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PAPER

PATHOLOGY/BIOLOGY

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Manual and Automated Cardiopulmonary Resuscitation (CPR): A Comparison of Associated Injury Patterns*,†

ABSTRACT: The purpose of this study was to identify and compare patterns of trauma associated with AutoPulse® CPR and manual CPR. Finalized autopsy records from 175 decedents brought to the Harris County Institute of Forensic Sciences were reviewed, 87 received manual-only CPR, and 88 received AutoPulse® CPR (in combination with manual CPR as per standard protocol). The characteristic pattern observed in manual-only CPR use included a high frequency of anterior rib fractures, sternal fractures, and midline chest abrasions along the sternum. The characteristic pattern observed in AutoPulse® CPR use included a high frequency of posterior rib fractures, skin abrasions located along the anterolateral chest and shoulder, vertebral fractures, and a few cases of visceral injuries including liver lacerations, splenic lacerations, and hemoperitoneum. Knowledge of the AutoPulse® CPR injury pattern can help forensic pathologists differentiate therapeutic from inflicted injuries and therefore avoid an erroneous assessment of cause and manner of death.

KEYWORDS: forensic science, forensic pathology, trauma, cardiopulmonary resuscitation, device-assisted cardiopulmonary resuscitation, AutoPulse®

Advancements in device-assisted cardiopulmonary resuscitation (CPR) have greatly improved their use in recent years. With device-assisted CPR, emergency personnel employ the use of equipment to provide chest compressions *in lieu* of traditional CPR where the compressions are performed manually. Device-assisted CPR can be divided into two categories, manual and automated. Manual device-assisted CPR, also known as active compression-decompression CPR (ACD-CPR), uses a manually operated suction cup apparatus such as the CardioPump® or ResQPump® that is placed over the anterior mid-chest with the goal of producing more efficient blood flow (1). These devices require the constant efforts of emergency personnel to administer chest compressions. On the other hand, automated device-assisted CPR produces continuous chest compressions autonomously, thus allowing emergency medical personnel to tend to other lifesaving tasks and to also allow for continuous compressions during transport downstairs or other uneven surfaces. There are two types of automated CPR devices, one uses a piston and the other uses a band. Piston chest compression devices, such as the Thumper® and the LUCAS™, provide anterior chest compressions with the use of a piston located at the terminus of an automated arm (2). Automated load-distributing band (LDB) devices, such as the AutoPulse®, constrict the chest through a band that encircles the chest to stimulate blood flow.

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With the introduction and development of various models, testing and validation studies have been, and continue to be, conducted to evaluate their efficacy in increasing survival rates of patients in cardiac arrest. The mode of delivery of CPR varies between these devices, particularly in how compressive forces are administered to the body. The devices range from compression to the anterior mid-chest mimicking manual CPR to LDBs that provide repetitive circumferential compression to the entire rib cage. According to Wigginton et al. (3), device-assisted CPR, particularly automated CPR devices, results in improvement of hemodynamic effects, coronary perfusion, and spontaneous circulation when compared with manual CPR. In contrast, manual CPR often results in first aid responder fatigue, inconsistent rates of delivery, inefficient venous return, and inhibition of full chest wall recoil due to the weight of the responders against the patient's chest (3). Researchers have found increased benefits in the use of device-assisted CPR. Ong et al. (4) demonstrated that the use of LDB-CPR devices has better survival rates and even recommend their use when manual CPR is ineffective. Despite these findings, Hallstrom et al. (5) found that LDB-CPR results in lower survival rates and higher number of neurological problems. The researchers suggested some possible explanations for their findings including: learning curve for device use; bias in patient enrollment in the study; and toxicity from medications not designed for superior blood flow as delivered by LDB-CPR. With multiple factors affecting the results, the true efficacy of the devices in these studies is difficult to assess.

Trauma associated with manual and device-assisted CPR has been reported in the literature. Studies done of cases involving manual CPR report various soft- and hard-tissue injuries including sternal fractures ($\leq 43\%$), rib fractures (13–97%), spine fractures (0.1%), liver injuries (2–3%), spleen injuries (0.3–0.5%), and pneumothoraces (2.6%) (6–8). A limited number of studies have addressed injuries associated with automated device-assisted CPR such as liver lacerations, rib fractures, skin abrasions, and other soft-tissue damage in cases of AutoPulse® (an LDB device) and LUCAS® (a suction cup device) use (9–11). Baubin et al. (12) found that the use of the CardioPump® (a suction cup device providing ACD-CPR) on cadavers results in anterior and lateral rib fractures as well as sternal fractures.

