Sudden death resulting from ventricular fibrillation (VF) caused by a nonpenetrating chest wall impact, known as commotio cordis (CC), is the second leading cause of death among young athletes. To date, seven young athletes wearing chest protectors have died from CC. The purpose of this study was to determine whether a relationship exists between mechanical properties of chest protectors and occurrence of VF, previously determined by Weinstock et al., using an established swine model. A servo-hydraulic material tester was used to determine properties of the chest protectors, including displacement, permanent deformation, stiffness, and area of pressure distribution. These properties were then compared with the occurrence of VF. We found that a decreased proportion of hits resulting in VF was significantly associated ($R^2 = 0.59, p = 0.001$) with an increase in the area of pressure distribution. These findings are a limited, but crucial, first step in understanding the prevention of this complex and perplexing phenomenon.

Key Words: sports, quasi-static compression, lacrosse, baseball, safety equipment

Commotio cordis—the second leading cause of death in young athletes—is sudden death (or aborted sudden death) resulting from a nonpenetrating chest wall impact in the absence of structural damage to the heart, ribs, or sternum (Link, 2003; Maron, 2003). This sudden death syndrome most commonly occurs in young, healthy athletes as the result of a blow from a blunt object, such as a baseball, lacrosse ball, or hockey puck. Commotio cordis has the greatest chance of occurring if the impact takes place during the vulnerable period, at 15 to 30 ms before the peak of the T-wave in the cardiac cycle, thus resulting in ventricular fibrillation (Link et al., 1998). Surprisingly, these fatal impacts usually result from projectiles moving at relatively low speeds (48.3–80.5 km/hr [30–50 MPH]) (Maron et al., 2002). Although the underlying causes of this potentially deadly condition are still unknown, understanding commotio cordis has become a priority of many doctors, researchers, and athletic associations.

Commotio cordis arises in many different settings, including child abuse cases, motor vehicle accidents, recreational activities, and sporting events. In attempts to learn more about commotio cordis, a registry of all documented cases was established in 2001. Of the 128 cases in the original registry, only 28 (22%) of the victims were 18 years of age or older. The majority of these incidents took place during an organized sporting activity (79 of the 128 cases, 62%) (Maron et al., 2002).

Owing to the nature of sports that utilize hard balls, such as baseball and lacrosse, impact injuries should be anticipated. However, commotio cordis
occurs even in sports in which athletes are equipped with chest protectors intended to reduce the risk of injury. In fact, of the 128 confirmed cases in the commotio cordis registry, 22 (28%) of the individuals were wearing commercially available safety equipment. In seven of these cases (three lacrosse goalies, two baseball catchers, and two hockey players), it was documented that the projectile made direct contact with the chest protector (Maron et al., 2002).

Although the number of cases of commotio cordis per annum is quite low, the survival rate from these incidents is much lower. As of 2001, the survival rate of individuals receiving nonpenetrating blows to the chest was 16% (Maron et al., 2002); hence, the ability to understand and prevent commotio cordis has become extremely important. A swine model has been created to learn more about commotio cordis. Since its development, the swine model has been utilized to investigate many factors that contribute to commotio cordis (Link et al., 1998, 2001, 2003a, 2003b). Recently this animal model was used to investigate the relationship between commercially available chest protectors and the incidence of ventricular fibrillation (Weinstock et al., 2006). In this experiment, sections of commercially available chest protectors were fixed to the chests of juvenile swine, and control animals wore no protection. Then the animals were subjected to blunt impacts to the precordium at 17.88 m/s (40 MPH). The blows were timed so that they impacted the chest during the vulnerable period of the cardiac cycle.

Weinstock et al. found that none of the chest protectors were able to significantly reduce the proportion of hits resulting in ventricular fibrillation. However, one model showed a trend toward a reduced occurrence of ventricular fibrillation, which was promising owing to the fact that this particular model’s padding differed from that of the other models. However, no specific recommendation could be made as to which mechanical property could be modified to reduce the proportion of ventricular fibrillation. Importantly, although none of the chest protectors reduced the occurrence of ventricular fibrillation, Weinstock et al. did record a range of ventricular fibrillation values from approximately 20% to 55%. This led us to question whether there was a mechanical property of the chest protectors that could explain this range of values, which may assist in the design of safer equipment.

