Maxillofacial Air-Containing Cavities, Blast Implosion Injuries, and Management

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Purpose: Distinctive mechanisms of primary blast effects have produced a transitional era of facial trauma. Implosion mechanism damage is one of these. Implosion mechanism damage results in injury limited to the gas-containing structures of the auditory canal, paranasal sinuses, gastrointestinal tract, and lungs. Worldwide, the victims of explosive detonations have increased and advanced dramatically. The outcome is greater mortality and morbidity and new types of injuries, especially in the maxillofacial region. Thus, the knowledge of, and experience with, their management should be shared globally by colleagues through publications.

Materials and Methods: The implosion and mini re-explosion of compressed air sinuses leads to skeletal crush injury to the nasal-orbital-ethmoidal, maxillary sinuses, and nasal bones. A variety of surgical approaches were used successfully under conditions of war. The assessment of the associated injuries to the lung and/or brain is the initial priority to any life-threatening blast injury. This article describes the biophysical results of blast injuries to the middle third facial skeleton and associated injuries and details the management and protection of crushed air containing paranasal spaces.

Results: Easy, simple, and fast treatment and management were used successfully on the pulverized, fragmented skeletal architecture of the facial middle part without increasing morbidity and with the avoidance of unnecessary surgical trauma.

Conclusions: Injuries in one of the most difficult esthetic, physiologic, and anatomic regions of the body is best treated with an understanding of the biophysical effects of the implosion mechanism on air-containing spaces in the maxillofacial region. The introduction of new methods for the management of severe destruction of hard and soft tissue will decrease the incidence of complications and the operative time.

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At the turn of this century, war dominated life in more than 80 countries worldwide.[1] Statistics have revealed that a total of at least 54 local wars and armed conflicts were taking place in the world in 2008, of which 11 were new. These numbers are greater than those in 2007 for both counts.[2]

This significant, near epidemic increase in the number of conflicts is counterintuitive to logical expectations when contrasted with civilization's achievements during the same period. This might have surprised Ares, the Greek god of war, that he still wields his influence over mankind. The growing number of conflicts has led to an unprecedented increase in using improvised explosive devices, rocket-propelled grenades (RPG-7 to RPG-29), thermobaric "enhanced-blast explosives," and explosive-formed projectiles. This dramatic, hugely destructive, easy to operate, inexpensive, and available weaponry should claim the health care provider's attention to conduct more research and distribute the results of successful clinical experience. These weaponries are responsible for the significant increase in civilian mortality in today's wars. An estimated 10 civilians die for every 1 soldier or fighter killed in battle.[1] The new reality of this aggression is civilians killing civilians more now than at any time in history.

All the aforementioned devices have been shown to not only dramatically increase maxillofacial injuries, but also to have caused new and specific pathophysiologic injuries. These types of injuries should claim more attention from the maxillofacial academia to

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reappraise blast injuries and contribute to their emergency and surgical management and protection. Blast maxillofacial trauma includes *1*) transverse mandible and maxillary fractures; *2*) transverse teeth fractures; *3*) crush injuries of the nasal-orbital-ethmoidal (NOE) skeleton; *4*) rupture of the eyeball; *5*) soft tissue facial shredding; *6*) burned facial skin; and *7*) associated multisystem injuries, such as to the lungs, brain, and so forth.

Blast Physics

The detonation of solid or liquid explosive material releases a large amount of heat and gaseous products that are transmitted as the blast (shock) wave, a pressure pulse a few millimeters thick that travels at supersonic speed outward from the point of the explosion.[3-5] The physical processes involved in the body's response to explosion blasts occur in 1/1,000 of 1 second, with consequent exposure to ambient pressure changes, rapid winds, and the heat wave. Clinical findings have revealed how the spherical leading edge of the blast wave exercises a severe crushing, shattering, and shearing effect resulting from the increase in ambient pressure. The air molecules are compressed to such a density that the pressure wave itself acts more like a solid object striking a tissue surface. This thin layer of compressed air forms a shock front that is propagated spherically in all directions from the explosion's epicenter. A longer negative under pressure (relative vacuum) follows the peak positive overpressure. Because the intensity of the blast (the peak overpressure) decreases rapidly proportionate to the distance from the detonation, personnel must be very close to an explosion to sustain a primary blast injury[6] (Fig 1).

