60] however, again with no data showing improved long-term survival.[118] No other drugs have been shown to increase survival and are therefore not recommended for routine use during ALS.[119] It would appear that more studies on vasopressors and drugs in general are needed. If IV access is difficult, intraosseous administration of drugs is an alternative[120] and easy to perform.[121] The latest ERC guidelines conclude: "*…although drugs and advanced airways are still included among ALS interventions, they are of secondary importance to early defibrillation and high-quality, uninterrupted chest compressions.*"[47]

- *Post-resuscitation care:* The complex pathophysiological process that follows whole-body ischemia is called the post cardiac arrest syndrome.[122] This has to be taken into account in patients following ROSC, and treatment includes controlled ventilation without hyperventilation, sedation (if indicated), control of seizures, coronary angiography and percutaneous coronary intervention, targeting mean arterial blood pressure, correcting electrolyte disturbances, avoiding hypo- and hyper-glycaemia, avoiding hyperthermia and inducing mild therapeutic hypothermia.[60] Some report significantly improved outcome after implementing standardised treatment protocols in before and after studies,[7,8,123] and post-resuscitation care has in recent years gained much more attention.[124] Except for therapeutic hypothermia in some patients, the effects of the different treatment modalities have not been thoroughly investigated.

4.4.   CPR training

With the available knowledge about CPR, optimal training for both lay people and professionals is important for achieving the necessary skills to save patients with cardiac arrest. Training should be tailored to the needs of different types of learners and learning styles to ensure acquisition and retention of resuscitation knowledge and skills.[125] The willingness to perform CPR is generally high among trained CPR providers,[126] and training increases the chances of performing CPR.[127]

Norway has a long tradition for first aid training, obligatory in schools since 1929.[128] In 1960, a teaching strategy was developed at a conference arranged by the Norwegian Society for Anaesthesiology to make Norwegians into lifesavers, especially children and youngsters. Equipment for training was needed, and a cooperation between Åsmund Lærdal and Bjørn Lind in Stavanger and Peter Safar in USA resulted in a resuscitation manikin in 1960. Within a short period of time, 6.900 school children were trained in artificial ventilation,[36] and after

two hours of training, 70% of the pupils were able to perform MTM ventilations satisfactorily. Mass media were recruited to inform about this new technique.[128] In 1967, a conference in Oslo concluded that external chest compressions could be taught to all health care workers as well as selected groups of lay people.

Resuscitation manikins have been an essential element of CPR training for half a century. They have been modified over the years to allow defibrillation and advanced life support (ALS) measures like intubation and intravenous (IV) cannulation. Traditional manikins have normally been used as part of instructor-led courses with initial theoretical lectures followed by practical manikin training. During the last decade alternative learning methods have been developed aimed at increasing training efficiency. These include peer instruction,[129-131] computer-based learning programs,[132] voice-advisory manikins,[133,134] personal resuscitation manikins with self-instruction video[135,136] and simulation.[137]

In-hospital CPR training is also very important, as cardiac arrest is a frightening and challenging event for hospital employees at all levels. IHCA occurs in about 1.3 of 1,000 hospital admissions,[138] and the majority of hospital employees feel that CPR training is insufficient.[139] CPR training for health care workers requires some key components to be successful; teaching the correct skills to the correct people, change in performance should be measurable, retraining intervals need to balance skills decay, it must be affordable and the employees must be empowered to deploy their skills.[140] So far, however, few studies have shown improved survival for IHCA as a result of in-hospital BLS training.[141]

4.4.1. Stress

"*Stress*" is defined as "*pressure or worry caused by the problems in somebody's life*".[142] The prefix "*socio*" means "*connected with society or the study of society*", and "*emotional*" means "*connected with people's feelings*".[142]

It is known that pilots commit more errors during high workload.[143] Mental fatigue impairs human physical performance[144] and it has been suggested that the arousal response when called to a cardiac arrest may negatively affect performance.[145] The excessive ventilation frequency often seen in adult[146] and paediatric[147,148] patients undergoing ALS, with potential detrimental effects[149] might be an example of this. Further, many health care workers believe that family presence will distract the resuscitation team during CPR,[150] and a study among emergency medical residents showed that the presence of a family witness had a

significant impact on physicians' ability to perform critical actions during simulated resuscitations.[151]

   High fidelity simulation may elicit a significant stress response[152] and even reveal haemodynamic effects.[153] It has therefore been suggested that stress management should be included in ALS courses.[154]

4.4.2.   Chest compression decay

"*Fatigue*" is defined as "*a feeling of being extremely tired, usually because of hard work or exercise*".[142] "*Decay*" is defined as "*the process or result of being destroyed by natural causes or by not being cared for*".[142]

   Performing chest compressions requires moderately hard work.[155] In 1995, Hightower et al. described that the percentage of correct chest compressions declined from 93% during minute 1 to 18% in minute 5 during five minutes of CPR.[156] As no study subject indicated fatigue, they concluded that medical providers couldn't perceive the onset of compression impairment from fatigue and recommended frequent rotation of personnel providing chest compressions. Ochoa et al. confirmed their findings in 1998 and stated that rescuer fatigue occurs before 60 seconds of chest compressions.[157] Some later manikin studies confirmed their results and demonstrated that a decrease in chest compression depth occurred during the first few minutes of CPR.[158-161] Similar findings were seen in clinical studies,[162,163] including an increase in NFR.[164] As a consequence, rescuer fatigue has been recognised as a problem during CPR,[165] and guidelines still recommend CPR providers to change roles every two minutes if there is more than one rescuer present.[15,60,166,167] Therefore, provider switches for the person providing chest compressions are now taught on BLS and ALS courses and refresher training worldwide, both for lay rescuers, first responders and health care professionals. However, frequent provider switches might also lead to substantial pauses during resuscitation,[168] and a switch is therefore not always beneficial. Moreover, the quality of some of these studies, however, is questionable – they all study groups of CPR providers, many are of a very short duration, and the clinical studies do not take into account when provider switches occurred. Therefore, more studies are needed to evaluate the degree of chest compression decay or fatigue in CPR providers to optimise individual resuscitation attempts.
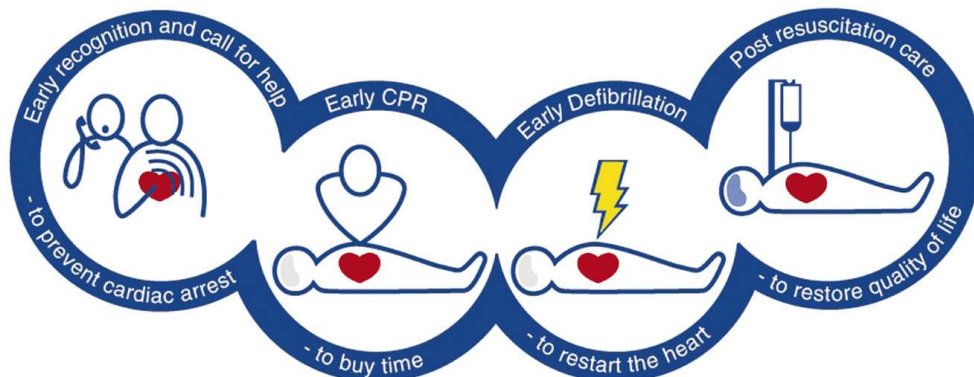
4.5.   The Chain of Survival

Figure 1. The Chain of Survival. Reprinted with permission.

To save a cardiac arrest victim without major sequelae, several vital measures have to be undertaken within a certain time limit, and include early recognition and call for help, early good quality CPR, early defibrillation and early, good standardised post-resuscitation care. These vital steps for survival are called the Chain of Survival (figure 1) and were first introduced in 1991.[169] This concept was revised in 2005 to highlight the importance of early call for help and good quality post-resuscitation care.[170] Strengthening all links in the Chain of Survival can increase survival from cardiac arrest,[7,171,172] but then they have to be identified and challenged within the local systems.

It is well known that adherence to CPR guidelines is suboptimal. This has been shown for lay people,[64,173] first responders,[78] health care students,[174] health care and rescue workers,[175] and for health care professionals performing ALS.[94,95,176-178] The development of good clinical guidelines does not ensure their use in practice,[179] and implementation of changes takes time.[180] Therefore, one should look at improving the performance of skills rather than concentrating solely on the content of the guidelines.[177]

It has been suggested that patient outcome is a product of medical science, educational efficiency and local organisation.[181] This has been called the Formula of Survival (figure 2).[182]

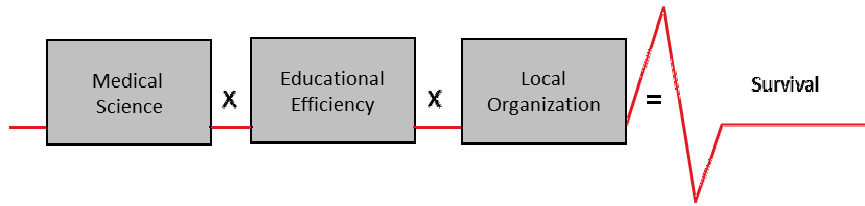**Figure 2.** The Formula of Survival. Reprinted with permission.

If, for instance, guidelines are only 70% of ideal, educational efficiency 70% and local organisation 50%, than the patient outcome would only be 0.7 x 0.7 x 0.5 = 25% of the best possible outcome. Although this is only a speculation, it does give an idea of the potential when all three factors in the Formula of Survival are optimised.

5.   Aims of the thesis

The aim of this thesis is to challenge some aspects of established practice and current guidelines in CPR with the overall goal of improving training and performance of future basic CPR skills.

The thesis consists of four manikin studies, all addressing different aspects of the second link in the Chain of Survival - CPR. They all challenge parts of current CPR guidelines and resuscitation practice with special focus on the CPR providers. Paper I examines the efficiency of an in-hospital CPR training campaign. Paper II studies the quality of CPR over time with different C:V ratios. Paper III examines the effect of socioemotional stress on the quality of CPR during ALS, and paper IV studies the effect of chest compression decay during prolonged ALS.

5.1.   Paper I

The hypothesis to be tested was that a BLS training concept consisting of a personal resuscitation manikin and a self-instruction video distributed and shown at the hospital, would improve hospital employees' self-reported confidence and practical BLS skills.

5.2.   Paper II

The hypothesis to be tested was that chest compression depth and rate would decline during 10 minutes of BLS within each of three different C:V ratios (15:2, 30:2 and 50:2).

5.3.   Paper III

The hypothesis was that exposure for socioemotional stress would impair the performance of CPR and ALS among professional ALS providers in a simulated cardiac arrest manikin study.

5.4.   Paper IV

The hypothesis to be tested was that chest compression decay would vary substantially between individual rescuers during a prolonged period of ALS in a manikin study. We

focused specifically on the initial chest compression depth and if and when a decay in the chest compression depth or rate occurred.

