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Postmortem Findings in 22 Victims Due to Two Grain Silo Explosions in France

ABSTRACT: In 1982 and 1997 there were explosions of barley-containing silos in France, one in Metz (1982) and the other in Blaye (1997). There were a total of 25 victims, including 23 fatalities (12 in Metz and 11 in Blaye). In each case there was one survivor. This report is a retrospective study of 22 victims (11 at each site); all of them had multiple lesions due to the explosion and the immediate aftermath. The lesions demonstrated direct involvement of the blast effect associated with silo destruction, the heat from the explosion, the effects of toxic gases and asphyxia. The forensic pathologist is an important member of the emergency response team. This team has the responsibility for initially assessing the damage and for identifying the victims. The role of the forensic pathologist is therefore essential and they should be included in emergency planning to facilitate the initial assessment, shorten the time taken to identify the victims and improve safety procedures. Although dust explosions in agro-business plants are occurring more frequently, postmortem data are rare.

KEYWORDS: forensic science, explosion, silo, grain, injury, postmortem

Dust explosions occur at sites where any organic or mineral matter is produced, handled or stored, and when airborne byproducts are suspended in the air at an inflammable concentration (1). Since the beginning of the century, accidents have become more frequent in mining installations and where agro-business products are stored, particularly cereals (1). In France, the first fatal explosion occurred in 1980 at an oil refinery. One person was killed and 12 injured (1). Since then, there have been two major explosions. The first was an explosion of a malt silo in Metz in 1982, which killed 12, and the second, an explosion in 1997 in Blaye, which killed 11. Silo explosions can cause numerous injuries and produce other medical consequences. There are primary blast lesions resulting from the shockwave; these are organic due to the closed environment. The secondary blast can cause lesions due to flying debris; generally fractures and riddle wounds. There are also injuries from the vicitim being thrown through the air and when this occurs the body may disintegrate and limbs become amputated (2,3). Victims may also be burnt, poisoned by toxic gases, and crushed or buried by debris (3).

Description of the Explosions

Both silo complexes (which included silos and support buildings at their base) were located on a river and were compact cylindrical towers constructed of reinforced concrete and thick walls.

The victims were all adults (19 men, 3 women), and ten of the victims were employees of the damaged sites and 12 were contractors. At the time of the explosions, all the fatalities were inside the silo complex, except for one of the victims in Blaye who was fishing close by.

The possible causes of explosion are spark or mechanical rubbings, static electricity, electric spark and self-overheating of the dust tank. The cause of the explosion in Blaye was determined to be an explosive mixture of dust and air, whereas that for Metz is unknown. After the explosion, the silos had totally collapsed on the support buildings (Figs. 1 and 2). Concrete fragments and other debris were found as far as 100 m away from the silos. The two survivors were found outside the support buildings covered with debris, and both were burnt. In particular the survivor in Metz showed a pelvis fracture with a rupture of the bladder, a muscular crushing and a left pneumothorax. All the victims were found within 100 m of the silos.

Pathology and Toxicology

In Metz it was necessary to perform pathology and toxicology on four of the vicitims (Cases 13, 15, 16 and 19). Microscopically the lungs showed the classic signs of blast lung, type hemorrhagic. For these four cases, the carboxhemoglobin saturation was less than 2% in three of them and in the fourth (Case 13) was 42%. Methemoglobin was also found in Case 13. This presence of carbon and methemoglobin in blood confirms, according to Nagao (6) that the victims breathed in a toxic Co rich atmosphere before being buried.

Results

Burns—All 22 victims had widespread burns. These covered the whole body and were mainly of the phlycten type. The phlyctens were frequently broken and revealed extensive parchment-like areas. The hands of one victim were carbonized. The burns were presumably due to the immediate action of heat on the teguments, as there were no lesions pointing to a real fire.