To better understand how high explosives possess such shattering power one can compare this to the

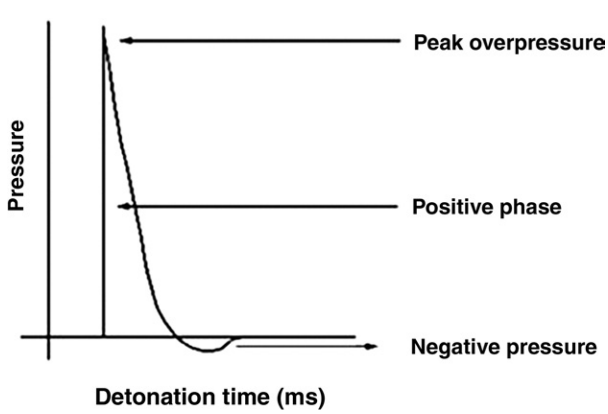

FIGURE 1. Positive and negative phase (pressure/time) of air blast shock wave.

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small changes in atmospheric pressure that can lead to high-velocity winds. For instance, a peak pressure of as little as 0.25 psi can generate winds as great as 125 mph. However, the overpressurized blast wave from the center of a detonator for high explosives can be as much as 3.7 to 18.6 miles per second, or 13,421 to 67,108 mph, resulting in a shattering effect. The temperatures from the explosive gases can reach 3,000°C in the center zone, particularly in a thermobaric explosion.[7,8]

Blast Injury Mechanism

These weapons depend on the explosion of solid or liquid chemical materials that rapidly release energy and produce a large volume of gaseous product, which induces 4 categories of tissue injury. The first is the primary blast effect resulting from an explosive. The primary blast effect changes potential energy to kinetic energy induced by the spherical front blast wave consisting of a few millimeters of overpressurized air. This results in a discontinuous increase in pressure, density, and high temperature, known as a shock front.

The second is the secondary blast effect caused by the different kinds and shapes of objects ranging from conventional shell fragments to car fragments, ground particles, sand and pebbles, or other components that can cause devastating damage to the body. A secondary blast injury is much more common than the primary blast injury, and it is the most common cause of death in blast victims.

Third is the tertiary blast effect, which results from the propelling of the body against walls or objects, crush injuries, or blunt trauma.

Finally, the quaternary blast effect causes asphyxia by inhalation of toxic fumes, burned materials, and burns by high thermal temperatures generated by the explosive effects.

PHYSICAL AND PATHOPHYSIOLOGIC EFFECTS

Living tissue can be damaged by the different mechanisms of the primary blast effects. These can be termed implosion, acceleration-deceleration, spalling, and pressure differentials. However, at these short ranges, fragment injuries and thermal burns can mask some of these serious effects of primary blast injury; therefore, these have not been widely covered in published studies.

Acceleration-deceleration injury is initiated by movement of the body tissue in the direction of the blast wave. Adjacent structures with different physical properties will accelerate at different rates, resulting in the shearing or disruption of tissues.[9,10] Solid parts of the body simply vibrate as the blast wave passes through them. In the maxillofacial region, this

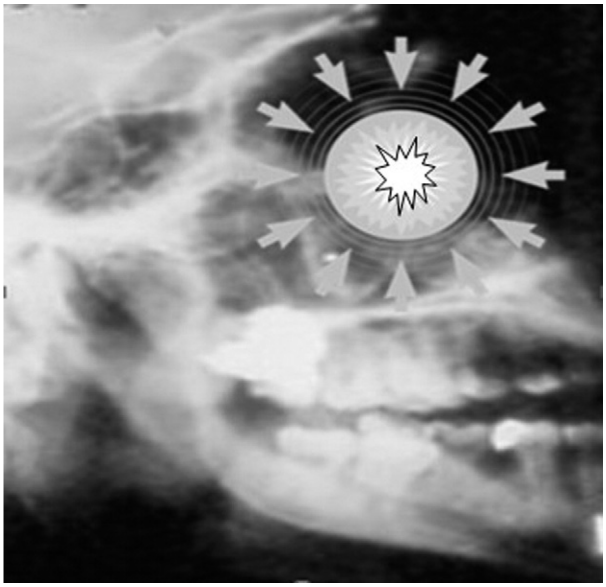

FIGURE 2. Biophysical blast implosion effect on air-containing sinuses experiencing blast injuries by implosion phase.

