Case report

Aerial fireworks can turn deadly underwater: Magnified blast causes severe pulmonary contusion

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A B S T R A C T

Firework injuries have been reported in the literature but usually with regards to mangled extremities, superficial burns and disfiguring soft tissue injuries. Unbeknownst to most lay handlers of recreational fireworks, the blast effect of even a small explosive charge is magnified significantly when detonated underwater, turning a modestly charged firework into a potentially deadly weapon. While the literature is abundant in injuries sustained from underwater detonations of military grade explosives, we found only a single case report of traumatic brain injury resulting from an illegal M80 explosive [4]. We describe a young man who sustained severe life-threatening haemorrhagic pulmonary contusion resulting from incomplete launching of an aerial firework that detonated in the water where he was partially submerged. This report reviews the mechanism of underwater blast injuries and the factors contributing to severe internal organ damage from relatively small-charge and commercially available explosive devices.

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1. Case

A 21-year-old swimmer was almost fully submerged with only his head above water when one of the fireworks known broadly as an “aerial shell” failed to launch into the air and landed in the water approximately 1.5 m away from the swimmer. Immediately following the blast, the patient complained of severe pain and difficulty breathing. The patient arrived having been orotracheally intubated at a nearby facility secondary to severe respiratory distress with a Glasgow Coma Scale (GCS) of 8 T, blood pressure 135/91, pulse 116, respirations 32, and O2 saturation 95% on a conventional ventilator at 100% FiO2. Physical exam was significant for diminished breath sounds on the right and no external injuries. Initial CT scan (Fig. 2) revealed multilobar, haemorrhagic pulmonary contusions with bilateral volume loss, a small right-sided haemothorax, and no evidence of intra-abdominal process. Arterial blood gas (ABG) revealed significant respiratory acidosis, with a pH 7.26, PaCO2 54, and PaO2/FiO2 222. A right-sided chest tube was placed, and the patient was transferred to the trauma ICU. Initial therapy was directed towards supportive management of the pulmonary contusion with pulmonary toilet, mechanical ventilation, inhaled corticosteroids and beta agonists. The morning after admission, approximately 4 h after initial radiograph was obtained, a repeat chest XR (Fig. 1) revealed complete opacification of the right hemithorax. ABGs and physical examination were also unimproved. Bronchoscopy at bedside revealed blood and serosanguinous secretions. These findings in conjunction with the worsening clinical course confirmed presence of pulmonary contusion and aggressive pulmonary toilet and critical care management were continued.

On the morning of hospital day #2, a chest XR taken only 10 h after decline in clinical course, marked aeration of the right lung was evident and physical exam showed an alert and awake patient with improved breath sounds bilaterally. On the following afternoon, the patient was successfully extubated to 40% venti mask and continually improved, allowing rapid step-down and discharge from the hospital having made a full recovery. Telephone follow-up over 2 years following hospitalization revealed no sequelae or lingering effects of the injury.

2. Discussion

Blast injury is commonly categorized into four types. Primary injury is caused by the blast wave itself. Secondary injury is caused by flying debris displaced by the blast. Tertiary injury describes the collision of the victim with stationary objects, and quaternary...
injury is secondary to radioactivity and heat [2]. Injuries from blasts occurring underwater, as with our patient, are primarily caused by the initial shock wave. Secondary and tertiary injuries are rare because the marked drag caused by water, as opposed to air, quickly limits the energy of shrapnel and debris. Similarly, the milieu of water which rapidly dissipates heat makes quaternary injury rare as well. Therefore, an understanding of primary blast injuries provides insight on our patient.

The damage imparted by the initial shock wave after an explosion is determined by several factors. These include the type and size of the explosive charge, the distance from the charge to the target, the medium through which the wave will pass, and the composition of the target. The strength of the charge is typically expressed by a standardized methodology known as the detonation velocity. TNT, having a detonation velocity of approximately 6900 m/s, is the frequent benchmark to which all explosives are compared. Some modern plastic explosives have detonation velocities in excess of 10,000 m/s [3].

The medium through which the shock wave travels is an important determinant of the energy that will eventually reach the target. Air is extremely compressible and as such absorbs much of the energy of the initial blast. Water, being relatively incompressible, transmits much more of the energy farther [5]. In water, the formula derived by Arons yields the pressures generated in underwater explosions in terms of the size of the charge (w) and the distance from the charge to the victim (R): The constant $2.16 \times 10^4$ is specific for TNT [1].

$$P_w = 2.16 \times 10^4 \left(\frac{w^{1/3}}{R}\right)^{1.13}$$

Using a derivation of this formula, Hirsch demonstrated the relationship of pressures within differing mediums at the same distance from the blast as functions of their density and speed of sound in each medium [4].

$$P_a = P_w \frac{D_aC_a}{D_wC_w}$$

where $P_a$ and $P_w$ are relative shock wave pressures occurring after blasts in air and water medium, respectively, $D$ is the density of the medium and $C$ is the speed of sound in the medium. Thus,

$$\frac{D_a}{D_w} = \frac{1.16}{1000}$$
$$\frac{C_a}{C_w} = \frac{1}{5}$$

$$P_w = P_a \frac{5000}{T}$$

Demonstrating that the pressure wave of a similar charge, at a similar distance will be 4310 times greater when occurring underwater compared in air.

The characteristics of the target are also important for several reasons. First, when the shock wave travels through a medium less dense than the target, such as air to a human body, much of the wave is reflected and not absorbed by the victim [7]. When the target and medium have similar densities, such as a human body and water, the energy of the sound wave is almost entirely transmitted to the victim. When the wave goes from a denser to less dense medium, rarefaction waves cause cavitation [6]. This mini-explosion causes shear stress and explains why most damage occurs in the air-filled organs of the lung, bowel, and tympanic membrane [8].

To predict the degree of pressures endured by our patient, we take into account the composition of this type of aerial fireworks available to consumers, which range from 3 to 10 g of explosive powder comparable to TNT, and 1.5 m, the distance at which our patient’s family approximated the firecracker detonation was from him. Calculating initial overpressures alone, we determine a $P_w$ range of $3.6-5.7 \times 10^5$ Pa, exceeding the lung threshold pressure of $1.0 \times 10^5$ Pa by ten-fold.

3. Conclusion

This is a unique case demonstrating the lethality of small explosives occurring underwater. The rapid worsening and similarly rapid improvement of lung injury seen in our patient emphasizes the importance of prompt treatment and supportive care. Thus, potentially fatal respiratory complications due to delayed therapy can be prevented by emergency health care providers’ awareness of the amplified pressures in underwater explosions and their effect on organs containing an air–liquid
interface, especially since these injuries may not be apparent in the absence of external injuries on presentation.

More importantly, there is a need to inform the public of these adverse outcomes. While there is an abundance of organizations providing information on safe use of fireworks, none of these warn against use in or near water. In the 2011 Fireworks annual report, the U.S. Consumer Product Safety Commission (CPSC) reported over half of firework-related injuries seen in the emergency department were burns and a minimum of 4 deaths related to firework injury, with no mention of injuries similar to our case [9]. Regardless of mechanism, a public awareness campaign is still an important part of fireworks-related injury prevention, but strategies should include a mention of easily preventable injuries such as those from underwater blast magnification.

Conflict of interest statement

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References