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Head and Neck Lesions (see Table 1)—Seventeen victims had cranial bone fractures, mainly at the base of the skull. In three cases the skull had either burst or been crushed. The fractures were multiple and generally concerned all levels of the base of the skull. They were always associated with maxillofacial fractures. All these lesions pointed to the association of the blast effect and the projection or falling of concrete fragments. The subjacent cerebral lesions observed in 10 victims were mainly due to cerebral laceration and/or subdural intracranial bleeding (four cases). Of the three cases in which the skull was crushed, two had suffered ocular enucleation. In four victims, the soft tissue of the neck had been lacerated at the level of the larynx with subjacent cartilaginous fractures. The anterior structure of the neck had been torn back as far as the spine in one case.

FIG. 1—*The silos in Blaye after the explosion.*

FIG. 2—*The silos in Metz after the explosion.*

Thoracic Lesions and Content (see Table 2), Rib cage—Sixteen of the 22 victims had broken ribs; three of which had an opening of the thorax into the pleural cavities. In half of the cases, concrete fragments were visible inside the thorax, consistent with the crushing. In other half of the cases, the blast effect was associated with multiple fractures of the costal arches in crushed victims. The rib fractures and in some cases the total destruction of the ribs caused the perforation of the intra-thoracic organs and the diaphragm. The diaphragmatic ruptures had pushed the heart and lungs towards the abdominal cavity after they had been torn away by the blast wind. This led to the emptying of the thorax in two victims (Cases 2 and 17).

Heart and Lungs—Ten of the 22 victims had cardiac and pericardial lesions. Of these 10 victims, six had lesions due to the blast effect, specifically ruptures to the ventricular or auricular walls, a heart torn out (Cases 2 and 17) and a burst heart (Case 14). Two of the 10 victims (Cases 4 and 9) had a lacerated heart due to the projection or falling of concrete fragments. The other two victims (Cases 8 and 18) had lesions of the bursting or laceration type, presumably due to the blast and to foreign bodies. Pericardial rupture was associated in all cases except two (Cases 1 and 21) with a hemopericardium. Aortic involvement was associated with heart lesions and fractures of the thoracic spine.

Seventeen of the 22 victims had pulmonary lesions, including 11 with a ruptured parenchyma. Three of these were due to the blast effect including two cases of petechial bleeding. In the eight other cases, rupture was due to the blast effect and to the falling of concrete fragments. In all these cases, rupture was associated with pulmonary perforation subjacent to the rib fractures. In the other six cases, the major lesions were petechial bleeding and lung congestion due to the blast effect, or a suffocating type of asphyxia, or brutal thoracic compression. Pathologic analysis of the lungs without visible macroscopic lesions demonstrated the classical pulmonary blast lesions.

TABLE 1—*Head and neck lesions.*

	Cases																					
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
Fracture of skull bones	fb	+	+	+	+	+	fb	+	+	+	fb	+		+			fb	+		+	+	
Fracture of facial bones	fb	+	+			+	fb	+	+	+	fb						fb	+				
Fracture of jaws	fb		+			+	fb		+	+	fb						fb					
Ocular lesions	+						+															
Intracranial bleeding						+														+	+	+
Cerebral lesions	fb		+			+	fb	+	+		fb						fb			+	+	
Neck lesions		+		+			+		+													

fb: foreign body.
+: blast or foreign body.

TABLE 2—*Thoracic lesions and content.*

	Cases																					
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
Opening of thorax		fb						fb	fb													
Rib fractures	+	fb	fb	fb	+	+	fb	fb	fb	+	+	fb		+			fb	+				+
Rupture of diaphragm		+	fb									fb		+			fb	+				
Organ disintegration		+															+					
Hemothorax	+																				+	+
Hemopericardium	b																				b	
Cardiac lesions	b	b		fb				+	fb					b			b	+		b	b	
Rupture of aorta		b															b					
Blood penetrating lungs												b	*		*	*				*	*	*
Rupture lungs	b	+		+	+	+		+	+	+								+			b	b
Lung congestion													*		*				*			
Barley seed in trachea													*						*			

b: blast.
fb: foreign body.
+: blast or foreign body.
*: blast or asphyxia.