6. Materials and methods

6.1.   Paper I

6.1.1.   In-hospital BLS training campaign

In November and December 2006, all hospital employees at Stavanger University Hospital (SUH) were offered and encouraged to participate in an in-hospital BLS training campaign. The campaign was widely advertised through posters and the in-hospital intranet, and was organised by 11 employees.

Each SUH employee was offered a personal package containing an inflatable resuscitation manikin (MiniAnne, Laerdal Medical, Stavanger, Norway) and a 24-minute instruction video on DVD. The employees were given three options to complete the training:

· *In a hospital meeting room:* The video was shown on a large screen following an advertised time schedule, with space for 50 employees to practice on the floor with their personal manikin and no BLS instructors available.

· *In their own department:* either alone or together with one or a few colleagues.

· *At home.*

They were further encouraged to train family members and friends with their personal manikin and video.

6.1.2.   Self-reported BLS skills and training experience

Before the distribution of the personal packages, each employee was asked to complete a questionnaire (appendix 1) about their age, gender, experience in CPR and self-judged BLS skills.

Approximately nine months after the initial training, a second questionnaire (appendix 2) was distributed to all hospital employees by mail. In this questionnaire we asked about their training experience with the campaign, their current self-judged BLS skills and how many people, in addition to themselves, that had received BLS training with their manikin package.

6.1.3.   Practical BLS skills

To evaluate the quality of practical BLS skills in a practical test before and after the training campaign, 62 hospital employees were randomly chosen from a list of employees from

different departments. All professions were considered for inclusion in the study, except personnel working at critical care and emergency areas.

Without any preparation, and before participation in the training programme, the study participants were presented for a simulated cardiac arrest scenario on a manikin. They were told that they had just found an apparently unconscious 50-year old woman (simulated by a MiniAnne manikin) on the floor, and asked to do the necessary tasks. This manikin was modified and contained a specially designed counting device (figure 3)[183] which counted the number of correct chest compressions and MTM ventilations during the first two minutes of BLS. The counting device was covered and thereby invisible during the test.

Figure 3. The MiniAnne counting device. The number of correct chest compressions (top) and mouth-to-mouth ventilations (bottom) during the first two minutes of BLS.

In addition, the following tasks were recorded manually: assessment of responsiveness, opening of the airways before assessing respiration, assessment of respiration, whether they performed a pulse check, calling for help before initiation of BLS, correct telephone number (1-1-3[*]) for activating the emergency medical services (EMS) and correct compression:ventilation ratio (30:2).

Approximately six months after the initial test, a new identical test was performed using the same study subjects. There was no information beforehand and no possibility for the employees to prepare for this test.

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[*] This number (1-1-3) is different from the telephone number used to activate the in-hospital cardiac arrest team (8-8-8-8).

6.2.   Paper II

6.2.1.   Study subjects

Paramedics from the SUH EMS were invited to participate in the study. They were all well trained in the 2000 BLS and ALS guidelines,[58,108] and should thereby represented the optimally trained rescuer. Paramedics were recruited according to availability in cooperation with the EMS dispatch centre. The study was conducted during the autumn of 2005, before the 2005 guidelines were published,[59,184] and the paramedics were not informed about the upcoming guideline changes.

6.2.2.   Study design

A Resusci Anne Simulator connected to a laptop with PC Skillreporting System (Laerdal Medical, Stavanger, Norway) was used. The computer screen was not visible for the participants and no feedback was given during the study. The paramedics performed, in random order, single-rescuer BLS with C:V ratios 15:2, 30:2 and 50:2 for 10 minutes each. Inbetween the scenarios they rested for a minimum of 25 minutes. No additional equipment was used.

6.2.3.   Measurements

The number of chest compressions, mean compression depth, mean compression rate, NFR and number of MTM ventilations for each 2-minute period during 10 minutes of BLS were recorded. Due to software failure we did not record ventilation volume, only the number of ventilations. Chest compression quality measures (number of compressions, compression depth and compression rate) for each 2-minute period was compared with the first 2-minute period to enable measurement of the degree of chest compression decay over time.

6.3.   Paper III and IV

Paramedics from the SUH EMS participated twice (in random order) in this manikin cardiac arrest study performed under two different conditions; one with and one without exposure to socioemotional stress. Paper III examines the quality of CPR under these two different

conditions, whereas paper IV examines the quality of chest compressions over time in the scenario with exposure for socioemotional stress.

6.3.1.   Study subjects

Paramedics on duty at SUH participated in this study. They are ALS certified annually, and at the time of the study they were trained to follow the Norwegian 2005 guidelines,[48] which are slightly modified from the ERC 2005 guidelines.[184] Each paramedic team consisted of two paramedics, and their specific tasks in the study were randomised. One managed the airway (ventilation and endotracheal intubation), whereas the other performed all chest compressions. They were not allowed to change tasks. They were supported by a third paramedic (from the research team) to allow ALS provision, since our EMS does not allow ALS when only two paramedics are present. The third paramedic was allowed to communicate with the dispatch centre, insert an IV line, start IV fluids and give medication, but only at the discretion of the other two paramedics. He was not allowed to perform any ventilations or chest compressions.

6.3.2.   Study design

The study was conducted at the Stavanger Acute Medicine Foundation for Education and Research (SAFER) centre. We used a small flat in the simulation centre equipped to simulate a living environment with furniture, a carpet on the floor, a television, an adjacent kitchen and a separate entrance with door bell and post box. The manikin was located on the floor in the living room.

A Skillmeter Resusci Anne (Laerdal Medical, Stavanger, Norway), located on the living room floor, was used to simulate the patient. This manikin cannot record the ventilation rate correctly when chest compressions and ventilations are delivered simultaneously. The manikin was therefore modified by adding an additional lung attached in parallel with the original lung allowing accurate measurement of ventilation rate (but not of exact ventilation volume).

Immediately before inclusion the paramedics were informed that the aim of the present study was to examine emergency medical treatment under different conditions. No further details were given. The paramedic teams performed ALS twice in random order under two different conditions with 20-minute rest between; one with and one without exposure to socioemotional stress. They were not aware of the differences or similarities between these

two conditions, and were assigned the same tasks in both conditions. The same paramedic performed chest compressions in both conditions.

At the start of each scenario the paramedics received the following instruction: *"You have been called to a flat where an adult woman has been found unconscious on the floor, not breathing normally, presumably having a cardiac arrest. You will provide ALS treatment according to Norwegian guidelines including early endotracheal intubation, defibrillation, intravenous cannulation and medication."* The initial cardiac rhythm was VF, changed after the first shock to PEA in both scenarios and remained in that condition throughout the resuscitation attempt without achieving ROSC. Each scenario was discontinued 10 minutes after confirmation of endotracheal tube placement.

The two different conditions

Without socioemotional stress (control condition)[†]

In the setting without exposure for socioemotional stress, only the manikin was present in the room. The paramedics could perform ALS in a quiet environment without any interference from other persons.

With exposure for socioemotional stress (stress condition)

In the setting with socioemotional stress the paramedics were exposed for continuous stimuli;
· The television was turned on, a family portrait and toys were present in the room.
· A bystander was present upon the paramedics' arrival (acted by two different persons according to availability).
· The bystander acted like he was in psychological distress and performed BLS upon their arrival but was unable to continue due to back pain.
· He said he was a close friend of the patient and that he was a physician from the United Kingdom.
· He could only speak English, so the paramedics had to talk with him in what for them was a foreign language.

[†] A video sample of the control condition can be viewed at http://links.lww.com/ccm/a192, and of the stress condition at http://links.lww.com/ccm/a193.

· He further informed them that the patient was a 35-year-old woman with two young children soon arriving home from school.

· He also stated that the patient had the Romano-Ward syndrome, a congenital long QT syndrome susceptible to cardiac arrest, and asked the paramedics if they were familiar with this syndrome.

· He further claimed that she had an implantable cardioverter defibrillator (ICD), that she used metoprolol, and that the acute condition had started with breathing difficulties.

· During ALS performance he insisted that the paramedics should follow the guidelines, but he was obviously just aware of the very different ERC 2000 guidelines[108] and insisted on giving three shocks instead of one and on performing one minute of CPR between shocks instead of three.

· He further recommended both a precordial thumb several minutes into the scenario, and that the paramedics should administer amiodarone despite PEA (not according to ERC 2000 guidelines).

· He also asked them to consult a Norwegian physician.

· When the interest in his suggestions declined he shook their shoulder to grab their attention and distract them from their work.

· He made it utterly clear that he was unsatisfied with their treatment and that the patient would likely die if they didn't improve their performance.

· He also consulted a cardiologist from London on his cell phone, who repeatedly called him back, revealing a loud and unpleasant ring tone.

6.3.3. Measurements

All measurements were made during both conditions, except chest compression decay that was only measured during the stress condition (to obtain independent observations).

The quality of CPR (chest compression depth and rate, ventilation rate, time to first shock) was recorded by PC Skillreporting System (Laerdal Medical) and converted to QCPR Review version 2.1.0 (Laerdal Medical) for analysis. Time to intubation and IV access was measured using video recordings. The time to first shock was recorded by the manikin, and time of intubation was defined as the time point when the endotracheal tube cuff was inflated. The time of IV access was defined as the time point when the stylet from the IV cannula was removed. These time intervals were all calculated from the start of the scenario (when the paramedics performed the first chest compression or ventilation).

Chest compression quality

Compression depth was measured for each compression. Compression rate was measured only during the performance of chest compressions, i.e. pauses in chest compressions exceeding one second were excluded from this analysis. No-flow-ratio (NFR) was calculated as the time fraction without chest compressions divided by the time of the total ALS scenario. Pauses in chest compressions were measured if their durations were more than one second.

   To measure the degree of chest compression decay, we calculated average chest compression depth for each of the first twelve minutes for each individual chest compression provider in the stress condition. Based on the CPR quality over time, the resuscitation attempts were divided into three:

· *Good:* CPR with average chest compression depth ≥40 mm for every minute during the 12 minute resuscitation attempt. Average chest compression rate 100-120 for every minute.

· *Bad:* CPR with initial average chest compression depth <40 mm. Chest compression rate <100 or >120 per minute at the start of the resuscitation attempt.

· *Decay:* CPR with initial average chest compressions depths ≥40 mm which dropped below 40 mm. Chest compression rates 100-120 per minute that decreased to <100 or increased to >120 per minute.

Level of stress

To measure the paramedics' perception of workload and performance, we asked each of them to answer six questions using a visual analogue scale (VAS) from 0 to 100. We used the National Aeronautics and Space Administration Task Load Index (NASA TLX) for this survey (appendix 3)[185] immediately following each resuscitation attempt.

6.4.   Statistical analyses

Statistical analyses were performed with SPSS version 14 (paper I and II) and 17 (paper III and IV) (Chicago, IL, USA). A significance level of 0.05 was used unless otherwise stated.

