Chapter 8

THE PATHOLOGY OF PRIMARY BLAST INJURY

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INTRODUCTION

The pathological changes associated with primary blast injury (PBI) have been studied extensively for at least 75 years, since it became apparent that some soldiers who had been exposed to blasts on the battlefield were severely debilitated or killed but showed no external signs of injury. Researchers set out to study the effects of explosion-generated pressure waves on the body, and have conducted many animal experiments to document blast-related pathological and physiological changes, to **determine blast-dose responses**, and to develop predictive models for blast injury.

The lesions of PBI result from the complex interaction between the passing blast wave and the body tissue. When a blast wave strikes the body, it has effects that are similar to those of other kinds of blunt trauma. It displaces the body wall into the body cavities, resulting in a rapid change of organ volume and the displacement of internal tissues. Air-containing organs **are** the most likely to **change** volume as **a** result of blast, and thus their tissues are the most susceptible to distortion and stress. When the stress on the tissue exceeds the tissue's inherent tensile strength, the resulting failure may be manifested as detectable pathological change.

Blast may cause injury in a variety of body tissues (Table 8-1). The most common serious effects of PBI include *(a)* injuries to the respiratory system, *(b)* the introduction of air emboli into the circulatory system, and *(c)* gastrointestinal **damage.** Although it is usually not debilitating, the most common manifestation of PBI is rupture of the tympanic membrane, which may occur even at low blast doses. If the blast pressure is great enough, less common injuries can occur, such as solid-organ rupture.

Most blast injuries that occur on the battlefield or in terrorist bombing incidents are complicated by the more apparent secondary blast injury, which is caused by flying objects, and tertiary blast injury, which is caused by displacement of the entire body.' When PBI occurs in conjunction with secondary or tertiary blast injuries, or with other injuries like burns or radiation, the resulting damage is termed *combined* injury. Secondary, tertiary, and combined blast injuries are usually obvious on external examination; diagnosis and treatment of these injuries fall into the realm of ballistic injury. Because the integumentary system is very resistant to the blast wave, however, the lesions in a casualty who has pure PBI will usually not be obvious on examination of the body surfaces, and the source of the casualty's difficulties may indeed perplex the uninformed diagnostician. In spite of the fact that secondary and tertiary blast injuries are more common and more easily detected by the physician, there have been numerous reports of PBI alone and as a component of combined injuries.[2-8]

Because of the insidious nature of these potentially deadly injuries, a thorough knowledge of the clinicopathological signs of PBI will greatly enhance the medical officer's ability to provide **care** to these casualties. This chapter will outline, by organ system, those pathological changes that characterize PBI, based on a review of the literature and on the authors' experiences with animal blast-injury models. Several excellent reviews of the lesions of blast injury are particularly noteworthy.[9,10]

TABLE 8-1

CATEGORIES OF PRIMARY BLAST INJURIES

The Respiratory System	
	Pulmonary hemorrhage
	Alveolovenous fistula (air-embolism production)
	Airway epithelial damage
The Circulatory System	
	Cardiac contusion
	Myocardial ischemic change (air-embolism production)
The Digestive System	
	Gastrointestinal hemorrhage
	Gastrointestinal perforation
	Retroperitoneal hemorrhage
	Ruptured spleen or liver
The Eye and Orbit	
	Retinal air embolism
	Orbital fractures
The Auditory System	
	Tympanic-membrane rupture
	Ossicular fractures
	Cochlear damage

THE RESPIRATORY SYSTEM

Because the respiratory system is the only system in the body that is entirely filled with air and is therefore especially vulnerable to the effects of a blast overpressure, any discussion of PBI must begin with a discussion of respiratory-tract lesions. The respiratory system comprises *(a)* the lungs and bronchi and *(b)* the upper airways, including the trachea, the pharynx, the larynx, the nasal passages, and the sinuses.

The Lungs

Within the respiratory system, the lungs are especially vulnerable to the overpressure wave because of their unique structure and location.

The primary function of the lungs is to provide a site for the exchange of gases between inspired air and blood. To do this, the lungs contain innumerable capillaries, the walls of which are only one cell thick so that molecules of **gas can** pass through them. The surface area over which air comes in contact with these tiny blood vessels must be large enough to sustain a level of gas exchange that is adequate to keep the body alive, and so myriad air spaces (called *alveoli)* are embedded within the delicate capillary-containing membranes of the lungs. The resulting spongelike structure of the lungs provides the greatest possible air-blood interface within the limited anatomical space. However, it also results in the lung tissues' relatively low tensile strength and their inability—because of their contiguity with the air pockets—to withstand the effects of strong blast waves.

