Bomb Explosions in Acts of Terrorism – Detonation, Wound Ballistics, Triage and Medical Concerns

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Bombing and explosions directed against innocent civilians have become the primary instrument of global terror and induce death, injury, fear and chaos. Until "every terrorist group of global reach has been found, stopped and defeated" (Presidential Congressional Address, 20 September 2001), the reality of terrorist bombing will remain a political, civil and social problem worldwide. While in the past, most bomb explosions were the results of military conflicts, at present, terror-related bombings predominate despite the continued existence of warfare and military engagements. Some bombings are part of criminal activity or acts of the mentally disturbed, but the large majority originates from ideological, political, racial or international conflicts. Since the start of this millennium, terror bombings have occurred in many and diverse locations, and if this trend is extrapolated, future global terror will surpass military violence if not stopped by an intensive international coordinated effort.

Although other types of terror using biological and chemical agents have been practiced, bombing will remain a major instrument of terror, because bombs are easily and inexpensively manufactured, simple to activate, and require no more than a determined perpetrator. The ease with which bomb-making instructions can be obtained and distributed, combined with fundamentalist beliefs and extreme ideology, should concern every member of modern society.

This paper summarizes and outlines our experience of more than 2 years in treating victims of terror bombings. Emphasis will be placed on the mechanisms of injury, triage, treatment and related medical aspects, with the hope that this painfully gained knowledge will help victims of future acts of terror.

Characteristics of bombing casualties

Data, collected from the recent years of Israeli-Palestinian conflict by the Israel Center for Disease Control, identified differences between injuries caused by explosion and those resulting from all other mechanisms of trauma. Terrorism caused more severe injuries, reflected by the higher ISS (injury severity score) of patients admitted to hospital following terror attacks (30% with ISS>16 vs. 10% in all other trauma admissions), and consequently also increased mortality. In-hospital death among terror victims (6.2%) was double that of all other trauma victims combined (3%). While in-hospital mortality from gunshot wounds from acts of terrorism was 22.8%, that of bomb explosions victims was 4%, probably because immediate mortality of explosion victims is very high and could reach 29% for explosions in enclosed spaces.

Surgical interventions, especially procedures related to the musculoskeletal system, were performed significantly more frequently in survivors of bomb explosions than in casualties of all other kinds of trauma. The length of hospital stay and the need for intensive care were also significantly increased for bombing victims.

Table 1. Age of casualties in terror attacks and in other trauma

Age group (yrs)	Terrorism (%)	Other trauma (%)
0–14	8.1	30.3
15–29	61.7	22.8
30–44	17.9	13.8
44–59	9.0	9.7
60+	3.3	23.5

Figure 1. Bodies of victims of ultra-confined space explosion with almost no external injury.

Table 1 depicts differences between the age breakdown of victims of terror and of other trauma events. More young individuals are among the victims of terror, the consequence of the intentional targeting of crowded places such as malls, pubs or buses, which are frequented by young people more than by older citizens.

Injuries in terror attacks in Israel were almost equally divided between gunshot wounds and bombing injury (each category accounting for 47% of injured). However, while the management of patients sustaining gunshot injuries is similar to that of those injured during military or criminal activities, the management of bombing casualties is unique and justifies this special discussion.

Death from bombing

Mellor and Cooper [1], examining bodies from bomb explosions in Northern Ireland, found that 14% of the bodies were completely disrupted, indicating proximity to the explosion. Thirty-nine percent had multiple injuries, 21% suffered head and chest injuries, 11% had only chest injuries and 12% had only head injuries, a rather high rate of injury for an organ accounting for only 20% of the body's surface area.

When conspicuous injuries are found in fatalities of explosions, it is easy to determine the cause of death, but sometimes no distinctive injuries are identifiable [Figure 1]. It is postulated that in some victims without obvious external injuries, cardiac dysrhythmia or air emboli caused cardiac arrest and eventual death. This type of hidden injuries is related to the effect of the blast generated by the explosion.