The purpose of this study was to determine whether a relationship exists between the occurrence of ventricular fibrillation and the mechanical properties of the chest protectors, including displacement, stiffness of the padding material, and the area over which pressure is distributed by the chest protector. Our hope is that one of these properties could be manipulated to increase the safety and effectiveness of baseball and lacrosse chest protectors with regard to commotio cordis.

Methods

Eleven models of commercially available chest protectors (Table 1, Figure 1) were evaluated to determine whether their mechanical properties were predictive of the previously reported proportion of hits resulting in ventricular fibrillation (percentage). These models were identical to those used in the Weinstock et al. study and had been chosen based on their widespread use by baseball catchers and lacrosse goalies, and the fact that they represented most products on the market today in terms of composition and design. Each chest protector had a soft, compliant layer of padding (foam in all but one model) varying in density and thickness. The thickness was measured with calipers (Series 50 Digimatic ABSolute type Caliper, Mitutoyo Measurement Technology). Many models (e.g., Heart-Gard, ProVest, BCP550, Ventilator Pro, GBP, Icon, and Goalie Guard 5000) also had a layer of hard plastic either imbedded within the layers of foam or on the surface of the chest protector. One model, the Brine Ventilator Pro, differed from the other models because it was constructed of expanded polypropylene beads, instead of closed-cell foam.

A total of 25 test sites across the 11 models were chosen for investigation. For each chest protector model, the area covering the cardiac silhouette was determined following consultation with Dr. Link, during which the age of the potential users and proper fitting of the equipment were taken into consideration. Test sites were then chosen so that each type of padding within the region covering the cardiac silhouette would be tested. These test sites included the middle of padded sections within the selected regions, as well as sites along seams. For each test site, four additional sites of equivalent composition were chosen to ensure that we were investigating the properties of undamaged chest
Table 1  Commercially Available Chest Protectors Sorted by Test Site With Results for the Various Properties Investigated in This Study

<table>
<thead>
<tr>
<th>Make</th>
<th>Model</th>
<th>Ball (cm)</th>
<th>% VF</th>
<th>Thickness (mm)</th>
<th>Area (mm(^2))</th>
<th>Displacement (mm)</th>
<th>Percent deformation</th>
<th>Permanent deformation (mm)</th>
<th>Low stiffness (N/mm)</th>
<th>High stiffness (N/mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rawlings</td>
<td>BCP550</td>
<td>7.62</td>
<td>41</td>
<td>15.72</td>
<td>1305.77</td>
<td>14.33</td>
<td>95.50</td>
<td>10.80</td>
<td>−36.11</td>
<td>−4104.73</td>
</tr>
<tr>
<td>Rawlings</td>
<td>Youth LBP-1</td>
<td>7.62</td>
<td>35</td>
<td>24.57</td>
<td>863.36</td>
<td>16.73</td>
<td>68.09</td>
<td>13.12</td>
<td>−12.19</td>
<td>−5692.88</td>
</tr>
<tr>
<td>Cooper</td>
<td>BP-40</td>
<td>7.62</td>
<td>35</td>
<td>19.48</td>
<td>1536.20</td>
<td>18.40</td>
<td>94.46</td>
<td>5.40</td>
<td>−22.00</td>
<td>−5479.20</td>
</tr>
<tr>
<td>ProVest</td>
<td>ProVest</td>
<td>7.62</td>
<td>22</td>
<td>19.80</td>
<td>1781.51</td>
<td>17.58</td>
<td>88.79</td>
<td>11.34</td>
<td>−21.81</td>
<td>−2425.42</td>
</tr>
<tr>
<td>ProVest</td>
<td>ProVest - side</td>
<td>7.62</td>
<td>49</td>
<td>11.38</td>
<td>897.13</td>
<td>7.09</td>
<td>62.28</td>
<td>2.53</td>
<td>−48.03</td>
<td>−7335.44</td>
</tr>
<tr>
<td>S&amp;M H.P.P.</td>
<td>Heart-Gard</td>
<td>7.62</td>
<td>41</td>
<td>10.41</td>
<td>1141.10</td>
<td>12.24</td>
<td>117.54</td>
<td>6.40</td>
<td>−48.24</td>
<td>−6003.96</td>
</tr>
<tr>
<td>Cooper</td>
<td>Pro BPX</td>
<td>7.62</td>
<td>27</td>
<td>25.82</td>
<td>1690.66</td>
<td>16.76</td>
<td>64.92</td>
<td>9.78</td>
<td>−28.97</td>
<td>−4386.31</td>
</tr>
<tr>
<td>Brine</td>
<td>GBP</td>
<td>6.35</td>
<td>33</td>
<td>19.91</td>
<td>1565.89</td>
<td>18.16</td>
<td>91.23</td>
<td>5.55</td>
<td>−32.07</td>
<td>−2843.69</td>
</tr>
<tr>
<td>Brine</td>
<td>GBP - side</td>
<td>6.35</td>
<td>50</td>
<td>19.32</td>
<td>1205.82</td>
<td>17.64</td>
<td>91.32</td>
<td>5.29</td>
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<tr>
<td>STX</td>
<td>Aegis</td>
<td>6.35</td>
<td>50</td>
<td>24.24</td>
<td>1212.08</td>
<td>15.34</td>
<td>63.27</td>
<td>7.92</td>
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<td>−3379.15</td>
</tr>
<tr>
<td>Brine</td>
<td>Ventilator Pro</td>
<td>6.35</td>
<td>21</td>
<td>23.96</td>
<td>1851.78</td>
<td>18.32</td>
<td>76.46</td>
<td>9.69</td>
<td>−23.66</td>
<td>−3558.15</td>
</tr>
<tr>
<td>DeBeer</td>
<td>Icon</td>
<td>6.35</td>
<td>38</td>
<td>20.01</td>
<td>1458.86</td>
<td>17.93</td>
<td>89.61</td>
<td>6.92</td>
<td>−27.71</td>
<td>−3802.45</td>
</tr>
<tr>
<td>Warrior</td>
<td>Goalie Guard 5000</td>
<td>6.35</td>
<td>33</td>
<td>19.67</td>
<td>1341.11</td>
<td>19.73</td>
<td>100.32</td>
<td>7.40</td>
<td>−25.13</td>
<td>−3639.23</td>
</tr>
<tr>
<td>Warrior</td>
<td>Goalie Guard 5000 - side</td>
<td>6.35</td>
<td>50</td>
<td>18.40</td>
<td>1178.25</td>
<td>18.35</td>
<td>99.75</td>
<td>8.33</td>
<td>−21.49</td>
<td>−3881.19</td>
</tr>
</tbody>
</table>