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has caused a new type of fracture seen only in the teeth and mandible caused by blasts and typically showing the succession movement of the transverse wave. Because not all the teeth and mandibular bony tissues will be equally capable of withstanding the forces, it will lead to transverse mandibular shearing fractures at the points of weakness as described by Shuker.[8]

Spalling or broken fragments can occur at the interface of 2 different media when the shock waves move from a high density to a lower density medium. For example, when air meets water, the water surface is broken up into showers of droplets.[5,9,10]

Implosion damage is limited to the gas-containing structures of the auditory canal, paranasal sinuses, gastrointestinal tract, and lungs.[8] A rapid displacement of the chest wall causes local compression of the lung parenchyma that cannot be relieved through the airways, thus stressing the lung tissue. This is one of the main causative factors of primary blast mortality from lung injuries. Organs containing fluid (urinary bladder, gallbladder) are almost never damaged by the implosion mechanism of the blast primary effect. In the maxillofacial region, the implosion mechanisms of the primary blast cause the most dramatic effects, observed in the fractures to the middle third of the face. This was reported for the first time, with their management, by Shuker[10] in 1995.

The middle third facial skeleton consists of large, skeletal, air-containing cavities that are second in size to the lungs, the largest air-container in the body.

The blast wave causes injury by its instant, rapid, external loading from an explosive detonation that manifests by compressing the air-containing sinus walls. These parts of the skeleton are similar to an egg shell or a crystal ball that is crushed and then splinters into fragments, with the exception that the periosteum membrane preserves the bone fragments' connection to their location.

Because the pressure differential across the sinus wall cannot be balanced by airflow through the sinus ostia, this, in turn, causes significant compression that stresses the sinuses' thin bone plate walls with air that originally filled the sinus cavities. This is followed by a miniature re-explosion or expansion of the compressed air sinuses (Figs 2, 3).

If the blast loading increases slowly enough, the internal pressures will have time to equilibrate the rapid external loading, avoiding significant damage to the tissue. The blast wave itself can cause fractures in the sinus walls with or without major external laceration. The victim who is in a facially oriented position as "en face" to the blast wave offers little resistance to the dynamic pressure component of the wave, especially the NOE region, which contains multiple air sinuses and thin bone plate walls. A single sole primary blast injury to this region is relatively uncommon in survivors because these types of trauma require high overpressurized air, which can lead to associated injuries, such as brain and lung injury.[9,11,12]

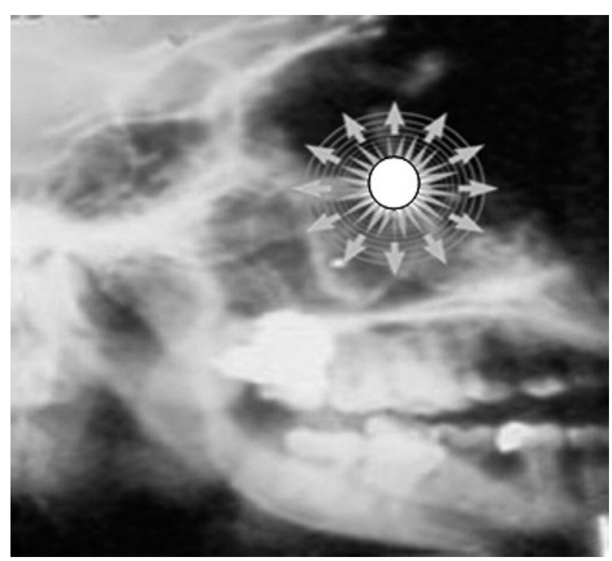

FIGURE 3. Re-explosion of compressed air inside sinuses returning collapsed structures to approximately original shape.

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Management

The assessment of the patient's general condition, as well as any associated injuries to the lung and/or brain, is the initial procedure which should be the priority to any life-threatening injury. Middle facial skeleton fractures from civilian trauma, such as a blowout or road traffic accident, are frequently segmental bone fractures, roughly at the point of weakness (ie, the "Le Fort 1901 classifications"). Treatment of this type of fracture is done by reduction and fixation using external fixation, suspension wiring, simple intraosseous wiring, or miniplates.