In 2007, Houston, Texas was selected as a test site for the ZOLL AutoPulse® Noninvasive Cardiac Support Pump (13). The AutoPulse® is a portable LDB device consisting of a short back supporting platform and an attached band (LifeBand®). First Responder protocol for AutoPulse® use dictates that the patient must receive manual chest compressions until the device is ready to use. The patient is placed supine on the platform, and the band is secured around the patient's chest. When employed for use, the band automatically adjusts to the size, shape, and resistance of the patient's chest which should be no more than 9.8–15 inches in width and provides approximately 80 compressions per minute which constrict the chest depth by 20% (14). Full compression and release occurs with each cycle. According to ZOLL, the benefits of this device include continuous CPR without fatigue, relief for EMS personnel who are then free to perform other lifesaving tasks, and improved blood flow for patients with cardiac distress (15). The device is not recommended for individuals under the age of 18 years, trauma patients, or individuals whose body weight exceeds 300 pounds.

The purpose of this study was to identify and compare patterns of trauma associated with manual-only CPR to device-assisted CPR, in particular the AutoPulse®. The goal was to report injury patterns typically associated with medical intervention, to raise awareness of the injury, and in turn reduce the potential to misidentify therapeutic injury as accidental or inflicted injury.

Accurate recognition and interpretation of trauma is critical in the forensic setting for correct classification of cause and manner of death. The pattern of injuries is used to help differentiate therapeutic, inflicted, and accidental trauma. Failure to accurately differentiate therapeutic injury from traumatic injury may lead to an erroneous classification of cause and manner of death and associated judicial implications.

This study expands on previous research that found upper body skin abrasions associated with AutoPulse® use (9) through documenting all hard- and soft-tissue trauma associated with both manual CPR and the AutoPulse®. Due to the differences in biomechanical forces sustained by the body during these two types of CPR, manual CPR involving localized anterior to posterior compression and AutoPulse® CPR involving circumferential compressions, variations in location and distribution of fractures as well as visceral injuries are expected.

Methods

A retrospective analysis of 175 autopsy reports finalized between 2005 and 2009 by the Harris County Institute of Forensic Sciences (HCIFS) in Houston, Texas was conducted. A keyword search using the term "cardiopulmonary resuscitation" was used to identify cases of medical intervention. Only injuries attributed to CPR attempts were recorded. The manner of death for the study sample included natural (67%), accident (24%, primarily deaths due to drug toxicity), suicide (5%), homicide (3%), and undetermined (1%). The study sample consisted of 87 autopsies involving manual-only CPR and 88 autopsies involving the combination of manual and AutoPulse® CPR, as per standard protocol for AutoPulse® use. In the manual-only CPR group, 38 were females, and 49 were males ranging in age from 16 years to 89 years (median age of 48 years). In the AutoPulse® CPR group, 35 were females, and 53 were males ranging in age from 15 years to 84 years (median age of 54 years). The research variables in this study included sex, age grouping ($\leq$45 years and 45+ years), body mass index (BMI) of the decedent (underweight <18.5, normal 18.5–24.9, overweight 24.9–29.9, obese >30), absence/presence of sternal fractures, absence/presence of rib fractures, location of rib fractures (anterior, anterolateral, lateral, posterolateral, posterior), presence/absence of vertebral fractures, presence/absence of abrasions, and presence/absence of visceral injuries.

Statistics

Using STATISTICA, a statistical analysis software package, descriptive statistics were generated, and Shapiro–Wilks Normality tests were performed to check for distribution normality of the variables. Because the data were nonnormal, appropriate nonparametric analyses (Kruskal–Wallis analysis of variance [ANOVA]) were then used to compare the effects of manual-only CPR to AutoPulse® CPR.

Results (Ribs)

Overall

There is a statistically significant difference in the frequency of overall rib fractures between the manual-only group and the AutoPulse® group (Table 1). The manual-only CPR group has a higher overall occurrence of rib fractures (p = 0.0038). ANOVA results demonstrated a significant difference (p < 0.0001) in anterior fractures between the manual-only and AutoPulse® CPR groups, with the higher frequency in the manual-only group. In addition, a significant difference (p < 0.0000) was also observed in posterior fractures between the two CPR groups, with a higher frequency in the AutoPulse® group. There were no significant differences in fractures between the anterolateral, lateral, or posterolateral regions with respect to the two CPR groups.