Note. VF = ventricular fibrillation.

Figure 1  — Commercially available chest protectors investigated in this study.
Mechanical Properties of Chest Protectors

Quasi-static compression testing was performed on each model using a servo-hydraulic material tester (Instron Corp., Canton, MA). Each chest protector was placed on a rigid plate and was compressed with a rigid spherical object at the chosen experimental sites described above. This rigid spherical object was a hardwood ball with a diameter of 6.35 cm or 7.62 cm, representing lacrosse balls or baseballs, respectively (Figures 2 and 3). These surrogate balls were chosen so that the data collected during mechanical testing would reflect the properties of the chest protectors, not those of baseballs and lacrosse balls. As in the Weinstock study, the ball type was chosen based upon the manufacturer’s stated sport for the particular chest protector. A maximum compressive load of 6,000 N was chosen based on a previous study that found the peak force of impact versus ball stiffness at three different impact velocities. From these data, we extrapolated that the 6,000 N was the force associated with an impact velocity of 17.88 m/s (40 MPH), the speed used to investigate the occurrence of ventricular fibrillation on the various models of chest protectors (Hendee, Greenwald, & Crisco, 1998).

Pressure-sensitive film (Ultra Super Low Fuji Film, Fuji Photo, Ltd., Tokyo) was placed between the chest protector and rigid plate, directly below the compression site of the hardwood ball. When pressure (0.2–0.6 MPa) was applied to this film, microspheres burst, leaving a red patch of color over the entire area of pressure distribution. This film remained in place as the servo-hydraulic material tester cycled five times from compressive loads of 10 N to 6,000 N at a rate of 0.1 Hz. A new film was used for each test site, and five pressure film samples were collected for each test site. Following the compression tests, the areas over which the pressure had been distributed were measured with NIH Image Software (Scion Image, Frederick, Maryland). The five area values for each site were then averaged.