The location of the lungs also contributes to their vulnerability to blast. They are contained in a relatively rigid cage comprising the ribs and intercostal muscles, vertebral column, sternum, and diaphragm. In addition, they bracket the firm, muscular heart. When the thorax is struck by a blast wave, the sternum and rib cage (along with the intervening intercostal muscles) are rapidly displaced into the thoracic cavity, causing these structures to momentarily compress the lungs. The same blast wave displaces the abdominal wall, moving the diaphragm forcefully against the lungs. The lungs, in turn, are displaced into the heart and vertebral column, which act as barriers, causing further damage.

The specific lung lesions caused by the blast wave can be best understood by examining the anatomical subcomponents of the lung and the effects of the blast on each of them. Each lung consists of *(a)* the *pleura,* which covers the entire organ, *(b)* the *parenchyma,* where gas exchange occurs, and *(c)* the *bronchovascular structures,* through which blood and air flow to and from the parenchyma.

The pleura is a serous membrane that comprises a single layer of mesothelial cells and an underlying layer of connective tissue. It forms both a protective covering for the lung parenchyma and a lining for the thoracic cavity. The portion of the pleura that surrounds the lungs is called *visceral pleura;* and the portion of the pleura that lines the thoracic cavity is the *parietal pleura.* The visceral pleura contains numerous blood and lymphatic vessels, and it is thin enough to be relatively transparent, so that damage to underlying tissue can often be seen through it.

The parenchyma is the functional portion of the lung. After being transported by the conducting airways, the air arrives at the sites of gas exchange, which are tiny respiratory units called *acini.* Acini comprise the respiratory bronchioles, alveolar ducts, and alveoli, but because the surface area of the alveoli is much greater than that of the other structures, most of the gas exchange occurs there.

The wall between adjacent alveoli (called the *alveolar septum)* is a thin, delicate membrane that is 10–15 microns thick (Figure 8-1). Lining the air space on either side of the membrane is a continuous layer of epithelial cells with underlying basal lamina. Sandwiched between these two epithelial layers is the septal interstitium, which contains a meshwork of capillaries, fibroblasts, and connective-tissue fibers, along with occasional macrophages, mast cells, and lymphocytes.

The wall between the capillary lumen and the alveolus consists of *(a)* capillary endothelium and its basal lamina, *(b)* a scant interstitial space, and *(c)* a single layer of alveolar epithelial cells over its basal lamina. As the site of gas exchange, this blood-air barrier may be as thin as 0.2 microns, and averages only 0.5 microns.[11]

The bronchovascular structures (which include the branches of the pulmonary vessels and the intrapulmonary conducting airways) are embedded in the parenchyma. They are considered together because they are located anatomically in the same arborizing pattern throughout the parenchyma, and because they are of relatively similar density when compared with the surrounding low-density alveolar tissue.