6.4.1.   Paper I

The questionnaire responses concerning self-judged BLS skills were compared using Student's t test. In the manikin study, the number of correct chest compressions and MTM ventilations were compared with Wilcoxon Signed Rank test since the data were not normally distributed. The other actions performed were compared using McNemar test. Results are reported as mean ± standard deviation when normally distributed, otherwise as median with interquartile range.

6.4.2.   Paper II

Data were presented as mean ± standard deviation due to the normal distribution. Ratios were compared with repeated measures ANOVA. Fatigue and chest compression variables from each 2-minute period were compared with the first 2-minute period for all three ratios using repeated measures ANOVA.

6.4.3.   Paper III

Based on paper II, we estimated that, with power of 80% and P=0.05, 18 paramedic teams were needed. The normally distributed variables were reported as mean ± standard deviations and the two conditions compared with paired Student's t test. Their "*experience as paramedics*" was not normally distributed and therefore reported as median.

6.4.4.   Paper IV

Chest compression depth and rate was reported as mean values for each minute for each paramedic. These values were illustrated graphically using Microsoft Excel 2003 (Microsoft Corp., WA, USA). The change in NFR was analysed using repeated measures ANOVA. We further analysed the difference between the first and each successive three-minute period using paired Student's t test with Bonferroni correction.

7. Main results

7.1. Paper I

Altogether, 5,118 manikins were distributed during the campaign, which amounts to 95% of all hospital employees. Among 3,466 employees that returned the first questionnaire, 9% reported that they had never been trained in BLS. The median time since their last BLS training was 15 months, and 40% stated that they had been in a situation where BLS skills were needed.

Among the 1,397 who replied to the second questionnaire, 65% had trained in the hospital meeting room, 26% in their own department and 5% at home. The self-rated competence increased from 3.1 before training to 3.8 nine months after training (P=0.031).

In the practical manikin study, the median number of good chest compressions during two minutes of BLS doubled from 60 before training (n=59) to 119 six months after training (n=39) (P<0.001). MTM ventilations did not improve and was suboptimal both before and after training.

7.2. Paper II

Total number of chest compressions increased for each increase in C:V ratio, from 604 with 15:2, to 770 with 30:2 and 862 with 50:2 ratio and there was a parallel decrease in NFR from 50% for 15:2 to 33% for 30:2 and to 23% for 50:2 (P<0.0005 for all). The compression rate was higher for 15:2 than for the other ratios, 118 vs. 115 for 30:2 (P<0.02) and 112 for 50:2 (P<0.0005 vs. 15:2), but was within the recommended 100-120 per minute for all three ratios.

Mean chest compression depth did not vary significantly between the three C:V ratios, 42 for 15:2 and 41 for 30:2 and 50:2. While all 2-minute periods had mean compression depth of ≥40 mm, it declined for each 2-minute period compared with the first 2-minute period with C:V ratios 30:2 (P<0.02) and 50:2 (P<0.02).

7.3. Paper III

Chest compression depth and rate were not different in the control and stress condition, 39 and 38 mm (P=0.214), and 113 and 116 per minute (P=0.065), respectively. NFR was 15% in

both conditions. Ventilation rate after confirmed endotracheal tube placement was 8.2 and 7.7 per minute in the control and stress condition (P=0.120). Time to first shock was longer in the control than in the stress condition, 209 vs. 121 seconds, respectively (P<0.001), with no difference in time to intubation (318 vs. 304 seconds, P=0.717) or time to IV access (123 vs. 98 seconds, P=0.382).

The NASA TLX survey of perceived stress indicated a marked and significant increase in four measures in the stress condition: mental demands, time pressure, effort and frustration. Physical demands did not change, nor did the subjective rating of achievement.

7.4. Paper IV

Large inter-individual differences in chest compression quality were already present from the initiation of CPR. Based on chest compression depth, 5 of 19 attempts were classified as good, 9 of 19 as bad with no signs of decay in compression depth during the 12 minutes of resuscitation in any of these 14. The other 5 of 19 paramedics experienced decay. Only one of these displayed chest compression depth below 40 mm within the first two minutes, the remainder after 4, 8, 11 and 12 minutes. Based on chest compression rate, 32% were good, 32% bad and 37% experienced decay, again at different times.

NFR, which averaged 17% for the entire 12-minute resuscitation period, remained unchanged at 22% for the first two three-minute intervals, but decreased to 14% in minute 7-9 (P=0.002), and further to 10% in the 10-12 minute period (P<0.001).

8. Discussion

8.1.   Paper I

Nearly all the 5,382 university hospital employees (95%) collected a manikin. We don't know how many actually trained, as only 27% returned the questionnaire nine months post training, but for those who did train, it was done in a very short time at modest costs[‡] without instructors. A necessary condition for the high frequency of in-hospital training was that this could be performed during their working hours. Mixing all kinds of hospital employees seems justified since BLS skills do not correlate with profession.[186]

The campaign succeeded in two ways; increasing the employees' self-rated BLS competence and increasing the number of correct chest compressions. The latter was very encouraging, since chest compressions are the most important resuscitation task in addition to early defibrillation. It is also satisfying that the performance was much better than pre training after six months, as there are many reports of significant decay in resuscitation skills three to six months after training.[187-189] Increasing employee self-rated skills is also important, since this presumably will increase the likelihood that they will try to perform BLS if needed. People are generally afraid of performing CPR,[190] and having recently completed BLS training increases the odds ratio for performing CPR in a real cardiac arrest situation.[127] One reason for the improvement in self-rated BLS skills might have been that the nine-month period from training until the second questionnaire was a shorter time interval than the median 15 months since their previous training, and in addition the increased focus gained through the campaign. Finally, nearly half of the employees did not know the correct C:V ratio in the first test before the campaign. This was likely caused by the recent change in C:V ratio that was published less than one year earlier.[59] Fortunately, this improved significantly after the hospital training campaign.

It was surprising that 9% had never before been trained in BLS, considering the widespread implementation of BLS courses. Further, it was not satisfying that the median time since last BLS training was 15 months, since the NRC recommend BLS refresher training at least every six months for hospital employees.[191] Based on this finding alone,

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[‡] The cost for this BLS campaing was 28.41 Euros per manikin and 30 minutes of training primarily performed during working hours. In addition, the 11 employees who organised the campaign worked a total of 370 hours which represents 4 minutes per employee trained.

further emphasis on BLS training for hospital employees would be warranted, especially since in-hospital life-threatening emergencies happen frequently and about one third of all cardiac arrests are IHCA.[5] This agrees with the finding that 40% answered that they had been in a situation where BLS skills were needed. If we assume that they had completed half of their career at the hospital (on average), and that the chances of experiencing cardiac arrest is constant, then 64% $(1 - (0{,}6)^2)$ of the employees would experience a situation where they would need BLS skills during their whole hospital career.

The campaign was less successful in other aspects. For those who answered the questionnaire and had participated in the training, their last training session with the manikin package was median 39 weeks earlier. This indicated that the manikins had primarily been used for the initial training and that the potential for refresher training had not been realised.[140] This means that it is easy to motivate for training during a campaign organised at the working place, but that refresher training needs to be organised and not left to individual initiatives.

In addition to the employees themselves, only one additional person was trained with each manikin during the nine month period when reported by the employees (22% replied). Thus, the full potential for cascade training of family and friends was not achieved since school children using the same training method trained an additional 1.9 persons per manikin.[192] Children might be easier to motivate, perhaps BLS training is more like a play situation than an obligation, and school children likely have more family members than hospital employees because they usually live together with parents and siblings.

The number of study subjects who assessed responsiveness and opened the airways before assessing respiration increased, but only about 70% assessed the respiration and this did not improve after training. Moreover, every third person checked for a pulse despite the fact that this task was removed from the BLS guidelines nearly ten years earlier and was not taught on the self-instruction video. This means that solely editing contemporary guidelines cannot change performance, and that implementation cannot be secured by a single training campaign. Continuous attention to changes seems warranted to modify resuscitation habits.

Finally, the performance of MTM ventilations did not improve after training. There seemed to be two reasons for that; 1) the test persons were not able to open the airways by head tilt and chin lift, and 2) some persons squeezed the manikin "trachea" with the heel of their hand when opening the airways, thereby obstructing the airways. The latter is a MiniAnne manikin limitation as the trachea is made of soft plastic and located on the anterior surface of the manikin neck, making it vulnerable to mechanical compression that does not

mimick the clinical situation. Performing ventilations appear difficult, both for lay people and hospital employees with limited training.[82,186] With the technology and pedagogic insight now at our disposal, MTM ventilations are difficult to learn by video self-instruction.[193]

8.1.1.   Limitations

The tests were performed on a MiniAnne manikin equipped with a counting device. It could not record supplementary CPR quality measures like compression depth, compression rate, NFR and ventilation volume. The manikin torso has to be inflated before training and no data exist on how different inflation pressures affect the compression depth/force relationship. The test was made in a low fidelity environment, we do not know if high fidelity simulation with exposure to stress would affect the CPR performance of hospital employees to a greater degree than paramedics.[151] The participation rate was high, but it is uncertain whether this would change for any future training or in the absence of a similar campaign. Finally, since we did not report any clinical IHCA data before and after the campaign, we do not know if the improvement in BLS performance in this study lead to improved quality of BLS or improved survival in real cardiac arrests.

8.2.   Paper II-IV

These are all manikin studies focusing on quality of CPR given by experienced CPR providers, with different aspects targeted in each paper. These papers are therefore discussed together. The main findings are that well trained individuals can perform good quality chest compressions for a prolonged time period both during single-rescuer BLS and even during ALS with continuous exposure for socioemotional stress. Chest compression decay (both depth and rate) occured, but it was rather infrequent in the initial two minutes in the resuscitation attempt, occured at different time points and was by no means universal during a prolonged CPR. This might be seen as encouraging, but the large inter-individual difference in CPR quality with many individuals performing too shallow chest compressions from the very start is concerning, and demonstrate the importance of systemwise improved training with higher requirements. Two paramedics did not perform one single chest compression that was deep enough during three 10-minute episodes of BLS. Considering the low cerebral and myocardial blood flow with such bad CPR quality, these paramedics will probably never save a patient neurologically intact after a prolonged resuscitation.[194] Thus, the phrase "*hearts too*

good to die" is still very relevant, and efforts to understand and analyse how to improve quality of CPR is indeed important.