A second set of quasi-static compression tests was used to examine displacement, permanent deformation, and stiffness at 25 sites. Using the experimental setup described above, load-displacement data was collected at a rate of 100 Hz as the machine cycled five times from 10 N to 6,000 N at a rate of 0.1 Hz. Displacement was measured for each chest protector by subtracting the minimum position measured by the servo-hydraulic material tester from the maximum (maximally compressed) measured position. Permanent deformation was determined by subtracting the position recorded at the initial preload from the position the machine measured after cycling and returning to the preload. Stiffness was calculated in two regions (a region of low stiffness from 0 to 400 N and a region of high stiffness from 2,400 to 5,000 N) for each test site. Stiffness was defined as the slope of the tangent along the linear portions of the load-displacement curves and was calculated using custom LabVIEW code (National Instruments, Austin, TX).
For statistical analysis, values over all trials were averaged, resulting in one value for each variable for all chest protectors, with the exception of three models. In the case of these three models, Weinstock et al. reported two values of ventricular fibrillation because there were two different material compositions covering the cardiac silhouette, hence resulting in a sample size of 14. We tested for relationships between the variables measured with mechanical testing (pressure distribution, displacement, stiffness, and impact area, depth, and volume) and the proportion of hits resulting in ventricular fibrillation elicited during previous testing with the same brands and models of chest protectors (Weinstock et al., 2006) using linear regression (SigmaPlot9.0, Systat Software, Inc., Point Richmond, CA). The \( R^2 \) value and the \( p \) value for the regression equation were both computed and a significance value of \( p < 0.05 \) was set a priori.

### Results

The average area of pressure distribution collected during quasi-static compression testing ranged from 863.4 mm\(^2\) with the Rawlings Youth LBP-1 to 1,851.8 mm\(^2\) with the Brine Ventilator Pro, which had a ventricular fibrillation proportion of 21%. We found that there was a significant decrease in the proportion of hits resulting in ventricular fibrillation as the area of pressure distribution increased (\( R^2 = 0.59, p = 0.001 \)). These findings suggest a linear relationship between the area of pressure distribution and the occurrence of ventricular fibrillation using a linear regression model with 95% confidence intervals (Figure 4).

The displacement at 6,000 N of these chest protectors ranged from approximately 7.1 to 19.7 mm. No relationship between the displacement of the chest protectors and the proportion of hits resulting in ventricular fibrillation was found (\( R^2 = 0.19, p = 0.125 \)). The percentage of deformation from the original thickness of the chest protectors ranged from 62.3% to over 100%, demonstrating that in some models the padding was so soft that they permitted a slight elastic deformation of the hardwood ball.

The values of permanent deformation ranged from 2.5 to 13.1 mm. These values showed a slight relationship with proportion of ventricular fibrillation (\( R^2 = 0.24, p = 0.076 \)). The stiffness was highly nonlinear in every model of chest protector. There was an initial range of very low stiffness (12 to 48 N/mm), then a toe region, and followed by a region of high stiffness (2,425 to 7,335 N/mm), which was assumed to be associated with the bottoming out of the chest protectors. Neither the low-stiffness region (\( R^2 = 0.18, p = 0.13 \)) nor the high-stiffness region (\( R^2 = 0.093, p = 0.291 \)) demonstrated a relationship with the proportion of hits resulting in ventricular fibrillation.

### Discussion

The purpose of this study was to determine whether a relationship exists between the occurrence of ventricular fibrillation and the mechanical properties of chest protectors. These mechanical properties included the displacement of the chest protector, stiffness of the padding material, and the area over which the chest protector distributes pressure. Although most of the tested properties demonstrated no significant relationship with the occurrence of ventricular fibrillation determined with Weinstock’s commotio cordis swine model, one property did. We found a significant linear relationship between the areas of pressure distribution and the proportion of hits resulting in ventricular fibrillation.

Measures must be taken to increase awareness of commotio cordis and develop more effective methods of prevention, including better equipment.
and universal safety standards. Despite the fact that all catchers and lacrosse goalies are required to wear commercially available chest protection, currently there are no safety standards for this equipment. A misconception exists among the players and governing bodies that the use of safety equipment, such as chest protectors, eliminates the risk of injury, including commotio cordis. This is not supported by the data because many commercially available chest protectors are ineffective at lowering the proportion of hits resulting in ventricular fibrillation (Weinstock et al., 2004). Safety equipment, therefore, may provide a false sense of security and cause athletes to be more careless and, consequently, more vulnerable to injury. In most cases, the main purpose of safety equipment, such as chest protectors, is to provide layers of padding to reduce the occurrence of superficial injuries, not to provide protection from a deadly condition like commotio cordis. However, at least one model, the Heart-gard, suggests that it will protect the athlete from cardiac injuries.