ANOVA results also demonstrated a statistically significant difference between the regions in each of the CPR groups. The anterior rib fractures (54%) were ranked as the most frequently occurring fractures in manual-only CPR and decrease in the following order: anterolateral (26%), lateral (19%), and posterior (0.4%) rib regions with no posterolateral fractures present (Note: The only case of posterior rib fractures associated with manual-only CPR was found to be the result of chest compressions administered to an elderly woman lying on an uneven surface)

TABLE 1—p-*Values of Kruskal–Wallis ANOVA Analyses Comparing the Frequency of Rib Fractures in Manual and AutoPulse® CPR*

Region	p-Value	
Overall	0.0038*	Manual > AutoPulse®
Anterior	0.0001*	Manual > AutoPulse®
Anterolateral	0.1664	
Lateral	0.0678	
Posterior	0.0000*	AutoPulse® > Manual
Posterolateral	0.1585	

*Significant at 0.05 level.

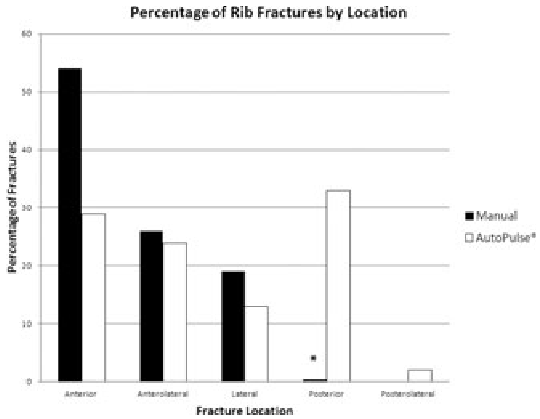

FIG. 1—*Distribution of rib fractures according to their location on the rib cage. (*Note: The one case of posterior rib fracture (0.4%) in the manual CPR group is an elderly woman who received manual CPR while lying supine on an uneven surface.)*

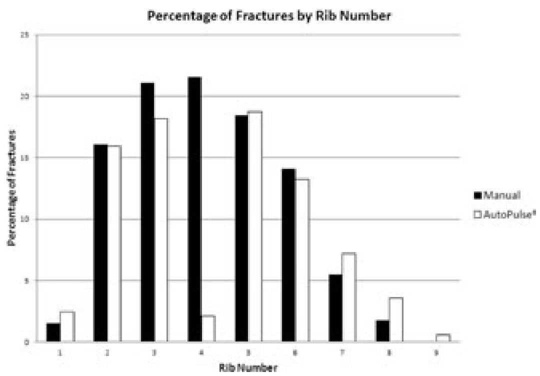

FIG. 2—*Percentage of fractures observed on each rib resulting from the two types of CPR.*

(Fig. 1). Significant differences were also found in the AutoPulse® CPR group; however, posterior fractures (33%) were the most frequently occurring fractures and decrease in the following order: anterior (29%), anterolateral (24%), lateral (13%), and posterolateral (2%) rib regions.

Difference by Rib Number

In both manual-only CPR and AutoPulse® CPR, ribs 3, 4, and 5 were the three most commonly fractured ribs with the frequency dropping substantially at rib 1 superiorly and rib 7 to rib 9 inferiorly (Fig. 2).

Side Difference

There is no statistically significant difference between the frequency of injuries on the left ribs compared with the right ribs observed in the manual-only CPR group or the AutoPulse® group.

Effects of BMI

ANOVA results showed no statistically significant difference between the underweight, normal, overweight, and obese groups with respect to anterior, anterolateral, lateral, posterior, or posterolateral fractures in either the manual-only CPR or the AutoPulse® CPR group.

FIG. 3—*Sternal fracture (arrow) resulting from manual CPR.*

Difference Between the Sexes

There were no statistically significant difference between the rib fractures in males versus females in either the manual-only CPR group or the AutoPulse® CPR group.

Effects of Age

A statistically significant difference between the $\leq$45-year-old group and 45-plus-year-old group was found in the anterior fractures of the manual-only group ($p < 0.05$), with the older group having a relatively larger number of fractures. No significant differences were found in the other regions of the manual-only group or any region in the AutoPulse® CPR group.

Results (Sternum)

Sternal fractures (Fig. 3) in the manual-only CPR group are found in 45% of all cases, a significantly higher frequency ($p < 0.05$) than those compared with the AutoPulse® CPR group, which exhibited sternal fractures in approximately 14% of all cases.