TABLE 3—*Abdominal lesions and content.*

	Cases																					
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
Penetrating abdominal wound		+	+	+				+	+					+			+	+				
Dispersion of organs		b		b														b				
Intraperitoneal effusion	+					+														+	+	
Ruptured liver	b	+	+	+	b				+									+		b		b
Ruptured spleen	b		+	+					+					b						b		b
Ruptured kidneys	b	+	+	+					+									+				
Pancreatic lesions			+						+													
Mesenteric lesions					b																	
Ruptured oesophagus																	b					
Ruptured stomach								b												b	b	
Ruptured intestines		+							+									+		b	b	

b: blast.
+: blast or foreign body.

In 20 victims, the lumen of the airways did not contain any black deposit, soot or grain. In two cases, the trachea and bronchi were obstructed by barley grain whose presence was due to the blast effect in one (Case 19) and to a phenomenon of asphyxia in another (Case 13). This victim (Case 13) apparently survived for a brief period and had been buried under a large mass of barley grain. The victim did not have any severe thoracic lesions apart from ecchymosis. The lungs, which had petechial bleeding, were congested and edematous. Moreover, the blood was 42% saturated with carboxyhemoglobin and contained methemoglobin (due to oxidizing agents). This victim had presumably been in a toxic carbon monoxide rich atmosphere before being buried.

Abdominal Lesions and Contents (see Table 3)—Fourteen of the 22 victims had severe abdominal lesions, including eight with penetrating wounds into the abdominal cavity. Evisceration and dispersion of organs such as the kidney, and even total abdominal evisceration accompanied these breaches in the wall. The liver and the spleen were the most highly affected organs. Nine cases of severe hepatic lesions were observed, including four due to the blast alone, since traumatic lesions of the abdominal wall did not accompany them. Seven victims had splenic involvement including four, which were due to the blast alone. These hepatic and splenic lesions were especially due to laceration of the parenchyma. Six victims had renal involvement, with renal hematoma or laceration. Three of 22 victims had involvement of the mensentery and pancreas. Despite the extent of the abdominal lesions, only four victims had a hemoperitoneum. With regard to the digestive tract, there was a rupture of the gastric (three cases), esophagous (one case) and intestine (five cases) with soiling of the

cavity by stools and/or food. These lesions were associated with abdominal wounds. Two cases of gastrointestinal rupture were due to the blast alone.

Lesions to Limbs, Pelvis and Spine (see Table 4)—Multiple fractures were observed in the pelvis, the arms, legs and spine. In the limbs the fractures were mainly open with muscle degradation, and involved the forearm (5 Cases) and legs (8 cases). Spinal fractures were mainly located at the cervical spine (atlas and axis) but also at the cervico-thoracic and dorso-lumbar junction, thereby separating the backbone into three parts in certain cases. The pelvis fractures were observed with pubian disjunction. Arm amputations involved the lower third of the arm or forearm, and those of the legs concerned the upper third. All were unilateral. Ripping concerned the root of the limbs, particularly the shoulder and the hip, with 2 bodies being totally sectioned in two at the level of the pelvis. It is reasonable to assume that these victims were seated at the time of the explosion. These lesions, which were due to the combined effect of the blast wind, the projection of shards and the collapsing building, led to the dislocation of eight victims.

Discussion

Although diffuse, the phlyctens found in these victims were superficial burns indicating a rapid thermal action. They were similar to the flash burns from explosions described by other authors (4–8). In our series, the most affected parts of the body were the thorax (100%), head (82% i.e., 18 of 22) and the abdomen (64% i.e., 14 of 22). These postmortem findings are different from survivors lesions described by Kennedy and Johnson (9). They reported only 10% of thoracic and abdominal lesions in them. Our postmortem findings are also different from those of Waterworth and Carr (10) who found a predominance of thoracic (66%) and abdominal (71.5%) wounds.

Eighteen of the 22 victims had head lesions. Seventeen of these 18 (94%) had a skull fracture which in 77% of the cases was due to the combined action of the blast and the falling or projection of concrete fragments. In 59% of cases, the fractures were associated with cerebral laceration and in 18% with extra and/or subdural meningeal bleeding.