Hemorrhage. The most obvious and consistent

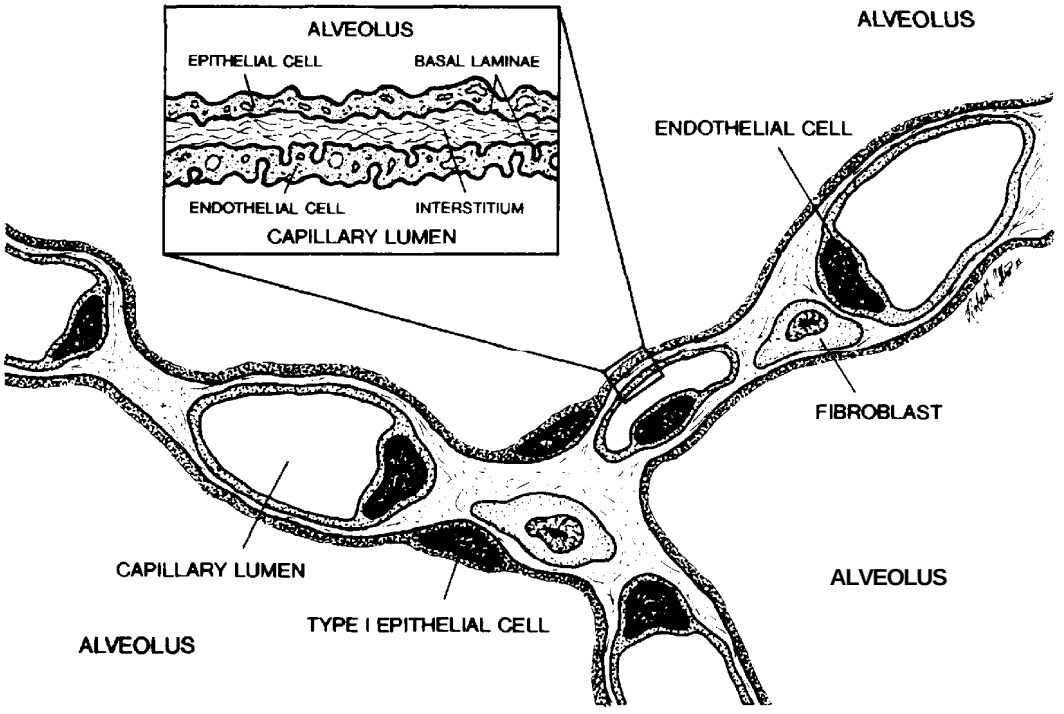

Fig. 8-1. This drawing shows the position of the alveolar capillaries within the alveolar septa. The weakest point of the wall is at the *diffusion membrane* (inset). The interstitiurn in this delicate membrane may vary from the relatively thick width suggested in the drawing to a much thinner width, in some cases, the interstitium of the diffusion membrane may be absent and the basal laminae of the endothelial and epithelial cells may be fused.
Source: Walter Reed Army Institute of Research

lesion of pulmonary PBI is hemorrhage, the amount and distribution of which depends on the level of blast exposure. The only external sign of lung hemorrhage is froth or blood that can be seen within the oral cavity or surrounding the nose and lips. At autopsy, hemorrhage is visible through the thin pleural membrane, and blood can be found oozing from the face of a cut section of the lung.

Although they frequently occur in combination, pulmonary hemorrhages can be divided anatomically into three distinct types: *(a)* pleural and subpleural hemorrhage, *(b)* hemorrhage that is multifocal or diffuse within the parenchyma, and *(c)* hemorrhage that surrounds the airway and vascular structures that are embedded within the parenchyma.

The first type of pulmonary hemorrhage is visible through the lung's thin pleural surface. With the exception of a small amount of extravasated erythrocytes that are found in the looseconnective tissue of the visceral pleura, this hemorrhage is actually located in the subpleural alveolar tissues (Figure8-2). It is visible at autopsy on the surface of the lungs in a bilateral and generally symmetrical pattern, although it will be more extensive on the side facing the blast source.

Pleural or subpleural hemorrhage may be visible as *(a)* a few petechiae as a consequence of a low blast dose, *(b)* ecchymoses from a medium blast dose (Figure 8-3), or *(c)* coalescing ecchymoses or diffuse subpleural hemorrhage (or both) from a high blast dose (Figure 8-4). Pleural rupture and hemopneumothorax (in which both blood and air escape into the thoracic cavity) may occur in the latter case. Lungs of casualties who have died from severe PBI exhibit such a distinctive appearance at autopsy that pathologists have come to recognize this damage as blast lung. A diffuse hemorrhage makes the entire organ, which is normally pink, look dark red or black. This corresponds to the same term **used** in the clinical setting, where blast lung refers to the signs and symptoms indicative of PBI.

Petechiae and ecchymoses appear in a multifocal pattern on the pleural surface and have a predilection