Results (Vertebrae)

Vertebral fractures were only observed in the AutoPulse® group in approximately 4.5% of cases, with injuries located in the thoracic and lumbar vertebrae. Two cases of fractured osteophytes on thoracic vertebra 10 (T10), one case of thoracic vertebra 4 (T4) and T10 body fractures (Fig. 4), and one case of lumbar vertebrae 1 and 2 (L1 and L2) right transverse process fractures were observed in the AutoPulse® group.

Results (Cutaneous)

A statistically significant difference was observed in skin abrasions between the manual-only CPR group and the AutoPulse®

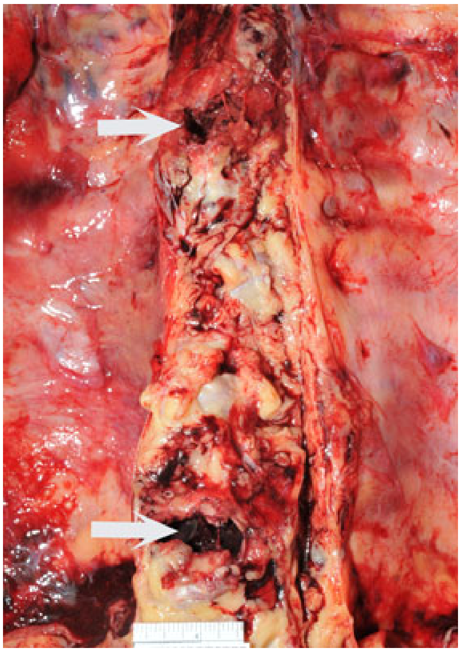

FIG. 4—*Transverse fractures of vertebral bodies T4 (upper arrow) and T10 (lower arrow).*

FIG. 5—*Midline abrasions resulting from manual CPR.*

CPR group (p = 0.0000). In the manual-only CPR group, 24% of the cases had skin abrasions present, while the AutoPulse® CPR group had abrasions in 96% of the cases. Manual-only CPR-associated abrasions were located at the mid-chest along the sternum (Fig. 5), while AutoPulse® associated abrasions were located along the axilla, shoulder, chest, and/or arm (Fig. 6).

Results (Visceral)

Only one case of manual-only CPR cases (~1%) had evidence of visceral injury, one case of a liver laceration located along the midline of the liver near the falciform ligament (Fig. 7). In the AutoPulse® CPR group, only three cases (~3%) had evidence of any visceral injury, which included posterolateral right lobe liver lacerations with associated injury to the capsule (Fig. 8), mesenteric lacerations, splenic lacerations, and hemoperitoneum.

FIG. 6—*Abrasions of the axilla, arm, and chest resulting from AutoPulse® CPR.*

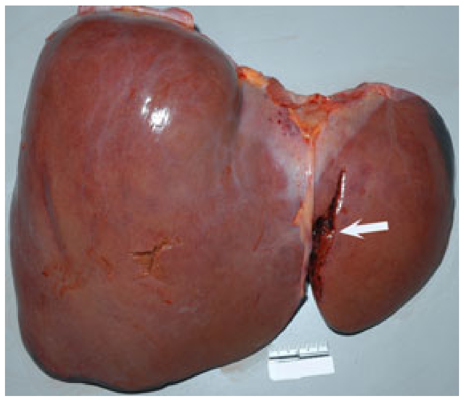

FIG. 7—*Lacerations of the liver (arrow) located near the falciform ligament in manual CPR.*

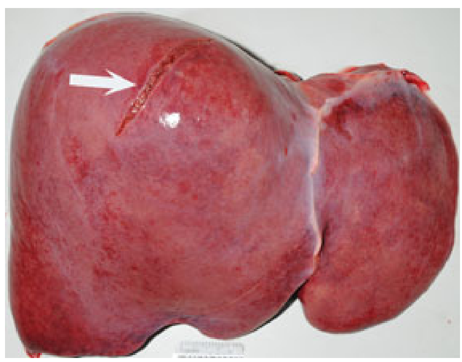

FIG. 8—*Lacerations of the liver (arrow) located along the right lobe of the liver in AutoPulse® CPR.*

Discussion

Significant differences were found between hard- and soft-tissue trauma associated with the two modes of CPR. The results of this