However, blast implosion injuries result in a new era of trauma and new type of injuries owing to the external blast wave loading from an explosive detonation resulting in a complicated crush of the architecture of the facial skeletal buttresses and plates. The restoration and reconstruction of the structures of a skeletal crushed eggshell middle third injury is an attempt to return the tissue to its original esthetic form and preserve physiologic functions, such as phonation and respiration. This cannot be accomplished using the classic techniques for typical facial trauma. For the restoration and reconstruction of skeletal middle third implosion injuries, the skeletal middle third was subdivided into 3 anatomic regions, each of which requires a different treatment approach.

NOE REGION

Treatment of the NOE region depends on the severity of the injury in this region. When this region is pulverized with shredded soft tissue, the canthal ligament should be explored using fine wires by guiding a 30-gauge steel wire through a thick portion and looping it through a hole placed in the posterior lachrymal crest on a piece of bone that the ligament is attached to and manipulating the 2 ligaments to an acceptable position. In cases in which no bone segment is left attached to the ligament, and the stump is free, the wire should be passed directly through the stump of medial canthal tendon.[13-16]

When the NOE region is crushed without shredding laceration of the soft tissue, the intercanthal space small bone fragment can be shaped by manipulation and squeezing it with 2 fingers to its original anatomy. Next, the area should be stabilized using 2 Portex tube-tailored wings or special buttons (Portex, Hythe, United Kingdom) to form the intercanthal space. While the bilateral medial orbital walls are squeezed, the stainless steel wire or nylon silk should be passed through holes in the Portex wing plates or buttons and the intercanthal tissue from one side to the other to maintain the stability of the proper anatomic region. The plates or buttons can be removed after 2 weeks, and the intranasal Portex tubes should be left in place for 2 to 4 weeks.

NASAL REGION

Treatment of severe blast injuries to the nasal region has frequently been difficult and prone to failure. Most of these cases are so severe, with fragments of bone and cartilage matted in soft tissue strands, that no anatomic landmarks will be evident. This type of blast injury and the patient's general condition necessitate simple, but reliable, and immediate measures. This is especially true for the severely collapsed nasal structure (with or without shredded soft and hard tissue of the NOE region) because immediate stabilization and reconstruction will prevent additional complications and, at the same time, maintain an adequate airway through the tubes.

Numerous methods have been devised to splint the fractured nose resulting from civilian trauma. However, none of these procedures is feasible for immediate missile or blast injuries with a severely avulsed or pulverized shredded nose, because the entire previous technique will end with an esthetically collapsed nasal shape, failure of the physiologic structure, and complicated later construction.

Shuker[17] introduced a new technique in 1988 with intranasal stabilization that was used successfully in severe nasal missiles and blast injuries. This was accomplished with a plain Portex tracheostomy tube (No. 7 or 8 tube) modified to fit the internal nasal cavity to preserve the anatomic shape and physiologic function. The convex curvature of the Portex tube arch is heated in a flame, squeezed with straight artery forceps, and immediately immersed in cold water to

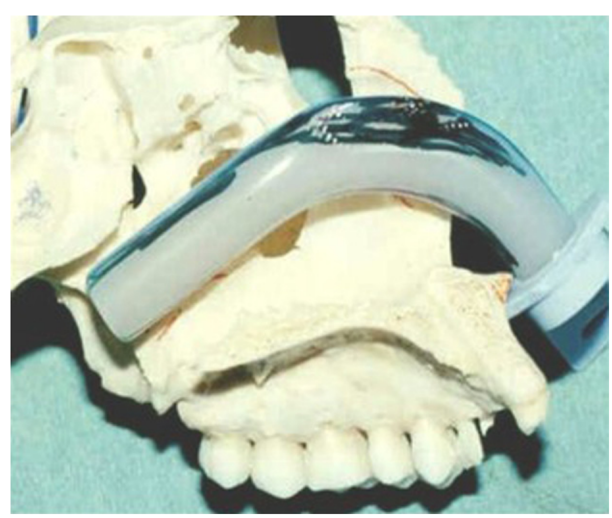

FIGURE 4. Portex trachesotomy tube showing convex curvature modeled to fit internal nasal arch.

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harden. A cross section of this segment will approximate a pyramid shape with the narrow apex uppermost and the round belly below—the same shape of the nostril cross section—preserving the physiologic functions of respiration and phonation (Fig 4).