8.2.1.   Depth and rate

There has been a concern that increased number of chest compressions with increasing C:V ratio would lead to a decline in chest compression depth. It was therefore satisfying to observe that compression depth was identical for all three ratios. The large inter-individual differences cause concern, however, and with 34% of all chest compressions too shallow (<38 mm according to current guidelines at that time) there is potential for improvement. It is unlikely that less trained CPR providers or lay people would do better, and with 2010 recommended compression depth of ≥50 mm,[15] this problem is presumably even greater now. It should therefore be more focus on compression depth for CPR training at all levels. There are indications that low-dose, high-frequency training can give acceptable performance on manikins,[195] but no studies have shown retention of good quality chest compressions for a prolonged period of time. Noteworthy, there is even a possibility that paramedics compress shallower on real patients than on manikins because of concerns of causing serious patient injuries.[196]

Chest compression rate was in the upper range of guideline recommendations for all three ratios. As expected and previously reported in manikins[197-199] and humans[200] total number of chest compressions increased with increased C:V ratio.

8.2.2.   No-flow ratio

In parallel to increased number of chest compressions per minute, NFR decreased for each increase in C:V ratio. Even for well trained paramedics, the 15:2 ratio gave NFR of as much as 50%, as previously demonstrated in manikin BLS[199] and human ALS.[95] This was reduced by one third with the 30:2 ratio now recommended for both BLS and ALS without advanced airway.[15,60] A human study also demonstrated declined NFR for ALS after the 2005 change in guidelines.[201] Considering the importance of reducing NFR,[202,203] this finding supports the guidelines change. NFR can be further reduced with two-rescuer BLS.[204]

8.2.3. Chest compression decay

Chest compressions depth decayed for only 5 of 19 paramedics during 12 minutes of CPR, and for only two before 8 minutes of CPR. It seemed more problematic that nearly half the paramedics compressed too shallow already during the first minute of ALS. If paramedics follow the guidelines and switch chest compression provider every two minutes, there is a possibility that one changes from a person performing good compressions to someone performing too shallow compressions.

Although chest compression decay was a smaller problem than expected, a discussion regarding change in chest compression quality over time is highly warranted, since several studies indicate that it is a major problem and because it is emphasised in the guidelines.[47] Fatigue is only one of several different explanations. Measured fatigue does not occur simultaneously with perceived fatigue,[157] and CPR has been performed efficiently for 10 minutes on manikins while eliciting only moderate physiological stress,[205] with sub-anaerobic energy expenditure and no significant differences over 10 minutes.[206] We therefore use the term "*chest compression decay*" instead of "*rescuer fatigue*" to include all potential reasons for a decline in chest compression quality.

Several papers address the challenge of chest compression decay in CPR, with the most important summarised in appendix 4. They differ in many aspects. The majority are in manikins,[155-161,173,196,205,207-221] which do not represent the large variation in chest damping and resistance found in humans during CPR.[222,223] In fact, most have no damping. We do not know if the degree of chest compression decay is different when CPR is performed in humans, and in a recent study where the manikin chest had damping and an increased resistance with increasing compression depth, modelled after human data, there was no or minimal decay during 10 minutes of 30:2 CPR even for lay people aged 50-76.[217] Most studies were also performed in training facilities without use of high fidelity simulation, hence the feeling of realism would be low, and we cannot rule out that it could affect the performance of CPR. Further, there is no information about chest compression provider switches, and the duration of CPR varied greatly between studies, the majority being short.

8.2.4. Impact of socioemotional stress

We implemented the following occupational stressors to increase stress among the paramedics; uncertainty, confusion, responsibility, conflict, hostility, aggression, role-conflict, isolation and language.[224] An increase in four measures of subjective stress indicated that this

was effective in causing stress. Physical demands did not change, hence they didn't feel the stress condition to be any heavier to perform. This was expected as the patient's medical condition was virtually identical in the two conditions. The subjective rating of achievement was also similar in the two conditions.

It was encouraging that chest compression depth was unaffected by exposure to socioemotional stress. On the other hand, chest compression depth was suboptimal (although only a few mm) in both conditions compared to the 2005 guidelines recommendation.[59] Importantly, however, figure 2 in paper IV does not indicate more prominent decay for providers with initial deep compressions.

NFR was also not affected. This means that it is possible to achieve NFR of less than 20% even in the presence of socioemotional stress. This has also been shown in recent clinical studies[116,201] and is far better than data from recent US Resuscitation Outcome Consortium (ROC) trials with NFR between 34 and 46%.[203,225] One reason for the low NFR in our study could be that they were instructed to intubate the patient. Although intubation in itself usually casues a period without chest compressions, it allows continuous chest compressions thereafter and hence a lower NFR.[79] The change to PEA eliminated chest compression pauses for shocks although pauses were still required for pulse checks every three minutes. Ventilation rate was not measured before intubation, but was below 10 per minute thereafter for both conditions and not affected by socioemotional stress.

Our findings differ from previous studies.[164,226-228] There are several potential explanations why our paramedics were unaffected by socioemotional stress exposure and perceived stress;[229]

· *Experience:* Our paramedics were highly experienced with a median working experience of 8.5 years.

· *Pre-hospital working environment:* Paramedics are used to working under the influence of bystanders in their daily work. This might make them more resistant to socioemotional stress than other health care workers. However, many health care providers think that family presence does not interfere with care provided to the patient.[230,231]

· *Realism:* A lack of realism could have made the paramedics more resistant to being affected by stress. This seems unlikely as their feeling of realism increased significantly from the control condition to the stress condition.

· *Regular training:* These paramedics receive refresher ALS training three to four times annually, although traditional ALS training might be insufficient as only half of the residents in an internal medicine training programme felt prepared to lead a cardiac arrest team.[232]

Simulation can improve performance of[233,234] and survival[235] after ALS. It has been shown that emotional stressors in high fidelity simulation can increase participant anxiety and long-term retention of applied knowledge.[236]

· *Procedure-related task:* The performance of ALS is a very protocolised task.[226] That could make it more resistant to stress compared to more cognitive tasks. The addition of emotional stress in high-fidelity simulation can improve performance.[237]

· *Non-technical skills:* The paramedics could be trained in non-technical skills like leadership, communication, task distribution and crisis resource management (CRM). Brief leadership instruction can improve CPR performance in a high fidelity simulation[238] as well as non-technical skills,[239] and CRM training.[240]

· *Priority:* The immediate threat to the patient could lead the paramedics to perform ALS instead of caring for and collecting information from the bystander. One paramedic said she neglected him completely when she realised that he could not contribute to the resuscitation.

· *Interpretation of socioemotional stress:* It is possible that the paramedics responded to the various stress elements as interruptions rather than distractions. Interruptions are common, often unremarkable and not associated with vulnerability, whereas distractions can be lengthier and pull attentional resources away from the primary task.[241]

8.2.5.   Practical implications and future perspectives

The guideline recommendation of changing chest compression provider every two minutes seems unsupported by this thesis. Chest compression decay due to physical fatigue was infrequent. Inaccurate chest compression depth seems a more reasonable explanation as some had inadequate compression quality from the onset of CPR while others did not show signs of decay after 12 minutes. Chest compression provider switches should rather be guided by actual compression quality regardless of the duration since last change. CPR feedback devices have improved CPR quality[225] but not survival after cardiac arrest.[242] Currently, the best available measurement tool might be capnographs, since capnography can indicate cardiac output.[243] A drop in end-tidal CO_2 has been used as an indicator for when to switch the person providing chest compressions,[244] and guidelines now encourage the use of capnography to guide CPR during ALS on intubated patients.[60] Further studies are indicated to find the optimal use of these technologies to optimise timing as the provider switch itself can lead to a significant proportion of NFR.[168] Also, further studies should be undertaken to measure the

degree of chest compression decay during real cardiac arrests when only one or two providers perform chest compressions.

The observation that nearly half of the paramedics compress too shallow already from the first minute of resuscitation causes great concern. More studies are needed to figure out whether these paramedics are physically capable of performing good quality chest compressions, and for how long. This challenge is not solved by switching every two minutes as there is a near 50% chance that one changes to someone compressing too shallow.

It was shown that it is possible to make highly realistic ALS simulations with increased workload and frustration, without affecting the physical demands, feeling of achievement or quality of CPR. By extending regular CPR skills with high fidelity training, it is hoped that the increased realism and attention to non-technical skills can improve CPR and ALS quality both during training, assessment and real cardiac arrests. It should be studied whether high fidelity simulation can compensate for lack of clinical experience. Further studies should evaluate which environmental factors are most likely to cause provider stress, and which strategies are effective in coping with them.

Finally, by optimising the second link in the Chain of Survival, basic CPR skills, and by optimising the Formula of Survival by improving guidelines, training and implementation, there is reason to believe that we can improve the results for what still remains the largest subgroup of cardiac arrest patients – the non-survivors.

8.2.6.　　Limitations

These were all manikin studies, it is unclear whether the results would be similar in real cardiac arrest patients. The large variations in stiffness and damping during chest compressions might influence compression quality.[222,223] We used paramedics in paper II-IV, and the results could be different for lay people or health care workers with less training.

We do not know if the stress level and CPR and ALS quality are similar in real resuscitations. The high score on realism of 8.0 out of 10 possible in paper III might indicate that the simulation with socioemotional stress exposure gave a feeling close to a real event, especially considering their long clinical experience. We do not know if the results would be similar for less experienced CPR providers or for other health care professions, or for providers with less frequent CPR training. We did not measure non-technical skills like communication, leadership and situational awareness that could potentially improve

teamwork.[231,245,246] In addition, the fact that they knew that they were observed could have affected their performance (the Hawthorne effect).[247]

　　We did not measure objective stress response such as salivary cortisol levels,[152,248] which could have validated our measurement of perceived stress. Similarly, we did not measure objective signs of physical fatigue like aerobic energy expenditure,[206] oxygen uptake,[205] heart rate,[205,210] or perceived fatigue.[155,161,196,208,209,214,217,219,221] A good correlation between number of correct compressions and muscle strength has been reported,[221] but paramedics do generally have physical fitness to perform chest compressions even on the stiffest chests.[196] Leaning was not studied in this paper. Finally, we studied chest compression decay when CPR was performed on the floor. Decay could be increased when CPR is performed in a hospital bed or on a soft mattress.[249]

9. Conclusion

9.1.   Paper I

A hospital-wide BLS training campaign with a personal resuscitation manikin and video instruction improved both employee self-confidence and practical BLS skills. This is a less time-consuming option to instructor-led courses to improve the first links in the in-hospital Chain of Survival for IHCA patients.

9.2.   Paper II

Paramedics were able to perform good quality chest compressions over a 10-min single-rescuer BLS period on a manikin. The number of chest compressions increased linearly and no-flow time decreased with increasing C:V ratio without affecting compression depth or rate. This indicates that single rescuers are able to perform good quality CPR even during prolonged BLS.

9.3.   Paper III

Simulated ALS with socioemotional stress resulted in a more realistic manikin scenario, increasing the paramedics' subjective workload and frustration, without affecting their physical demands, their feeling of achievement, or quality of CPR.