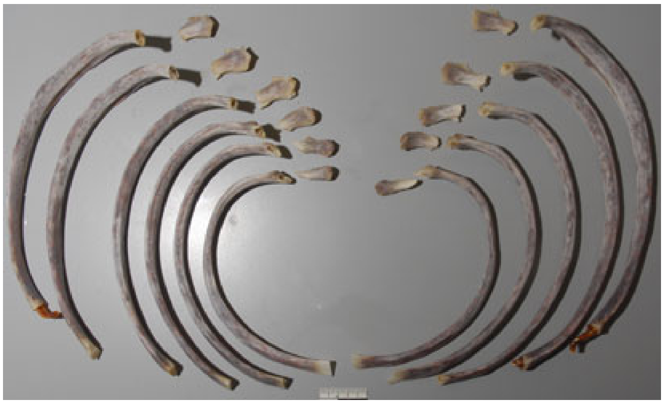

FIG. 9—*Posterior rib fractures are commonly seen in cases of AutoPulse® CPR. An example of complete transverse fractures through the tubercles of right rib 3 through rib 8 and left rib 3 through rib 7 from an individual who was administered AutoPulse® CPR.*

study demonstrate a differential pattern of trauma produced in manual-only CPR compared with AutoPulse® CPR with respect to skin abrasions, rib fractures, and sternal fractures. These findings suggest that the pattern of trauma associated with manual-only CPR include anterior rib and sternal fractures, while AutoPulse® CPR generally results in posterior rib fractures (Fig. 9) primarily with skin abrasions along the axilla, shoulder, or arm.

Manual-Only CPR

The manual-only CPR fractures observed in this study are consistent with previous studies (6–8), demonstrating a high percentage of cases with rib fractures and approximately half of the cases with sternal fractures. The results show that anterior rib fractures are the most frequent type of injury noted followed by anterolaterally and laterally located fractures. In addition, sternal fractures are also significantly higher in this CPR group likely due to bone fatigue after prolonged chest compressions. The cause of this rib and sternum fracture pattern is twofold. First, in a study of end-loaded isolated ribs, Daegling et al. (16) found that the anterior rib shaft is weaker compared with the posterior region of the rib. Therefore, loading of the ribs at or near the ends as is performed in manual-only CPR, applies the greatest force to the weakest point of the rib thus increasing the risk of fracture. Second, during manual chest compressions, both hands are placed at the mid-chest where the maximum biomechanical force is routed through the hypothenar regions surrounding the fifth metacarpal (17). The close proximity of these regions results in a large force over the sternal area, therefore resulting in sternal and anterior rib fractures. In addition, the three most commonly fractured ribs in the manual-only CPR group are ribs 3 to 5 corresponding to the standard location of palm placement during manual chest compressions.

Although BMI and sex did not have an effect on skeletal injuries resulting from manual-only CPR, a significant difference was observed between anterior rib fractures in the $\leq$45-year-old group and 45-plus-year-old group. A higher number of fractures were observed in the older group, likely resulting from a reduction in bone quality due to age-associated bone loss and therefore an increased predisposition to fractures.

Soft-tissue injuries, as previously reported, were also observed in this study. Only one case of visceral injury was present in the study sample. The midline liver laceration is consistent with the area of the chest where manual compressions are performed. The low frequency of visceral injuries resulting from manual-only CPR observed in this study is consistent with those reported in the literature (6,8). In the few cases of manual-only CPR with skin abrasions, these abrasions were located in the mid-chest and were likely caused by irritation and pressure to the localized area.

AutoPulse® CPR

In the AutoPulse® group, posterior rib fractures were the most frequent type of injury followed by anterior, anterolateral, lateral, and posterolateral rib fractures. In addition, skin abrasions, as have been previously described (9,11), were found in a high percentage of cases in the AutoPulse® group. The combined rib fracture and abrasion pattern are the result of the patient's body being secured to a back-stabilizing board. The abrasions are the result of the LifeBand® guards located on the sides of the board, which contact the patient's lateral torso and/or inner arm. By securing the back to a stabilizing board with bands, each rib forms what can be compared to as a first-class lever system in the posterior region of the rib. The costotransverse articulation becomes a fulcrum with the head as the load arm and the body as the applied force arm (18). When the chest is compressed, the body of the rib pivots around the fulcrum and because the load arm is immobile due to the combination of ligamentous attachments as well as the stabilizing board, the stress exceeds the failure point and a fracture occurs. Unlike manual-only CPR where force is only exerted on the anterior chest therefore resulting in mainly anterior fractures, compressive bands around the torso results in a varied distribution of fractures through the entire rib cage, as is observed in this study.