In most victims, death from explosion is the aftermath of combined blast, ballistic and thermal effect injuries. Only after recognizing the differing death patterns in such victims and understanding the underlying mechanisms can research and management of explosion injuries be realized.

Prognostic factors affecting patient outcome

Frykberg [2] identified a few prognostic factors that affect the outcome of explosion victims. The magnitude of the explosion (determined by the amount and type of explosive) is a key prognostic factor: the more explosive used the more devastating are the consequences of the explosion. Building collapse is another prognostic factor. People buried under the rubble will suffer more injuries and more tissue damage, leading to higher mortality. The confines of the location of explosion, namely open-air vs. enclosed spaces, are also an important prognostic factor since explosions in confined spaces cause higher mortality and increase the wounding potential [Table 2].

Table 2. Place of explosion and mortality and injury severity (%)

	Open space	Enclosed space	Bus
Mortality	2.8	15.8	20.8
ISS > 15	6.8	11.0	11.0
Multiple injury	4.7	11.1	7.8
Surgery required	13.5	17.6	14.9
ICU required	5.3	13.0	11.3

Obviously, the pattern of injury and the anatomic site of injury are important for survival. In bombings it is common to treat patients suffering from multiple site and multi-organ injuries caused by several mechanisms of injury. This we termed *multi-dimensional injury*.

Other crucial prognostic factors for favorable outcome are the immediacy of medical care and the availability of trained medical personnel. These are the only prognostic factors that can be changed, i.e., by preparing medical teams and educating them on the principles of explosion injuries management.

Four components of knowledge

There are four components of knowledge that we have identified as critical to master by medical teams intending to treat victims admitted following explosions. They include comprehension of the basic mechanisms involved in injury from explosion, and the potential for complications from such injuries. These components of knowledge are: a) detonation – the physics of the explosion, b) wound ballistics – understanding the resultant injury patterns, c) triage – the art of sorting patients according to the severity of injury, and d) medical concerns – treating multiple patients with multidimensional injuries and special injury patterns.

Detonation and explosion

The explosive, usually TNT, can be military, commercial, or homemade. Very often terrorists add many metal particles of various shapes to the explosive to increase its wounding potential. These include steel balls, nails, nuts and the like. The explosive is usually detonated by an electric charge activated remotely by a cellular phone or through a switch activated by the suicide bomber carrying the charge.

The transformation of the solid explosive into gas generates a highly pressurized wave of air that propagates radially from the site of the explosion, at the speed of sound, and is succeeded by a wave of negative pressure [Figure 2]. The leading front of the massive air

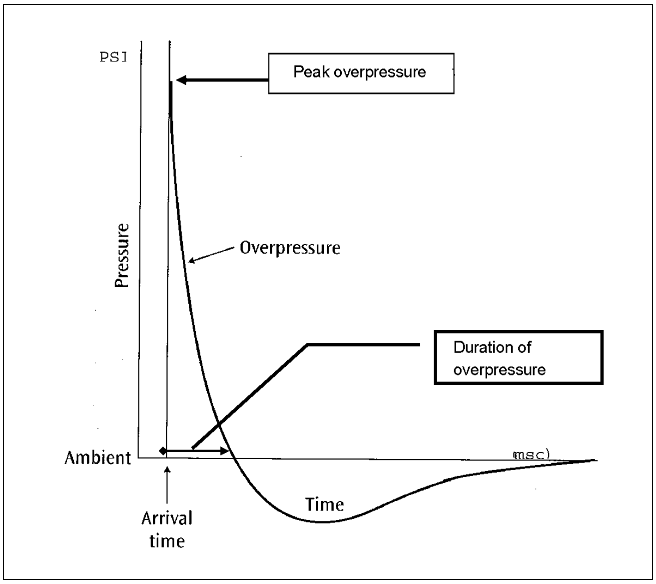

Figure 2. The behavior of the peak overpressure wave.

movement is the "blast front," which is responsible for the peak of high pressure that at different intensities will cause different types of damage. A charge of 25 kg TNT will induce a 150 psi peak overpressure for 2 msec that transverses at 3,000–8,000 m/sec, and more explosive will prolong the duration of the blast front, adding to the wounding potential. The blast wind movement induced by the explosion depends on the air density and the blast wind velocity: the higher the velocity the greater the generation of casualties.