With the patient under general anesthesia, the tethered tissue of the region is evaluated and replaced to where it belongs, usually without suturing, and the prepared Portex tube is inserted in position. When it is not feasible to see the nasopharynx of the devastated tissue, finger-touch should be used to detect the lacerated and mucosal surfaces and restore the mucosa to its proper position—medially and laterally to the finger. A speculum or 2 Howarth periosteal elevators (Medicon, Leeds, UK) should be placed around the little finger to prevent the flaps from collapsing. As the finger is withdrawn, the Portex tube should be inserted into position, and the fractured lacerated septum sandwiched in the middle between the 2 tubes. Hard and soft tissue builds can be performed on the tubes, which act as a parabolic arc scaffold. The tubes are secured on the ala of the nose and left in position for 1 month. Excellent healing can be achieved using this procedure, which encourages the tethered tissue to mend around the scaffolding created by the tubes, forming a vaulted or parabolic curve such that the proper anatomic contour is restored. During this period, the internal space of the Portex tubes should be regularly cleaned by suction to preserve normal breathing through them. Sometimes the nasogastric tube can be passed through the same tube hollow.

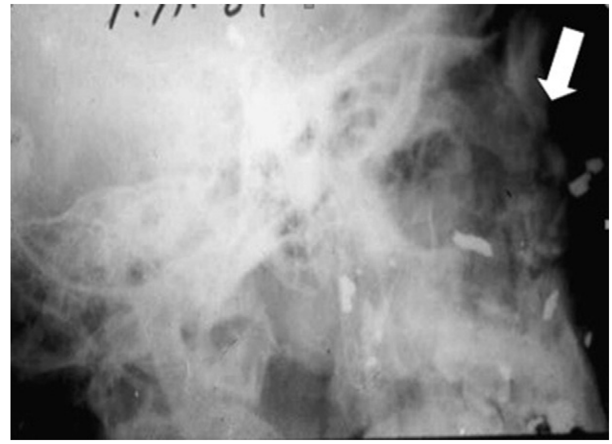

FIGURE 6. Skull lateral view radiograph showing total destruction of nasal orbital and ethmoidal region and small foreign body fragments.

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This technique results in superior stabilization for both the soft and the hard tissue, resulting in an acceptable appearance, and normal function, phonation, and air inspiration and expiration. In my experience, intranasal lacerated tissue has tolerated the Portex tube well, with no complications encountered, leading to an uneventful recovery (Figs 5-9).

MAXILLARY SINUSES

Treatment of crushed maxillary sinus walls should be initiated by irrigating the area with sterile water,

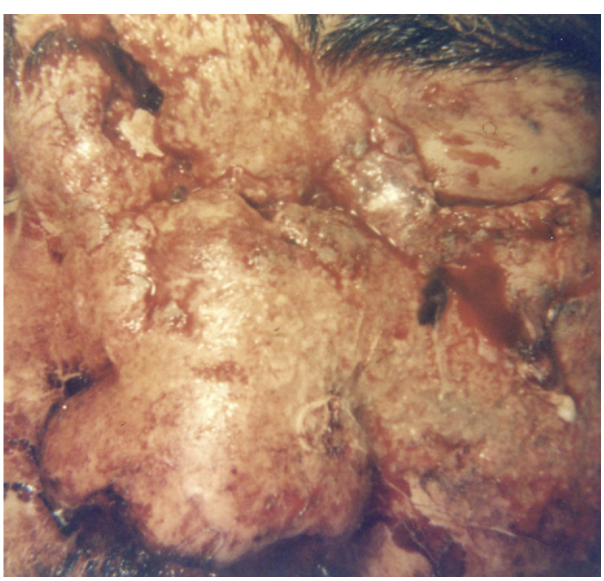

FIGURE 5. Severe NOE blast injury showing 6-cm-wide intercanthal space with pulverized, tethered, and shredded tissue and crushed nasal structures.

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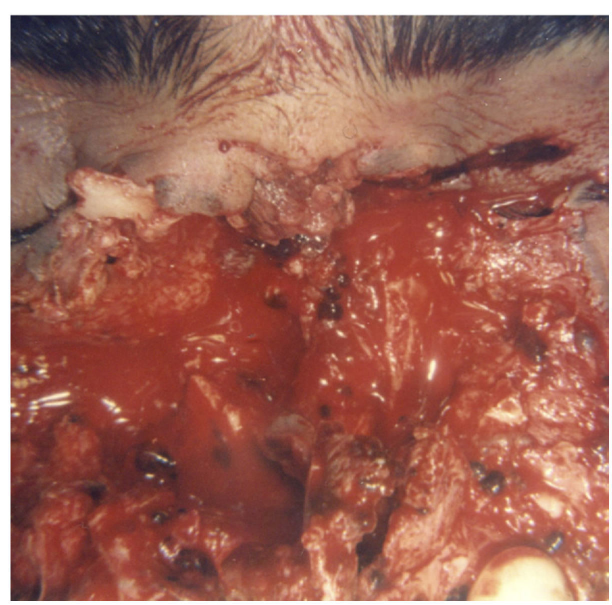

FIGURE 7. Severely pulverized NOE tissue from implosion blast mechanism.