There is a high percentage of anterior rib and sternal fractures in the study population, likely the result of the manual CPR. Resuscitation protocol using the AutoPulse® requires manual CPR to be used first while the equipment is being prepared. Not uncommonly, manual CPR is already being performed by a bystander prior to the arrival of the emergency personnel. Based on the type and location of the fractures, the anterior rib and sternal fractures are potentially caused during manual CPR; however, the compressive forces of the LifeBand® cannot be excluded as a contributing factor.

Vertebral fractures from AutoPulse® use may be due to the positioning of the body on the stabilizing board. The inferior end of the board is an inclined plane. The body is positioned on the board such that upper thoracic spine is on the flat region of the board and the lower thoracic spine descends along the incline. During the compressions, the back is forced to pivot at the point where the level board transitions into the incline. The vertebral fractures of the lower thoracic and upper lumbar spine are likely the result of the compressive force against an uneven plane.

With respect to visceral injuries, the liver lacerations in the AutoPulse® group are different from the manual group in that the lacerations are posterolaterally located and are associated with shearing of the capsule. The mechanism of injury is postulated to occur as a result of improper band placement and/or the rebound movement of the abdominal pannus against the lower ribs during use. In contrast, liver lacerations associated with manual CPR are located anteriorly, at the falciform ligament, and are not associated with shearing of the capsule. Hemoperitoneum is also observed in the AutoPulse® group and although not observed in this study sample has been found in cases of manual-only CPR (6). The difference between the hemoperitoneum encountered with the two types of CPR is that AutoPulse® use results in a much larger volume of blood (ranging from 300 –3000 ml), whereas blood resulting from manual CPR is typically < 250 ml (19).

The results of this study show that cutaneous, skeletal, and visceral injuries occur in cases of AutoPulse® use. The cutaneous and skeletal injuries occur at a higher frequency than visceral injuries. With AutoPulse® use, skin abrasions are generally located around the shoulder, axilla, and arm with skeletal injuries including rib, sternal, and vertebral fractures. The infrequent presence of visceral injuries demonstrates that although not common, these injuries can potentially occur in LDB-CPR. The direct cause of these injuries cannot be solely attributed to the AutoPulse® because similar skeletal and visceral injuries have also been observed in manual-only CPR (6,8), a technique employed prior to device use. It is very important for forensic pathologists to be aware of the injury pattern associated with automated CPR use in order to avoid an erroneous assessment of cause and manner of death.

Conclusion

A review of 87 autopsy cases involving manual-only CPR and 88 autopsy cases involving AutoPulse® CPR finalized at HCIFS was conducted. The purpose of the review was to compare the patterns of cutaneous, skeletal, and visceral injuries associated with the two types of CPR. The study population was represented by males and females with a median age around 50 years. The results of this study demonstrate that there is a clearly distinct pattern of injury associated with manual-only CPR, which differs from that associated with AutoPulse® CPR. Anterior rib fractures coupled with sternal fractures are commonly found in association with manual-only CPR, while posterior rib fractures and skin abrasions are commonly found in AutoPulse® CPR cases. No significant difference in rib fractures was found between the use of manual-only CPR versus AutoPulse® CPR with respect to sex, BMI, age (except for the anterior fractures in the manual-only CPR group), or rib side. Visceral injuries such as liver lacerations, splenic lacerations, and hemoperitoneum, were infrequent and when present, were only in cases of AutoPulse® use.

The significant findings in this study are that posterior rib fractures occur with a high frequency in AutoPulse® CPR cases. Utilization of this device in patients with potential blunt trauma could complicate interpretation of these injuries. With complete information regarding the circumstances surrounding the death, including the type(s) of CPR performed, and awareness of these known therapeutic injuries, forensic pathologists can reduce the potential to misidentify therapeutic injuries as inflicted.

Future Directions

A prospective study analyzing specific details of the fractures such as type of fracture (transverse, oblique, buckle, complete, incomplete) and rib surface involvement as well as variations in fracture location may provide better insight into the mechanism of these CPR-related fractures. Schmidt (20) found that direct impacts result in inward bending of ribs, whereas indirect impact result in outward bending and that dynamic loading results in different fracture patterns. These findings suggest that the mode of CPR has the potential to leave a signature in more than just the location of the fracture.

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