9.4.   Paper IV

Only half of the providers achieved guideline recommended compression depth during prolonged ALS. Large inter-individual differences in compression quality were already present from the initiation of CPR. Chest compression decay was rare before eight minutes of CPR.

10. Errata

10.1.   Paper III

Under the heading Experimental design in Materials and methods, second paragraph,
"*[intravenous] cannulation*" should be "*intravenous cannulation*".

Under the heading Level of socioemotional stress, "*p=<0.001*" should be "*p<0.001*".

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12. Appendices

12.1.   Appendix 1

Questionnaire distributed to all hospital employees before receiving their personal resuscitation manikin. English translation and Norwegian version.

Question 1

How long ago did you have training in cardiopulmonary resuscitation (CPR)?

_____ years and _____ months ago.   _____ Never received training in CPR.

Question 2

How capable do you feel that you are in performing cardiopulmonary resuscitation (CPR)?

Please check off one box. (1=very bad, 5=very good)

_____ 1 Very bad

_____ 2 Slightly bad

_____ 3 Medium

_____ 4 Slightly good

_____ 5 Very good

Question 3

Have you ever been in a situation where you needed cardiopulmonary resuscitation skills, whether at work or not? Please check off one box.

_____ Yes, at work   _____ Yes, outside work   _____ No

Question 4

a) What is your age?

_____ years

b) Gender?

_____ Female _____ Male

Question 5

What is your employment?

____ Physician   ____ Radiographer   ____ Bioengineer

____ Nurse   ____ Administration   ____ Psychologist

____ Nursing assistant   ____ Technical   ____ Ambulance worker

____ Physiotherapist   ____ Service   ____ Secretary

____ Occupational therapist ____ Cleaner   ____ Midwife

____ Other: _____

Question 6

At what department are you employed? Please check off one box.

____ Emergency Medicine   ____Surgical-Orthopaedic

____ Rehabilitation   ____ Haemato-Oncological

____ Gyn-Paediatric   ____ Specialised medicine

____ Director's Office   ____ Medical

____ Financial   ____ Research and Human Resources

____ Med. service   ____ Internal service

____ Psychiatric

Spørsmål før opplæring med Mini-Anne

Besvarelsene sendes i internposten til HLR-post, Akuttklinikken. Alle svar behandles konfidensielt. Spørsmål om denne spørreundersøkelsen rettes til Conrad Bjørshol på e-post: bjco@sus.no.

SPØRSMÅL 1
Hvor lenge er det siden du sist gjennomgikk opplæring eller øvelse i hjerte-lunge-redning (HLR)?

_____ år og _____ måneder siden.   ❑ Aldri fått opplæring i HLR.

SPØRSMÅL 2
Hvor godt synes du at du behersker hjerte-lunge-redning (HLR)? Sett ett kryss.
(1 = veldig dårlig, 5 = veldig godt)

❑ 1 Veldig dårlig   ❑ 2 Litt dårlig   ❑ 3 Middels   ❑ 4 Litt godt   ❑ 5 Veldig godt

SPØRSMÅL 3
Har du noen gang opplevd situasjoner hvor du har hatt bruk for ferdigheter i hjerte-lunge-redning (enten på jobb eller i fritiden)? Sett ett kryss.

❑ Ja, på jobben   ❑ Ja, utenom jobben   ❑ Nei

SPØRSMÅL 4
a) Hva er din alder? _____ år.   b) Kjønn: ❑ Mann   ❑ Kvinne

SPØRSMÅL 5
Hvilken stilling har du ved Stavanger Universitetssykehus?

❑ Lege   ❑ Radiograf   ❑ Bioingeniør
❑ Sykepleier   ❑ Administrasjon   ❑ Psykolog
❑ Hjelpepleier   ❑ Teknisk personell   ❑ Ambulansepersonell
❑ Fysioterapeut   ❑ Servicefunksjoner   ❑ Sekretær
❑ Ergoterapeut   ❑ Renhold   ❑ Jordmor
❑ Annet: _____

SPØRSMÅL 6
Ved hvilken klinikk er du ansatt? Sett ett kryss.

❑ Akuttklinikken   ❑ Kirurgisk-ortopedisk   ❑ Rehabiliteringsklinikk
❑ Blod- og kreftsykdommer   ❑ Kvinne-barn   ❑ Spesialmedisin
❑ Direktørens kontor   ❑ Medisinsk klinikk   ❑ Økonomi og finans
❑ Fag- og foretaksutvikling   ❑ Medisinsk service
❑ Intern service   ❑ Psykiatrisk klinikk

Takk for at du besvarer spørsmålene. Om noen måneder vil du motta et nytt spørreskjema.

**Stavanger Universitetssjukehus
Helse Stavanger HF**

12.2. Appendix 2

Questionnaire sent to all hospital employees nine months after receiving their personal resuscitation manikin. English translation and Norwegian version.

Question 1

Where did you perform the cardiopulmonary resuscitation training with your MiniAnne manikin?

_____ Hospital meeting room   _____ Own department

_____ At home   _____ Did not participate

Question 2

How long ago did you train in cardiopulmonary resuscitation (CPR) with your MiniAnne manikin?

_____ weeks or _____ months ago

_____ Did not participate, reason: _____

Question 3

How capable do you feel that you are in performing cardiopulmonary resuscitation (CPR) now? Please check off one box. (1=very bad, 5=very good)

_____ 1 Very bad

_____ 2 Slightly bad

_____ 3 Medium

_____ 4 Slightly good

_____ 5 Very good

Question 4

How many persons, in addition to yourself, have trained in cardiopulmonary resuscitation with your MiniAnne manikin/self-instruction video?

_____ persons

Question 5

Have you experienced any discomfort using the manikin?

_____ No   _____ Yes, please specify: _____

Question 6

Have you got any comments on the MiniAnne CPR training?

_____

Spørsmål til alle SUS-ansatte om opplæringen med Mini-Anne
(Har du svart på denne undersøkelsen tidligere trenger du ikke svare igjen.)

Det siste året fikk alle ansatte tilbud om opplæring i hjerte-lunge-redning (HLR) med Mini-Anne opplæringsdukke. For å vurdere effekten av opplæringen ønsker vi at du svarer på noen få spørsmål. **Besvarelsene sendes i internposten til HLR-post, Akuttklinikken.** Alle besvarelser behandles konfidensielt. Spørsmål om undersøkelsen rettes til Conrad Bjørshol på e-post: bjco@sus.no.

Spørsmål 1
På hvilken måte gjennomførte du opplæringen i hjerte-lunge-redning med Mini-Anne?

☐ Fellesundervisning i klasserom på sykehuset.

☐ Sammen med noen få andre på min egen avdeling.

☐ Hjemme.

☐ Har ikke gjennomgått opplæring med Mini-Anne.

Spørsmål 2
Hvor lenge er det siden du gjennomgikk opplæring i hjerte-lunge-redning (HLR) med Mini-Anne?

_____uker eller _____måneder siden.

☐ Fikk aldri gjennomført opplæringen i HLR med Mini-Anne. Årsak: _____

Spørsmål 3
Hvor godt synes du at du behersker hjerte-lunge-redning (HLR) nå? Sett ett kryss.
(1 = veldig dårlig, 5 = veldig godt)

☐ 1. Veldig dårlig   ☐ 2. Litt dårlig   ☐ 3. Middels   ☐ 4. Litt godt   ☐ 5.Veldig godt

Spørsmål 4
Hvor mange personer i tillegg til deg selv har fått opplæring i hjerte-lunge-redning med din Mini-Anne/DVD-film?

_____ personer.

Spørsmål 5
Har du fått noen plager eller ubehag pga. at du brukte Mini-Anne?

☐ 1. Nei   ☐ 2. Ja, beskriv: _____

Spørsmål 6
Har du kommentarer til opplæringen i hjerte-lunge-redning med Mini-Anne?
(Bruk eventuelt baksiden for mer plass)

Takk for at du besvarer spørsmålene!

Stavanger Universitetssjukehus
Helse Stavanger HF

12.3. **Appendix 3**

The NASA TLX questionnaire. English translation and Norwegian version.

· *Mental demands:* How mentally demanding was the task? How huge were the demands with respect to thinking and orientation after receiving information? (0=very low, 100=very high)

· *Physical demands:* How physically demanding was the task? Was it exhausting or relaxing? (0=not demanding, 100=very demanding)

· *Time pressure:* How much time pressure did you experience in relation to the task? (0=plenty of time, 100=very limited time)

· *Effort:* How hard were you forced to work (mentally and physically) to achieve what you did? How much effort did you experience during the task? (0=little, 100=much)

· *Frustration:* How annoyed, stressed, uncertain or upset did you feel while performing the task? How huge was your frustration level? (0=very low, 100=very high)

· *Achievement:* How well do you feel that you completed the task according to the instructions? How satisfied were you with accomplishing it? (0=bad achievement, 100=good achievement)

Vurdering av arbeidsbelastning

Dato: _____   ID: _____

Mentale krav

Hvor mentalt og perseptuelt krevende var oppgaven? Hvor store krav stilte oppgaven til tenking og orientering etter informasjon?

50

Meget lave — Meget høye

Fysiske krav

Hvor fysisk krevende var oppgaven? Var oppgaven belastende eller avslappet?

50

Ikke belastende — Meget belastende

Tidspress

Hvor stort tidspress opplevde du under oppgaven i forhold til hvordan oppgaven var lagt opp?

50

God tid — Lite tid

Anstrengelse

Hvor hardt var du tvunget til å jobbe (mentalt og fysisk) for å prestere slik du gjorde? Hvor mye anstrengelse opplevde du under oppgaven?

50

Lite — Mye

Frustrasjon

Hvor irritert, stresset, usikker eller urolig følte du deg under oppgaven? Hvor høyt var ditt frustrasjonsnivå?

50

Meget lavt — Meget høyt

Prestasjon

Hvor bra mener du at Du klarte oppgaven i henhold til instruksene? Hvor fornøyd var du med å klare det?

50

Dårlig prestasjon — God prestasjon

12.4. Appendix 4

Different published studies addressing the problem of chest compression decay during CPR. Abbreviations are listed at the end of the appendix.