Our findings are in agreement with those of Quintana et al. (11) who found 90% of skull fractures in 16 children died consecutively to the blast effect of bomb explosions. We have found 77% of skull fractures, 50% of facial fractures and 36% of jaws fractures. These maxillofacial injuries are frequently described like a consequence of the blast effect (12,13) but in our study, we cannot decide between blast or foreign body for the mechanism of wounds.

Rib fractures accounted for 73% of lesions including 19% of penetrating thoracic wounds. Half of these were caused by the collapsing of the building or were associated with the blast effect. Subjacent lesions at the level of the heart accounted for 45%. Pulmonary lesions 77% were due to the combined action of the blast effect, the falling or projection of concrete fragments and

TABLE 4—*Lesions to limbs, pelvis and spine.*

	Cases																					
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
Forearm amputation																						
Right																						
Left			+							+				+								
Amputation of leg																						
Right																		+				
Left			+										+									
Dismembered shoulder																						
Right							+											+				
Left		+																				
Dismembered hip																						
Right			+					+	+													
Left			+					+														
Fracture of Radius/Cubitus																						
Right		o							o					+								
Left																	+					+
Fracture of humerus right			+											o								
Left		+																				
Fracture of femur																						
Right											+											
Left								+	o													
Fracture of tibia/fibula right						o			o		o		+									o
Left									o					o	+			o				
Fracture of pelvis			+	+	+				+					+						+	+	
Fracture of spine		+	+	+		+	+	+	+													
Others fractures		+	+	+		+		+														
Dislocation of body		+	+				+	+	+	+				+				+				

+: blast or foreign body.
o: open fracture.

to the fractured ribs. The frequent association of a ruptured diaphragm, aorta and pericardium made the constitution of a hemopericardium or hemothorax unlikely. At the level of the abdomen, certain lesions such as ruptures to the digestive tube and the ripping away or bursting of organs were due to the blast effect alone. Others were subjacent to penetrating wounds (57%) with a high incidence of liver, spleen and renal lesions. Most of the latter were due to the projection of concrete fragments. Our findings are different from those of Waterworth and Carr (10). We have found 50% of victims who had abdominal lesions, 38.7% of these lesions came from the blast effect alone. Waterworth and Carr (10) have found more (53%). Although we disagree about the probable cause of the lesions, our findings are concordant regarding the predominance of hepatic and splenic lesions.

Skeletal injuries accounted for 82% of corporal lesions and were due to the blast effect and collapsing of the silos. 78% of these victims had limb lesions, of which 86% were fractures. These fractures mainly concerned the legs (57%) and the forearms (36%). Ripping injuries concerning the shoulders and hips represented 33% of all skeletal injuries. Amputations accounted for 28% and concerned the lower third of the arm or forearm and the upper third of the leg.

Such lesions have previously been described by studies about victims who had handled or walked on anti-personnel land mines or bombs (in Burma by Hougen, in northern Ireland by Hull, and in Sri Lanka by Meade) (15–17). Ripping injuries and limb amputations due to the blast wind caused the dislocation of 36% of victims (8 of 22).

The extensive lesions observed in our study are due to the site of the explosion, as in the study by Leibovici et al. (19). Explosions in a confined area such as a silo create a very strong primary blast with a higher number of severe lesions and a higher mortality rate than explosions outdoors. All the victims died instantaneously due to the combined effect of the shock wave, the falling or projection of concrete fragments, the blast wind itself, the heat and the toxic and asphyxiating phenomena. For each explosion, hypotheses can be stated about the cause of death of the victims:

- In Blaye, the death of the 11 victims was connected to a combination of blast effect with the falling of concrete fragments and thermal effects.
- In Metz, some of the victims did not show trauma or severe crushing. In four cases (Cases 13, 15, 16 and 19) major lesions were absent. The presence of grain or malt in the respiratory tract, carboxyhemoglobin and methemoglobin (in one case), as well as pulmonary lesions indicated that death was caused by a combination of blast effect, toxicity and mechanical asphyxia.

This difference in hypotheses on the possible causes of death might be explained by the nature of the grain in the two silos. The grain of malt (barley in germination) in Metz contained a certain level of humidity, which may have diminished its explosive power.

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