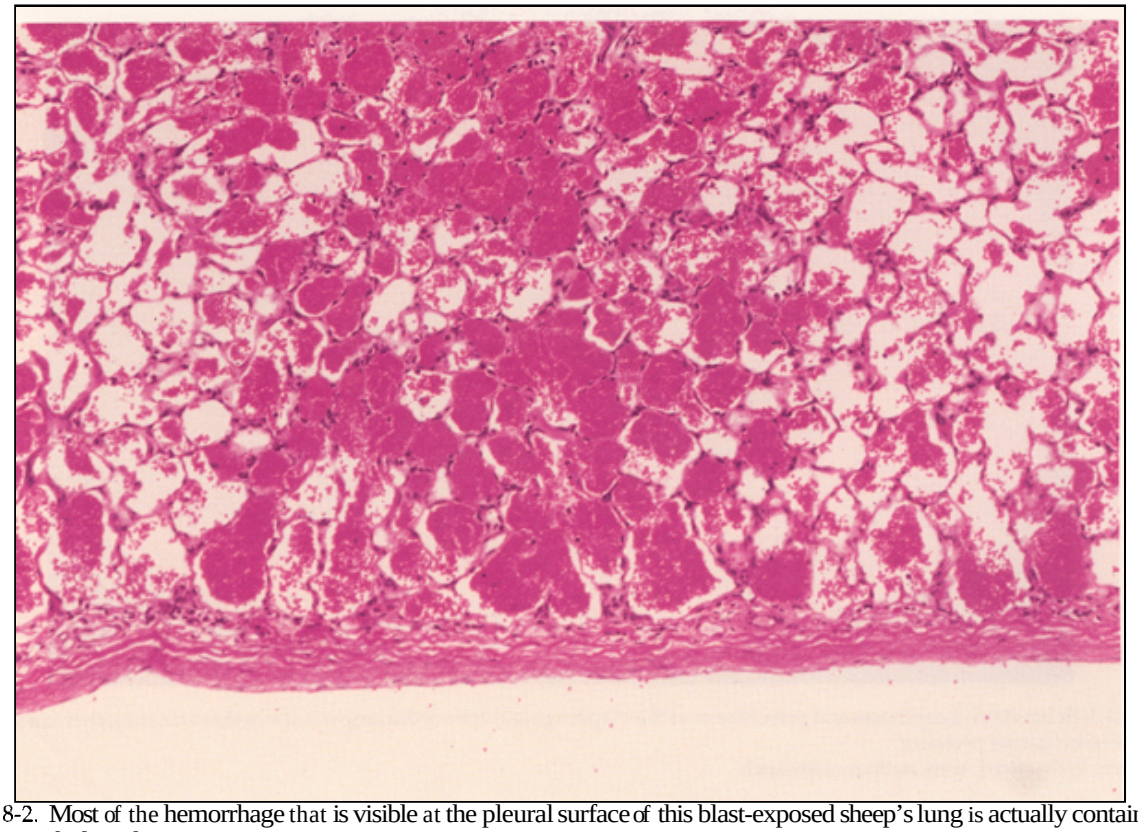

Fig. 8-2. Most of the hemorrhage that is visible at the pleural surface of this blast-exposed sheep's lung is actually contained within subpleural alveoli.
Source: Walter Reed Army Institute of Research

for certain sites, such as adjacent to the diaphragm, on the lung surfaces next to the heart, and on the posterior surfaces where the left and right lungs are in contact.

In addition, hemorrhages on the lateral lung surfaces often exhibit distinctive rib markings (Figure 8-4). The source of the rib markings has been the subject of thorough experimentation. At one time, the hemorrhagic rib markings were thought to correspond with the overlying ribs and to result from the ribs' displacement into the lung tissue. However, when a small amount of dye was injected into rabbits' intercostal spaces and the animals were exposed to blast, the rib markings corresponded in every case to the ink punctures from the intercostal spaces rather than to the ribs themselves.[12] When segments of the rats' ribs were removed in a later study, creating an artificially large intercostal space, this space was marked by a similar hemorrhage after the animals were exposed to blast.[13] Finally, thoracic-wall measurements of rabbits showed that intercostal tissue responded to the blast wave by moving inward faster and farther than the ribs did.[14] Thus, intercostal markings —rather than rib markings— would probably be a more appropriate name for these hemorrhages.

A second site of pulmonary hemorrhage is found in the parenchyma beneath the subpleural region. It probably occurs as the result of the stress that is concentrated at various sites in the parenchyma when the lungs are distorted by the blast wave. This stress may cause the delicate alveolar septa to rupture. The alveolar spaces and associated bronchioles rapidly fill with blood from severed alveolar capillaries, producing hemorrhagic foci that are visible when cross-sections of the lungs are examined at autopsy (Figure 8-5). Because alveolar-septa1 tears are difficult to see histologically, these hemorrhages appear as blood-engorged alveoli, with the acinar structures remaining essentially intact (Figures 8-1 and 8-6).

A similar tear may occur between the alveoli and the wall of an intralobular is known as an *alveolovenous* fistula, and the resulting direct communication between the air space and the circulatory system plays an important role in the production of air emboli. (Air emboli are the primary cause of imme-