First author/ Publication year	Manikin/ Clinical	Duration	Participants	Intervention	No. of resc-uers	Measurements
Miles[205] 1984	Manikin	10 min	10 male paramedics	15:2 and CCC	1	Oxygen uptake, capillary lactate, heart rate, stroke volume, cardiac output
Berden[173] 1992	Manikin	15 min	60 lay volunteers, CPR course 6-8 months earlier	15:2	1	CC depth, rate, compression/ relaxation ratio
High-tower[156] 1995	Manikin	5 min	11 nursing assistants	Closed chest compressions	1	Correct CC depth and placement
Ochoa[157] 1998	Manikin	5 min	38 ICU physicians and nurses	External chest compressions according to the recommended standards (15:2?)	1	No. of CC, incorrect location, insufficiant depth, correct compressions
Ashton[158] 2002	Manikin	2 x 3 min	40 ICU doctors and nurses	CCC	1	No. of CC (depth 4-5 cm)
Greingor[159] 2002	Manikin	5 min	21 professional healthcare providers	15:2 and 5:1, bag-mask ventilation	1	CC depth, rate, location
Huseyin[207] 2002	Manikin	rotating to 18 min	21 doctors and nurses	CC for periods of 1, 2 or 3 min	2 or 3	CC depth 4-5 cm, rate, correct hand position
Heiden-reich[160] 2006	Manikin	9 min	53 first and second year medical students	15:2 and CCC	1	CC depth, rate, placement, adequate ($\geq$38 mm)
Losert[164] 2006	Clinical	mean 11.2 min	80 CA patients at the ED at a tertiary care university hospital			Hands-off time
Yannopo-ulos[208] 2006	Manikin	5 min	10 EMS providers and 10 laypersons	30:2 and 15:2	1	Perceived fatigue

Results/Discussion

Compression efficiency ... did not change throughout the 10 min of CPR. Properly trained and experienced individuals can perform CPR efficiently for at least 10 min while eliciting only moderate physiological stress.

No substantial changes in … values of the six variables occured with time, and there was little variation with time for results from individual participants. Participants with good CPR technique during the first 2 min of resuscitation continued to apply good technique during the whole attempt, whereas initial shortcomings remained.

The percentage of correct chest compressions decreased dramatically, from 92.9% during minute 1 to 18.0% during minute 5 of CPR.

Rescuer fatigue occurs before 60 s of chest compressions. It seems reasonable to suggest that leaders of CPR teams ask for a change of the rescuer after 1 min of compressions, regardless of whether he notifies that he is tired.

However, the number of satisfactory chest compressions ... decreased during both 3-min periods of simulated resuscitation.
Seven subjects ... were unable to complete the second 3-min period because of exhaustion.
Performance of chest compressions over 3 min declines progressively.
Fatigue adversely affects the performance of an individual to maintain satisfactory chest compressions in a manikin model over 3 min.

Trained rescuers can perform CPR efficiently for at least 10 min.
There is a significant correlation between quality of chest compression and duration of activity group 15/2.
No correlation between correct compression and duration appeared for group 5/1.

This study shows that rescuers are technically most effective whilst performing ECC in 1 min periods. Cardiac compressions should be performed over periods of 1 min.

The number of adequate compressions per minute trended down over time in both CCC and 15:2.

The hands-off ratio was linearly associated with the duration of CPR.

There were no significant differences between the groups in fatigue measurements.

First author/ Publication year	Manikin/ Clinical	Duration	Participants	Intervention	No. of resc-uers	Measurements
Desch-ilder[155] 2007	Manikin	5 min	130 hospital personnel and students	30:2 and 15:2	1	VAS-score
Ødegaard[196] 2007	Manikin	5 min	80 ambulance personnel	15:2	2	CC depth, rate, actual number, NFR, degree of fatigue
Betz[209] 2008	Manikin	5 min	18 physicians, paramedics and EMT's	15:2 and 30:2	2	No. of CC, depth, rate, shallow CC and NFR, perceived exertion
Haque[210] 2008	Manikin	5 min	80 health care providers, most BLS/PALS certified	30:2 and 15:2 adolescent, child (1 and 2 hand), infant (2 finger and 2 thumb)	1	Mean heart rate and respiratory rate increases per minute
Jäntti[209] 2009	Manikin	10 min	44 experienced ICU nurses	30:2, switching provider every 2 min	2	CC depth and rate
Jäntti[161] 2009	Manikin	10 min	24 experienced ICU nurses	30:2 on the floor or in a bed, switching provider every 2 min	2	CC depth and rate, perceived fatigue and efficacy
Manders[212] 2009	Manikin	4 x 2 min	36 pairs of certified BLS nursing staff ED	30:2, switching provider every 1 or 2 min	2	No. of effective CC (≥38 mm and full recoil) for the entire scenario
Sugerman[162] 2009	Clinical	"*blocks*" of CCs up to 180 sec	135 "*blocks*" of CCs with duration > 90 sec from 42 in-hospital arrest episodes	CCCs after intial tracheal intubaion, single CC provider in "blocks" of up to 180 sec		CC depth and rate
Sutton[163] 2009	Clinical	Median 11.8 min	Health care providers in PICU and ED departments. 20 events in 18 paediatric patients aged ≥ 8 years.	Cardiac arrest requiring chest compressions		CC rate, depth, residual leaning force and NFF
Trow-bridge[213] 2009	Manikin	10 min	20 volunteers with current AHA certification in BLS, graduate students or faculty	30:2 and CCC	1	CC force and depth

Results/Discussion

Although people find the 30:2 ratio to be more exhausting, no evidence can be found that the 30:2 technique is more difficult to perform or to maintain over 5 min.

More fatigue was reported with the stiffest manikin...
Ambulance personnel were physically capable of compressing to the Guidelines depth for 5 min even on a manikin with chest stiffness mimicking the mean value of the upper eighth of the chest stiffnesses found in a recent clinical study from the same ambulance system.

Heart rate, lactate, and … were increased but these outcomes did not differ between the 15:2 and 30:2 groups.
Rate and depth of compression did not differ significantly between the 15:2 and 30:2 groups or during any minute of CPR.

No significant difference in the rescuers's ability to maintain these compression variables comparing the 30:2 versus the 15:2 ratios for each BLS group.

Mean chest compression depth per minute did not decline over time. Chest compression rate did not decline over time.

The mean chest compression depth declined over time on both surfaces.

No significant difference in the number of effective chest compressions between the groups.

A decrease in CC depth over time for a single rescuer starting at 90 sec of CPR, without any change in CC rate. These data provide clinical evidence for rescuer fatigue during actual resuscitations and support the need to rotate rescuers frequently during CPR as currently recommended by consensus resuscitation guidelines.

Shallow CCs and excessive residual leaning force were less prevalent during the first 5 minutes of the resuscitation. There was no significant difference for the quality parameters of CC rate and NFF between the entire resuscitation and the first 5 minutes of the event.

There was a significant time effect for chest compression force. There was … a significant time main effect for chest compression depth. A significantly greater decline in chest compression force occurred with Hands-Only CPR than with 30:2.

First author/ Publication year	Manikin/ Clinical	Duration	Participants	Intervention	No. of resc- uers	Measurements
Chi[214] 2010	Manikin	5 min	17 emergency medical professionals (EMTs and ED nurses)	15:2, 30:2 and 50:5	1	CC depth, rate, correct CC, force, percieved exertion and discomfort
Foo[215] 2010	Manikin	10 min	24 physicians and nurses, with working experience more than 2 years and had performed CPR more than 20 times	CCC kneeling, standing on a taboret and standing on the floor.	1	CC 38-50 mm
Neset[217] 2010	Manikin	10 min	32 lay persons aged 50-76 years, CPR training 5-7 months earlier	30:2 and CCC	1	CC depth, rate, NFR, actual number. Self-reported exhaustion and pain
Nishi-yama[218] 2010	Manikin	80 sec	213 lay persons immediately after training	CCC or 30:2	1	Actual no., fraction correct depth (3.5-5.5 cm), NFR
Vaillan-court[219] 2011	Manikin	5 min	42 lay persons aged $\geq$ 55 years	30:2 and 15:2	1	CC depth, rate, decom-pression, adequate CC (4-5 cm + full decompression), perceived level of fatigue before and after each CPR session.
Ock[221] 2011	Manikin	5 min	47 medical students	CCC	1	Total no. and no. of correct CC, perceived excertion
Heiden-reich[216] 2012	Manikin	9 min	17 doctors and nurses aged 60-84 years	30:2 and CCC	1	CC >38 mm
Hansen[220] 2012	Manikin	15 min	15 active healthcare professionals	CCC	1	CC depth, rate, correct CC (38-51 mm and correct hand placement)
Neset[82] 2012	Manikin	10 min	64 lay people aged 50-75, CPR training 8-11 months earlier	30:2	1	CC depth, rate

Results/Discussion

The fatigue, measured by VAS, was 2.20 ± 1.74, 2.76 ± 1.73, and 3.67 ± 2.04 at 15:2, 30:2, and 50:5, respectively. Experienced providers can maintain an adequate compression rate and compression depth throughout the 5-minute ECC session.
The compression force fell after 5 minutes at a ratio of 30:2.

Kneeling and standing on a taboret maintained 2 min of endurance while standing on the floor achieved only 1min of endurance.

Compression depth decreased slightly from the first to the tenth minute, from mean 43 mm to 41.
Reported physical strain for CCC and 30:2 was mean 4.7 ... and 3.7. Lay persons aged 50–76 are capable of performing 10 min of CPR with satisfactory quality.

The quality index gradually decreased from 86.6 ± 25.0 ($0 - 20$ s) to 58.2 ± 36.9 ($61 - 80$ s) in the chest compression-only CPR group and from 85.9 ± 25.5 ($0 - 20$ s) to 74.3 ± 34.0 ($61 - 80$ s) in the conventional CPR group over time. The decay of CPR was greater during the chest compression-only CPR. We recommend that rescuers should change their roles in CPR every 1min for chest compression-only CPR.

There was no difference in the number of adequately performed chest compressions over the entire 5 min.
The number of adequately performed chest compressions decreased significantly over time for each compression:ventilation ratio.
Perceived bystander fatigue was subjectively higher during the 30:2 compared to the 15:2.

There was a significant reduction in the percentage of correct compressions after the first minute. There were good correlations between the numbers of correct compressions with muscle strength.

The number of adequate compressions delivered per minute declines over time for both HO-CPR and STD-CPR in an elderly population.
Significantly more total compressions were delivered during HO-CPR than STD-CPR.

During sustained CCR the ventilatory threshold is related to chest compression quality for up to 5 min. After 5 min of sustained CCR, quality of chest compressions is related to maximal muscle strength. Blood lactate concentrations and heart rate were not related to CCR quality.

No fatigue was evident during 10 minutes of single-rescuer CPR.

Abbreviations:

AHA	American Heart Association
BLS	basic life support
CA	cardiac arrest
CC	chest compressions
CCC	continuous chest compressions
CCR	cardiocerebral resuscitation
CPR	cardiopulmonary resuscitation
ECC	external chest compressions
ED	emergency department
EMS	emergency medical systems
EMT	emergency medical technician
HO-CPR	hands-only CPR
ICU	intensive care unit
NFF	no-flow fraction
NFR	no-flow ratio
PALS	paediatric advanced life support
PICU	paediatric intensive care unit
STD-CPR	standard CPR
VAS	visual analogue scale

13. Reprints of paper I-IV

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II

IV

ORIGINAL RESEARCH   **Open Access**

Decay in chest compression quality due to fatigue is rare during prolonged advanced life support in a manikin model

Conrad A Bjørshol[1*], Kjetil Sunde[2], Helge Myklebust[3], Jörg Assmus[4] and Eldar Søreide[1]

Abstract

Background: The aim of this study was to measure chest compression decay during simulated advanced life support (ALS) in a cardiac arrest manikin model.