As the number of victims of commotio cordis increases, exposing the underlying mechanism and finding approaches for preventing it have become very important. Recent studies have evaluated chest protectors using swine models (Weinstock et al., 2006) and biomechanical models (Viano et al., 2000). Weinstock’s swine model determined how well commercially available chest protectors could prevent the occurrence of ventricular fibrillation (Weinstock et al., 2006). Viano’s biomechanical assessment utilized the viscous criterion to measure the fatality risk of five commercially available protectors (Viano et al., 2000). Both of these studies generated useful results in determining which models are potentially safer and were able to make recommendations for the future; however, neither study was able to establish a relationship between the occurrence of ventricular fibrillation and a specific property of the chest protectors that could be modified to reduce commotio cordis. Hence, the purpose of this study was to address this limitation by investigating the mechanical properties of the chest protectors and the occurrence of commotio cordis.

The observed linear relationship between area of pressure distribution, investigated in this study with mechanical testing, and the occurrence of ventricular fibrillation, studied with Weinstock’s commotio cordis swine model, seems quite intuitive and logical. This trend essentially implies that the chest protectors become more effective as their ability to distribute applied loads increases. Hence materials capable of distributing forces laterally should be investigated further for use in safety gear. This notion is supported by the finding that the Brine Ventilator Pro, which was constructed of expanded polypropylene beads, as opposed to closed-cell foam, demonstrated the lowest occurrence of ventricular fibrillation and the largest area of pressure distribution. Using the linear regression model in Figure 4, we could extrapolate that a chest protector capable of distributing the force from the impact of a ball to an area of 2,500 mm$^2$ or greater could potentially eliminate the risk of commotio cordis.

Although this work provides critical data on which further testing protocols can be based, one limitation of this study is that it has not proven that commotio cordis can actually be prevented with appropriate safety equipment. Clearly, the chest protectors on the market today lack the ability to protect all athletes from all harm, as is evident in the number of deaths from commotio cordis (Maron et al., 2002). Another limitation associated with this study is the fact that our findings are based on data collected quasi-statically. Even though our investigation utilized a servo-hydraulic material tester, dynamic mechanical testing could potentially produce results that could help to design a more effective chest protector. Until dynamic testing produces results on the mechanical properties of chest protectors, we still have the significant linear correlation between the decreased occurrence of ventricular fibrillation and the increased area of pressure distribution, which could be used to design more effective models. An additional limitation of our findings is the fact that some of the data presented in this study was actually collected at another testing facility. Although both laboratories tested the same chest protectors, it must be emphasized that our analysis and statistical relationships also used data collected in a separate study.

In addition to designing more effective sports chest protectors, there are further ways in which this research can be continued. Standards are used to define minimum performance requirements of personal protective gear. Currently, only helmet standards exist. Standards for sports chest protectors need to be established, but, in order to do so, experimental data is needed to define performance
requirements as well as a repeatable, cost-effective mechanical thoracic model. Although previous studies have investigated chest protectors using the swine model (Weinstock et al., 2006) and a biomechanical rig (Viano et al., 2000) and this study marks one of the first attempts to characterize the efficacy of chest protectors with mechanical testing, the findings are limited. Additional work is needed to develop and validate a biomechanical model capable of testing and ensuring that all chest protectors placed on the market for commercial sale meet specified standards. A standard range of acceptable areas for which a chest protector must be able to distribute pressure could be established for manufacturers to follow. This would ensure that the consumer’s risk for commotio cordis is reduced as much as possible.

The purpose of this study was to determine whether quasi-static mechanical properties correlated with the range of ventricular fibrillation occurrence values reported by Weinstock et al. We found that as the area of pressure distribution of the chest protectors increased, the proportion of hits resulting in ventricular fibrillation decreased. These findings have the potential to assist development of a prevention strategy for athletes’ deaths due to commotio cordis. It remains to be demonstrated whether incorporation of these findings into chest protector design can actually reduce the incidence of commotio cordis.

Acknowledgments

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References