Wound ballistics

Explosion induces four patterns of injury: a) primary blast injury induced by the blast, b) secondary blast injury caused by the projectiles, c) tertiary blast injury due to bumping the victim and wind disruptive injury, and d) quaternary blast injury resulting from fire and heat generated by the explosion.

The blast itself causes the primary and tertiary injury patterns. The ballistic effect forms the secondary pattern, and the thermal effects are responsible for the quaternary pattern.

- *The primary blast injury pattern – induced by the blast*

The primary blast injury results from the blast wave passing through the human body. Spalling, implosion, inertia and pressure differences are the putative mechanisms by which blasts induce damage in the tissue. Overpressure of 1.8 psi generates glass shards capable of penetrating the abdominal wall, and 3 psi overpressure can throw the human body, causing 1% fatality. Lung injury with 1% mortality is observed at 35 psi overpressure, but at 65 psi it results in 99% fatality.

The human body suffers damage in relation to the elastic properties of the involved tissues and their density and composition, resulting in different patterns of injury for different organs. Histologic examination of tissues injured by blast waves reveals torn alveolar septa with desquamated alveolar epithelium and alveoli filled with blood and edema fluid. Another pathologic hallmark of blast injury is the appearance of air emboli that fill the pulmonary vessels and the coronary blood vessels. This is most likely the leading mechanism of death in the undistracted victim who succumbed to the explosion. In some patients the blast traversing the body will induce hemorrhage in the gastrointestinal tract.

The human body is remarkably resistant to the blast wave. Solid and fluid-filled organs are rarely damaged, but air-containing organs suffer. The blast has two damaging components: the stress wave that damages relative to the amplitude of the wave's peak, and the shear wave that relates to the peak velocity and strain forces. While the blast wave has little or no effect on fluid-filled organs when hitting against them, the encounter increases the blast wave's velocity beyond the speed of sound, and so intensifies the potential of injury by greater stress forces.

Perforation of the eardrums and pneumothoraces are the hallmark injuries of the blast wave; perforation of hollow abdominal viscera is not as common. Eardrum perforation occurs at very low peak overpressure (15–50 psi, 50% likelihood of eardrum perforation) and therefore is considered an indication of the patient's exposure to the blast. One should be cautious however, because cerumen-filed auditory canals and eardrums of younger patients are resistant to the blast and can therefore be misleading as to the extent of the patient's exposure to the blast.

Blast lung is a more severe form of blast injury and usually results from 50–100 psi (50% chance of lung injury). Lung damage can develop with elapsed time, as depicted in Figure 3. Difficulty in ventilation, necessitating innovative ventilatory techniques, and massive air leaks are some of the problems facing medical teams treating these patients. It is critical to make an early decision as to whether the patient suffers from blast lung or lacerated lung – since the former demands careful management in intensive care, with repeated monitoring of blood gases and careful ventilation, while the latter may only occasionally require surgery.

Abdominal injury is rare. Injuries to solid organs (liver, spleen and kidney) are the result of deceleration of the organs. One possible injury mechanism is the acceleration of the organ upon impact of the blast wave, and then deceleration due to the organ's anatomic attachment (true blast injury mechanism). However, it is more likely that acceleration and deceleration of solid organs result from the tertiary blast mechanism, the bumping of the body against other objects.