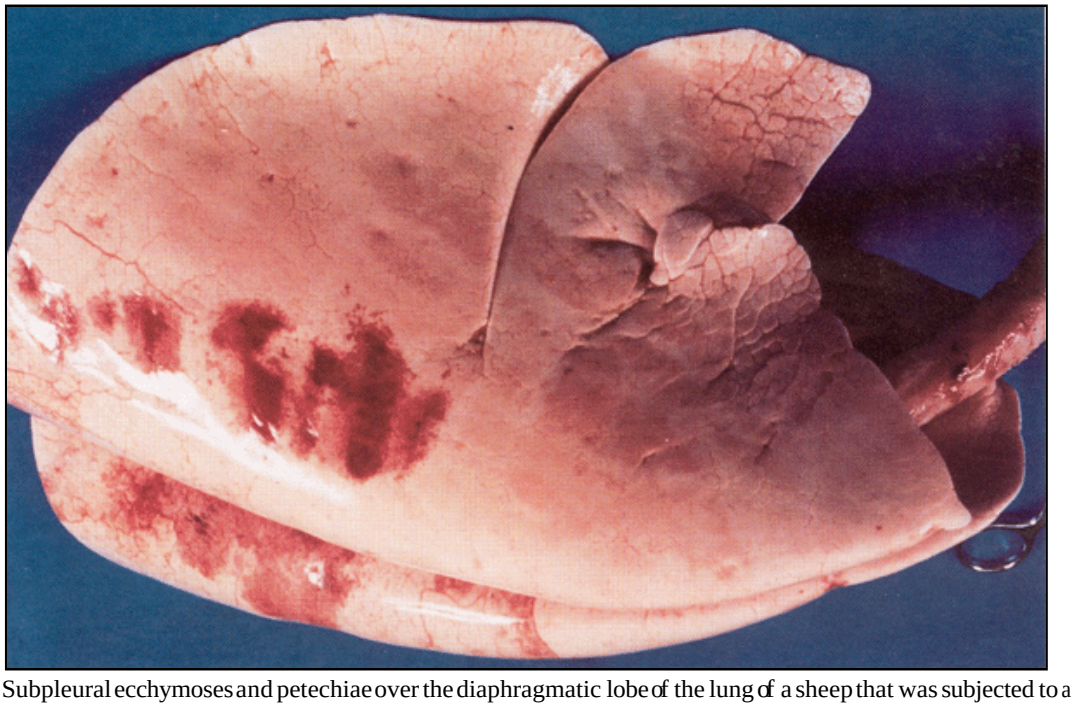

Fig. 8-3. Subpleural ecchymoses and petechiae over the diaphragmatic lobe of the lung of a sheep that was subjected to a single blast of moderate pressure
Source: Walter Reed **Army** Institute of **Research**

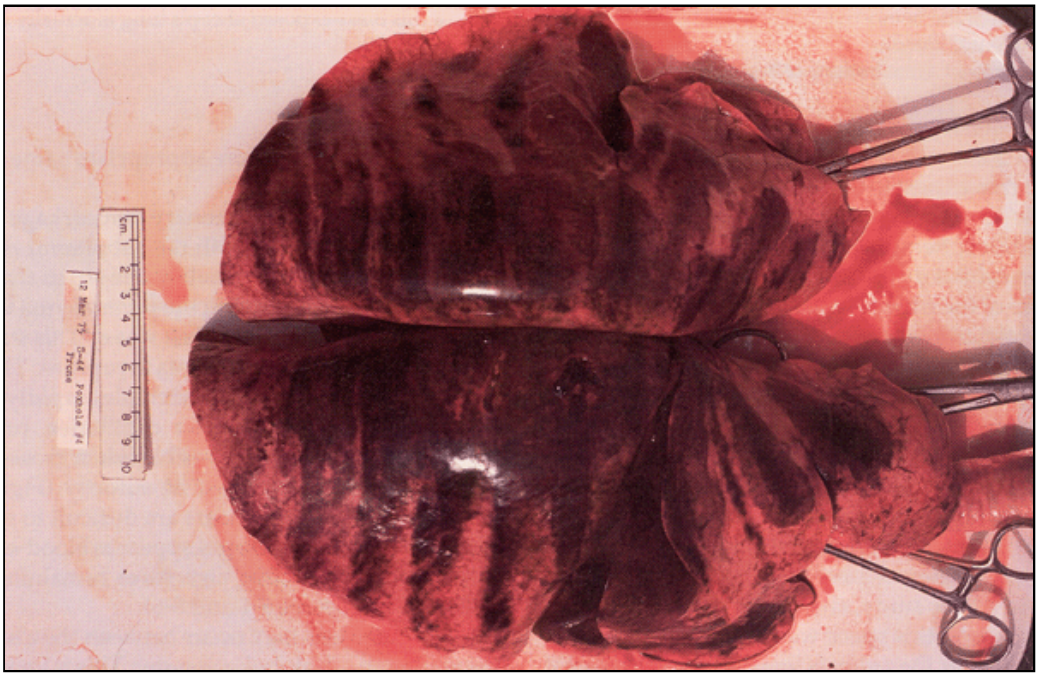

Fig. 8-4. This subpleural hemorrhage involves the entire posterior (dorsal) surface of the lung of a sheep that was subjected to a high-pressure blast. The darker portions of the hemorrhage that appear over the lateral surface of the diaphragmatic lobe actually mark the intercostal spaces, even though **they are** commonly called rib markings
Source: D. **R.** Richmond