Methods: 19 paramedic teams, each consisting of three paramedics, performed ALS for 12 minutes with the same paramedic providing all chest compressions. The patient was a resuscitation manikin found in ventricular fibrillation (VF). The first shock terminated the VF and the patient remained in pulseless electrical activity (PEA) throughout the scenario. Average chest compression depth and rate was measured each minute for 12 minutes and divided into three groups based on chest compression quality; good (compression depth ≥ 40 mm, compression rate 100-120/ minute for each minute of CPR), bad (initial compression depth < 40 mm, initial compression rate < 100 or > 120/ minute) or decay (change from good to bad during the 12 minutes). Changes in no-flow ratio (NFR, defined as the time without chest compressions divided by the total time of the ALS scenario) over time was also measured.

Results: Based on compression depth, 5 (26%), 9 (47%) and 5 (26%) were good, bad and with decay, respectively. Only one paramedic experienced decay within the first two minutes. Based on compression rate, 6 (32%), 6 (32%) and 7 (37%) were good, bad and with decay, respectively. NFR was 22% in both the 1-3 and 4-6 minute periods, respectively, but decreased to 14% in the 7-9 minute period (P = 0.002) and to 10% in the 10-12 minute period (P < 0.001).

Conclusions: In this simulated cardiac arrest manikin study, only half of the providers achieved guideline recommended compression depth during prolonged ALS. Large inter-individual differences in chest compression quality were already present from the initiation of CPR. Chest compression decay and thereby fatigue within the first two minutes was rare.

Keywords: Advanced life support (ALS), cardiac arrest, cardiopulmonary resuscitation (CPR), fatigue, resuscitation, chest compression

1. Background

In cardiac arrest, good quality cardiopulmonary resuscitation (CPR) is essential for survival [1-3]. Together with early defibrillation [4,5], the quality of chest compressions is the main prerequisite for good outcome, especially chest compression depth [6] and avoidance of unnecessary hands-off intervals [4,5,7,8]. Current guidelines recommend changing the person providing chest compressions every two minutes [4,5]. Fatigue is supposed to be the main reason for this recommended practice [9-11], but the scientific evidence is limited. Since unnecessary changes in chest compressions may affect the overall quality of advanced life support (ALS) [12], we think this important topic deserves new attention.

In 1995, Hightower et al. described, in a manikin study with 11 study subjects, a decline in the quality of chest compressions over the first five minutes after initiating CPR [9]. The quality of the chest compressions was judged as inappropriate if the depth or hand

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placement was not within the recommendations. Subsequent manikin studies confirmed a decrease in chest compressions with adequate depth during the first few minutes of CPR [10,11,13,14]. However, based on the methodology used in these different studies it remains unclear whether this poor CPR performance is due to fatigue or other reasons. In contrast, two manikin studies have shown that CPR providers are able to perform chest compressions efficiently for 10 minutes while eliciting only moderate physiological stress [15], requiring just sub-anaerobic energy expenditure with no significant differences over the 10 minute study period [16]. In a previous manikin study we found no signs of chest compression decay during 10 minutes of single rescuer basic life support (BLS) by paramedics [17], but there was a huge inter-individual distribution in the quality of CPR. Similar data, with no obvious decline in chest compression quality over 5-10 minutes of BLS have also been described in lay people manikin studies [18,19], even when elderly people were tested [19].

Therefore, we decided to evaluate chest compression quality during a prolonged period of ALS in a manikin study with the same paramedic providing all chest compressions. We specifically wanted to focus on initial chest compression depth and if and when a decay in chest compression depth or rate occurred. Our hypothesis was that the degree of chest compression decay varied greatly between individual rescuers.

2. Methods

In a recently published randomised manikin study [20], 20 paramedic teams performed ALS under two different conditions; with and without socioemotional stress. The paramedics used had a median working experience of 8.5 years and participated in organised ALS training three to four times a year. The study was approved by the Regional Committee for Medical and Health Research Ethics. All participants signed an informed consent before entry.

The manikin was a modified Skillmeter Resusci Anne (Laerdal Medical, Stavanger, Norway) allowing simultaneous recording of ventilations and chest compressions. The manikin was found in ventricular fibrillation on the floor, and developed pulseless electrical activity (PEA) after the first shock. The manikin never achieved return of spontaneous circulation (ROSC). One paramedic in each paramedic team was randomised to perform all chest compressions.

In the present study, we analysed specifically data from the condition where the paramedics were exposed to socioemotional stress, because this condition scored significantly higher on a subjective rating of realism (8.0 vs. 5.5, P < 0.001) [20]. The resuscitation attempts were discontinued at different times based on the time of intubation, but they all performed CPR for at least twelve minutes and continued the resuscitation attempt until they were told to stop. We therefore analysed the first twelve minutes of the resuscitation attempts. Starting by plotting the distribution of chest compression depth for each minute of ALS in a boxplot (Figure 1), this figure revealed, as demonstrated in our previous study [17], the great inter-individual variation in chest compression depth already evident in the first minute of ALS. Paramedics were thereafter described and grouped into different categories based on their initial chest compression depth. The resuscitation attempts were sorted into three different groups (good, bad and decay) based on the development of chest compression depth and rate over time. The following definitions were used, based on the recommendations from the 2005 guidelines [21,22]:

Good: CPR with average chest compression depth ≥ 40 mm for every minute during the 12 minute resuscitation attempt. Average chest compression rate 100-120 for every minute.

Bad: CPR with initial average chest compression depth < 40 mm. Chest compression rate < 100 or > 120 per minute at the start of the resuscitation attempt.

Decay: CPR with initial average chest compressions depths ≥ 40 mm which dropped below 40 mm. Chest compression rates 100-120 per minute that decreased to < 100 or increased to > 120 per minute.

The no-flow ratio (NFR) was defined as the time without chest compressions divided by the total time of the ALS scenario. The NFR was analysed in three minute
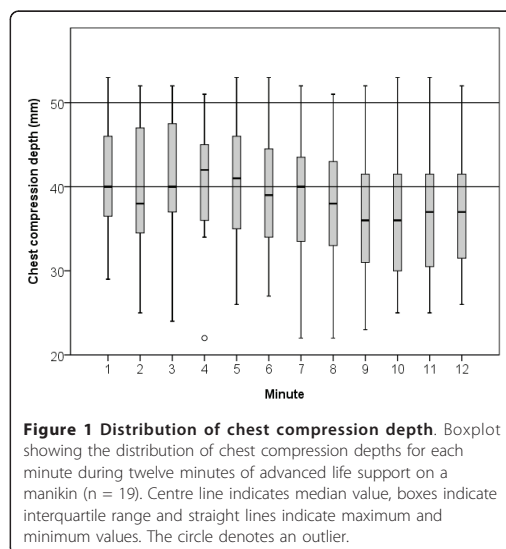

Figure 1 Distribution of chest compression depth. Boxplot showing the distribution of chest compression depths for each minute during twelve minutes of advanced life support on a manikin (n = 19). Centre line indicates median value, boxes indicate interquartile range and straight lines indicate maximum and minimum values. The circle denotes an outlier.

periods because Norwegian ALS guidelines [23] recommend analysis of rhythm every three minutes, as opposed to international guidelines with their two minute periods [24,25]. The paramedics in the present study followed the Norwegian guidelines and have been thoroughly trained in these guidelines since 2006.

Statistical analyses
We used SPSS version 17.0 (Chicago, IL, USA) for statistical analyses. Data are presented as mean values for each minute of ALS. We investigated the overall change in the NFR in the different three-minute periods using repeated measures ANOVA. Additionally we tested the difference between the first and each successive time interval pairwise using paired t tests. A P value of < 0.05 was regarded as significant. For the pairwise testing we had to take into account multiple testing effects, i.e. we adjusted the significance level using the Bonferroni correction. This leads to a significance level of 0.017 (3 pairwise tests).
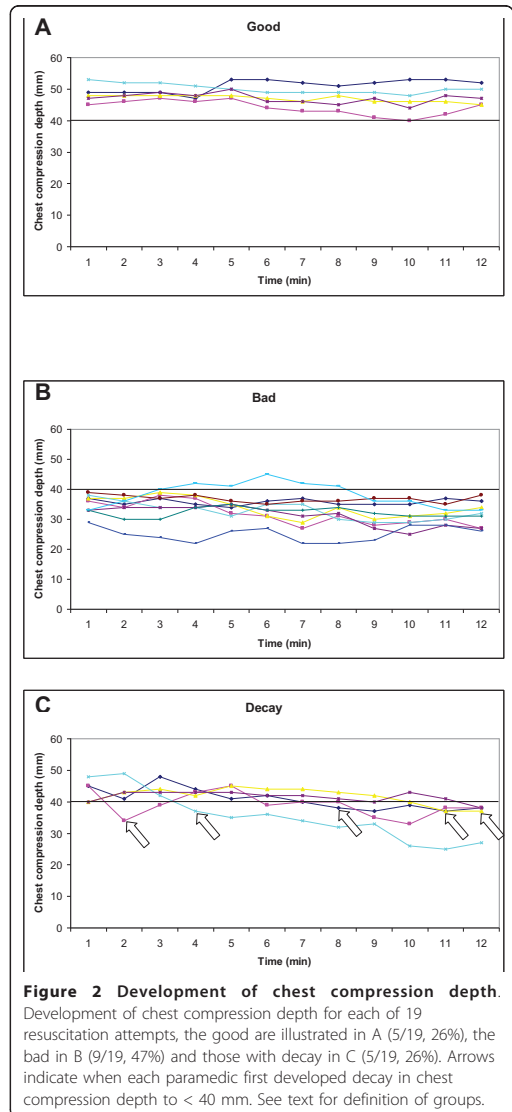
3. Results
Altogether 20 paramedic teams completed the study. One registration failed due to software failure. Hence, 19 ALS resuscitations were available for this chest compression quality analysis. In each resuscitation attempt, the same paramedic performed all the chest compressions, and 68% of the chest compression providers were male.