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FIGURE 8. Two Portex tracheostomy tubes used as nasal scaffold for tethered nose and showing severity of injury to NOE region.

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FIGURE 9. Excellent result of NOE region, without collapsed nasal saddle compared with severity of injury and eye movement and acceptable NOE distance.

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FIGURE 10. Implosion effects of blast with right lateral side, middle third facial skeleton crush injury, eye lash and skin burn, multiple facial shredded lacerations, and right ruptured eye injury.

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usually through the same wound or using a Caldwell-Luc approach. Any free fragments of bone should be washed with water and removed. Careful inspection and palpation will enable the floor of the orbit and other sinus walls to be identified and, by gentle manipulation, the various fragments can be pushed into position.

Iodoform paste on ribbon gauze or Whitehead's varnish should be laid down uniformly in the maxillary sinus layer by layer. This will make later removal easier. This pack preserves the bone fragments and anatomic features of the maxillary sinus in the correct position. The external end of the ribbon gauze should be in the oral cavity sulcus or in the nasal cavity. The sinus packs should be removed after 2 weeks.[12]

If the front blast strike point was at the "lateral face" or side on, it will lead to comminuted crushed fractures at the zygomaticomaxillary sinus bones with or without a ruptured eye, with the lateral facial side remaining unaffected. The patient shown in Figures 10 through 13 also experienced lung collapse.

All patients with suspected or confirmed blast-lung injury should immediately receive supplemental high-flow oxygen in sufficient quantities to prevent hypoxemia. The delivery method can be by non–re-breather masks, continuous positive airway pressure, or endotracheal intubation. Careful fluid use and patient oversight must be maintained to ensure tissue perfusion without volume overload.[18-20]

Protection

Wearing a visor designed to break and stand against the load of the wave pressure stress will provide protection against blast-induced injuries, in particular, the ocular–orbital region and the NOE and maxillary

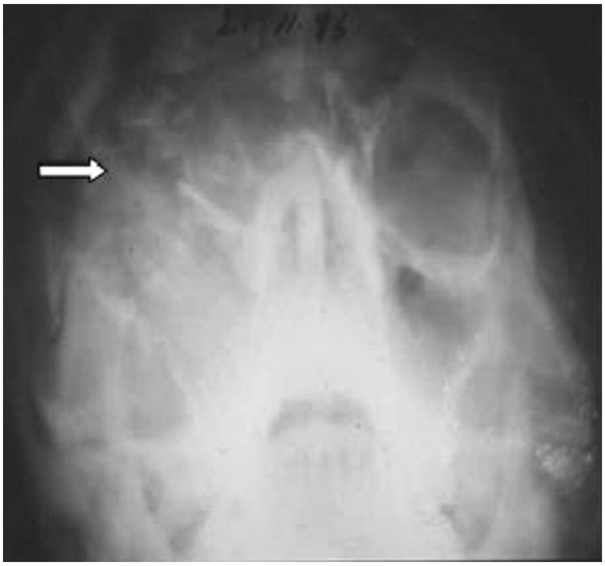

FIGURE 11. Occipitomental radiograph showing severe right middle third crushed implosion blast injury.

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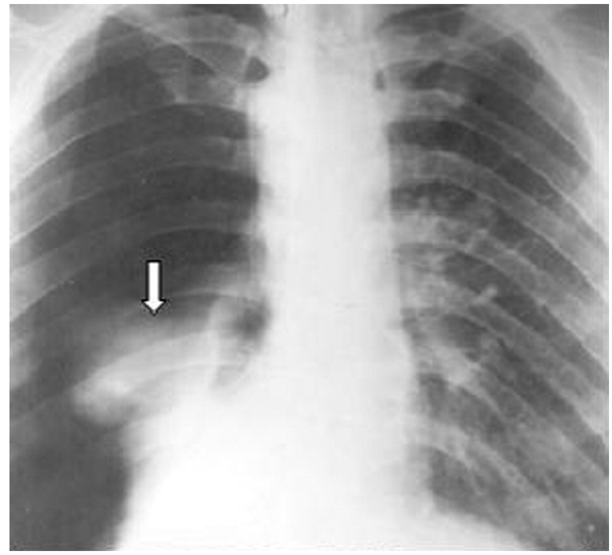

FIGURE 13. Chest radiograph revealing collapsed right side of lung.