Based on chest compression depth, 26% (5/19) and 47% (9/19) of the ALS resuscitations were classified as good and bad throughout the 12 minute scenario, respectively. In these cases no signs of decay or major changes occurred (Figure 2), except for one among the bad, where sufficient chest compression depth was achieved between 3 and 8 minutes (Figure 2B). In 26% (5/19) of the cases, decay in chest compression depth was present. Of these five cases, only one paramedic displayed chest compression decay to below 40 mm within the first two minutes, the remainder after 4, 8, 11 and 12 minutes (Figure 2C).
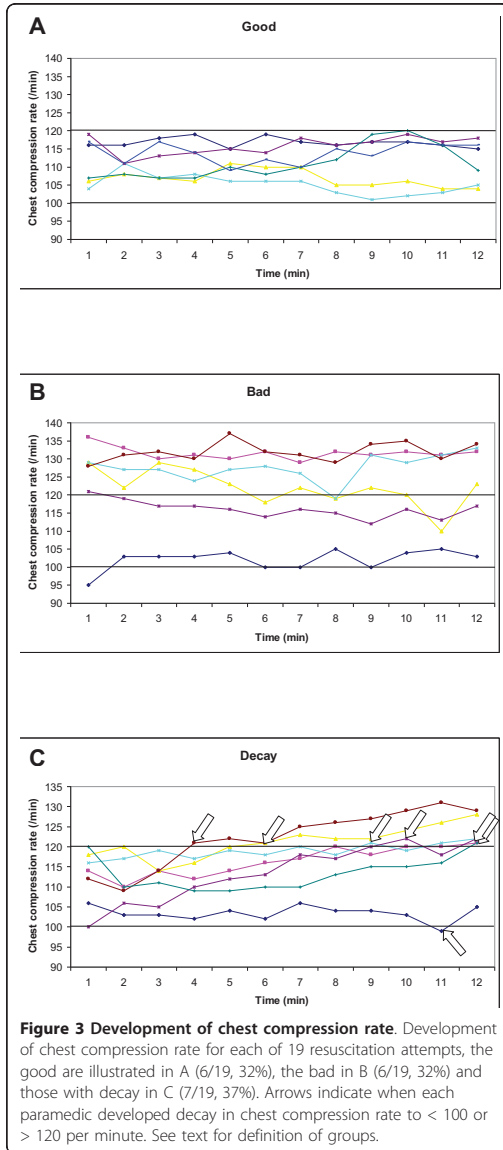
Based on chest compression rate, 32% (6/19) of the resuscitation attempts were scored as good and 32% (6/19) as bad. Among the bad, two achieved correct rate after the first minute. Decay was present in 37% (7/19) of the cases, and only one was evident in the first five minutes of ALS (Figure 3).

Average NFR for the 19 paramedics was 17%, with a range from 10 to 32%, and NFR changed significantly over time (P < 0.001). NFR remained unchanged at 22% in the 1-3 minute and 4-6 minute periods, but decreased to 14% from the 1-3 minute period to the 7-9 minute period (P = 0.002) and further to 10% from the 1-3 minute period to the 10-12 minute period (P < 0.001) (Figure 4).

Figure 2 Development of chest compression depth. Development of chest compression depth for each of 19 resuscitation attempts, the good are illustrated in A (5/19, 26%), the bad in B (9/19, 47%) and those with decay in C (5/19, 26%). Arrows indicate when each paramedic first developed decay in chest compression depth to < 40 mm. See text for definition of groups.
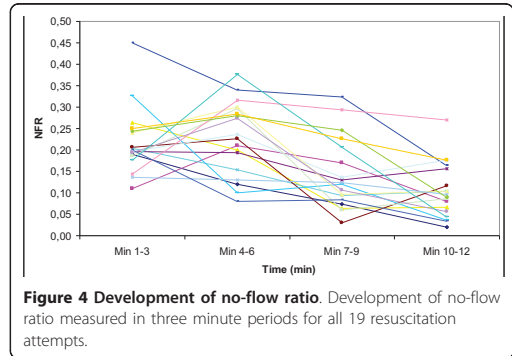
4. Discussion
In this manikin study, where each paramedic performed 12 minutes of chest compressions in a realistic ALS scenario, we demonstrated that huge inter-individual differences in chest compression depth and rate exist. This is present already from the initiation of ALS. Decay due to fatigue seems to be a less frequent problem, as only five and six out of 19 paramedics developed decay in chest compression depth and rate, respectively. Noteworthy,

Figure 3 Development of chest compression rate. Development of chest compression rate for each of 19 resuscitation attempts, the good are illustrated in A (6/19, 32%), the bad in B (6/19, 32%) and those with decay in C (7/19, 37%). Arrows indicate when each paramedic developed decay in chest compression rate to < 100 or > 120 per minute. See text for definition of groups.

Figure 4 Development of no-flow ratio. Development of no-flow ratio measured in three minute periods for all 19 resuscitation attempts.

decline in the percentage of correct compressions already evident in the second minute. The authors speculate that fatigue might be the reason for this compression quality decay without specifying whether the incorrect compressions were due to incomplete compression depth or wrong hand placement. Later manikin studies showed similar results with a decline in chest compression depth after the initial minutes of the CPR attempt [10,11,13,14,26]. A clinical study on in-hospital cardiac arrested patients [27] described a decay in chest compression depth that was statistically significant after only 90 seconds. However, no correction was made for different surfaces on which the patients were located. These previous studies all conclude that decay in mean chest compression depth is evident after a very short period of time. Importantly, their data analyses do not take into account the huge inter-individual differences among the CPR providers that will influence the results. We have in a previous BLS manikin study [17], as in the present ALS manikin study, documented that these inter-individual differences are present already from the initiation of CPR. Thus, it was necessary to analyse the data by sorting the individuals into different groups based on their initial chest compression quality, instead of calculating mean values for a large group of individuals.

In the 2010 guidelines optimal chest compression quality is even more emphasized than previously, and a chest compression depth of at least 50 mm is recommended [4,5]. Although our paramedics were trained in the previous guidelines recommending a compression depth of 40-50 mm, it is a cause of concern that 47% in the present study had chest compression depths of less than 40 mm already from the initiation of CPR. As seen in Figure 2B, this is not a result of fatigue or chest compression decay, but an inappropriate chest compression depth already from initiation of CPR. There are several potential reasons for this deviation from guidelines;

only one paramedic showed decay in chest compression depth within the initial two minutes, and only one showed decay in compression rate within the initial five minutes.

A manikin study by Hightower et al. from 1995, where 11 nursing assistants performed chest compressions for five minutes [9], described a significant and steady

insufficient muscular power, lack of sufficient body weight, as weight previously has been correlated with compression depth [28], an inaccuracy of chest compression depth because no feedback was available, or a fear of causing serious patient injury [29]. In a questionnaire among Norwegian and UK paramedics, Ødegaard et al. reported that many paramedics had concerns causing serious patient injuries if they compressed to the guidelines' depth [29]. Thus, it is very relevant to highlight chest compressions quality, especially compression depth, in ALS training and practise in the future. The fear of causing patient injuries must be overcome.

More positive, all paramedics had compression rates above 100 per minute for the majority of the resuscitation attempts. This is important as higher compression rates increase cardiac output resulting in increased myocardial and cerebral blood flow [30,31] and improved short-term survival in humans [32]. Decay in chest compression rate over time was rare and only evident in one paramedic within the first five minutes. 26% initiated CPR with chest compression rates above 120 per minute. This is unfavourable as coronary perfusion is reduced at rates over 120-130 per minute [31], thereby reducing the probability of successful resuscitation [33]. A metronome [34,35] or real time feedback [36] could improve the chest compression rate.

NFR did not increase over time in our study but actually declined, even though the same rescuer provided all the chest compressions for as long as 12 minutes. One likely explanation for this positive, continuous decrease in NFR over time is that the patient in our scenario developed PEA after the first shock, and hence there was no further need for charging the defibrillator and shocking the patient. On the other hand, an organised ECG rhythm necessitates pulse checks to differentiate PEA from ROSC in the absence of end-tidal CO_2-measurement ($ETCO_2$), and hence further increases the NFR. Further, as the patient was intubated after about five minutes [20], this could have contributed to the reduced NFR as this allows for simultaneous ventilations and continuous chest compressions [37]. A clinical observation study has also shown no increase in NFR over time [38]. Our paramedics had a NFR of 17% in the 12 minute study period which is comparable to recent clinical observation studies [39,40], and far better than data from the recent US ROC trials with NFR between 34 and 46% [36,41].

Importantly, based on our findings it seems unwarranted to recommend changing the person providing chest compressions every two minutes during ALS as recommended in the new resuscitation guidelines. It has been shown that provider switches account for at least 40% of NFR during CPR [12], and this can be reduced by avoiding unnecessary switches. Instead of changing

chest compression provider frequently, we recommend more attention on optimising chest compression quality already from the initiation of CPR, and that the chest compression quality should be monitored continuously with CPR feedback devices or capnography during ALS. CPR feedback devices have been shown to improve the quality of CPR, including chest compression depth and ROSC rate, but still have not led to increased long-term survival [36,42]. Capnography, with $ETCO_2$ measurements, predicts cardiac output [43] and is correlated with both ROSC and survival [44]. However, more studies are needed to show if CPR feedback devices or capnography can assist in finding the optimal time point for switching the provider of chest compressions.

There are limitations to this study. As it was a simulation manikin study, we do not know whether the quality of chest compression is compromised more or less in real cardiac arrest situations. It has been shown that paramedics are physically capable of compressing to guideline depth for 5 minutes even on a manikin with chest stiffness mimicking the upper eighth of chest stiffnesses in a patient population [29]. The manikin in our study does not represent the large variation in stiffness and damping found in human chests during CPR [45,46]. Further, our study included paramedics with a median experience of 8.5 years and frequent refresher training in ALS. We do not know if chest compression decay or chest compression quality in general is different for less experienced paramedics and other health care providers. As this is the first study to explore chest compression decay by sorting individuals based on compression quality, a power analysis was not performed and hence we cannot rule out that our results are caused by insufficient power. Finally, we followed the recommendations from the Norwegian 2005 guidelines in the present study [23], with 4 cm of chest compression depth regarded as good. We might speculate that the 5 cm recommendation from 2010 would have caused more decay and fatigue, especially if every paramedic initially compressed to the guidelines depth. Further studies are indeed warranted.

5. Conclusion
In this simulated cardiac arrest manikin study, only half of the providers achieved guideline recommended compression depth during prolonged ALS. Large inter-individual differences in chest compression quality were already present from the initiation of CPR. Chest compression decay and thereby fatigue within the first two minutes was rare.

6. Competing interests
CAB has a part-time employment as facilitator at Stavanger Acute Medicine Foundation for Education and

Research (SAFER). ES is medical director at SAFER. CAB and ES have received financial support from the Laerdal Foundation for Acute Medicine. HM is an employee of Laerdal Medical. KS and JA have no competing interests.

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Authors' contributions
CAB participated in study design, running the simulations, statistical analyses and manuscript writing, KS and ES in study design and manuscript writing, HM in study design, running simulations and manuscript writing, and JA in statistical analyses and manuscript writing. All authors read and approved the final manuscript.

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