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sinuses, and may prevent traumatic brain injury through the cribriform plates. In addition, the visor safeguards against the peppering of fragments from secondary blast effects and attenuates the primary blast stress force. Using the visor could save the vision of many victims of blast injuries. I advise not only those in uniform, but also civilians in unstable regions, to wear proper eye visors.

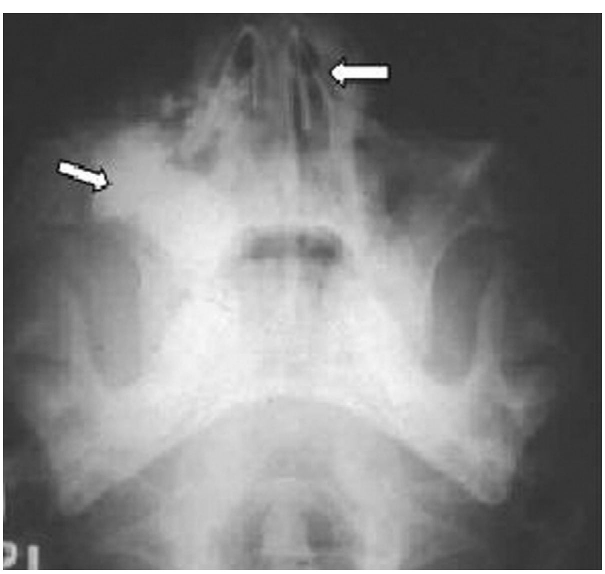

FIGURE 12. Occiptomental view radiograph showing iodoform gauze *(arrows)* filling right maxillary sinus and Portex tubes in nasal cavity.

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Discussion

The initial blast wave front of the overpressurized air implosion is one of the various dynamic effects of the primary blast wave. Implosion injuries are limited to the gas-containing spaces of the auditory canal, facial middle third, consisting mainly of the paranasal air cavities, gastrointestinal tract, and lungs. The en-face blast wave affects the paranasal sinuses, which consists of thin walls and the least-resistant bone plates. Consequently, severe bone plate fragmentation occurs. The implosion mechanism effects on the lateral facial side are less severe because of the round shape of the lateral maxillary sinus wall that is enforced by the zygomatic buttresses, which deflect the wave. In general, fewer lateral facial bones will be crushed than on the front or en-face side of the middle third, if exposed to equal blast wave kinetic energy. In the case of lung collapse, a chest tube and an experienced anesthetist familiar with pulmonary blast injury are needed, even when the findings from a chest radiograph are negative.

Advanced equipment alone without a good understanding of the biophysical blast dynamic effects and management will not help immediate providers and clinicians to decrease the mortality and morbidity from blast injuries. This report presents examples of easy, quick, and practical approaches that have proved to be successful methods for the management of blast injuries to the middle third, air-containing sinus walls and bone plates, including crushed egg-shell injuries, with or without ruptured eyes and other associated injuries.[6]

Primary blast maxillofacial skeleton injuries present with 2 different effects; the acceleration-deceleration mechanism of the blast wave causes mandible and teeth transverse fractures.[8] This is different from the pathophysiologic effects of crushed eggshell middle third facial skeleton injury from the blast implosion mechanism. The transverse mandibular fracture lines can be confirmed in between the line at the apices of the roots and just above the cortical bone of the lower border and teeth shearing at the cemento-enamel junction. In their research on the sheep head, Wang et al[21] approved the clinical finding of blast maxillofacial injury from a spherical explosive and the occurrence of its special wound in the maxillofacial region experimentally.

In my experience, miniplates, which are used successfully in severe road traffic maxillofacial injuries and allow fixation of larger bone segments, are not practical in the immediate management of severe blast injuries because of the small bone fragments, soft tissue mutilation, decreased blood supply, and time-intensive protocol needed at a critical stage.[22] Coronal or local flap exploration for these injuries is not the best surgical choice.

Acknowledgments

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