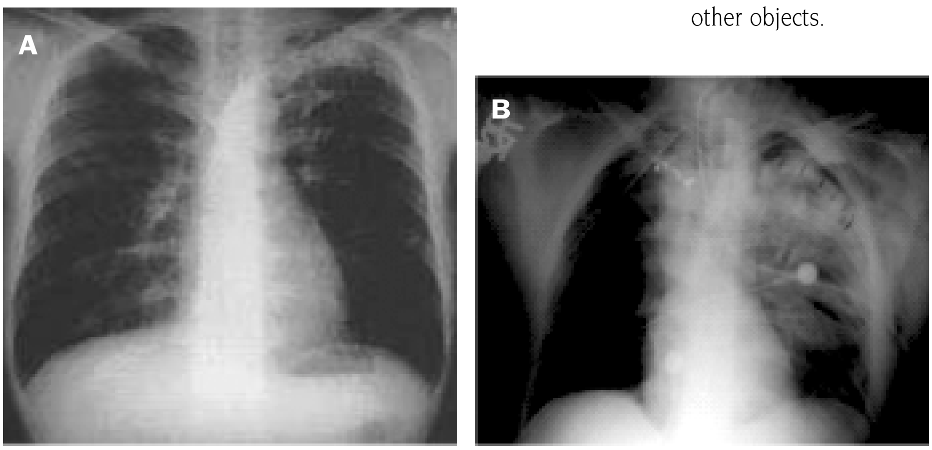

Figure 3. Chest X-rays depicting the gradual development of blast lung. **[A]** Upon admission to the emergency department. **[B]** Upon arrival in the intensive care unit.

Bowel perforations are rarely encountered (0–1.2%), although in the most recent bombing (30 April 2003), three patients with bowel injuries resulting in colectomies were encountered. This led us to conclude that the incidence of bowel perforation depends on the amount of explosive, proximity to the explosion, and the enclosure of the explosion site. The development of bowel perforation can be delayed for hours due to the special mechanism of their development. It was suggested that slow mucin dissection between the bowel

Figure 4. Chest X-ray showing multiple penetrations of spherical metal particles.

Figure 5. A hand amputated by the blast wind.

wall layers could belatedly result in this hollow viscous perforation. This injury's late presentation with its lucid interval raises concern about its early detection. Ultrasonography and computed tomography may not be determinative at early stages, and we have found diagnostic peritoneal lavage much more useful and accurate when treating patients with abdominal wall penetration by multiple metal projectiles. Also, in the intubated or unconscious patient whose signs of peritonitis may be obscure, the use of diagnostic peritoneal lavage is encouraged.

Other organs suffer true blast injuries as well. Head injuries are the cause of some of the "dead on the scene" events. In patients suspected of blast exposure, lucid interval of other brain injuries (hematomas, concussions, etc.) call for careful observation. Abrasions of the sclera and lens dislocations are rare but represent some of the blast injuries of the eyes. Coronary air emboli can result in cardiac ischemia and death.

- *Secondary blast injury pattern – induced by projectiles*

This pattern is caused by projectiles, such as nails and metal balls, embedded in the explosive. The metal objects gain energy from the blast and behave in flight according to ballistics rules – some will act as high velocity missiles and others as low velocity missiles, and their injury pattern will reflect their velocity and shape. Indeed, different injury patterns have been defined for spherical missiles, nails and screws.

Multiple penetrations to the human body demand special awareness during the patient's evaluation. One should use all means of evaluation to exclude cardiac or vascular injury when confronted with such a patient. Figure 4 is a chest X-ray of a patient who had suffered multiple penetrations of the chest. The patient presented hemodynamically stable, but an echocardiogram demonstrated pericardial fluid. A sub-xiphoid pericardial window revealed blood, and at operation laceration of the pulmonary artery was repaired.

- *The tertiary blast injury pattern – bumping of the victim and disruptive injuries*

The overpressure exerted by the blast wind has a long duration and, therefore, much wounding potential. The dynamic pressure from the blast wind is the cause of limb amputation encountered in some patients, as illustrated in Figure 5. When the victim hits stationary objects, the resulting injury resembles injuries of blunt trauma. Some investigators related solid organ injuries to this type of mechanism and not to the direct effect of the blast.

- *Quaternary blast injury pattern – result of fire and heat*

This injury pattern results from local fires, burning clothes, and proximity of the victim to the extremely hot explosion. Burns of various degrees are encountered, and combinations of burns with other injury patterns are not uncommon (multidimensional injury). High air temperature at the site of explosion can lead to the development of heat lung injury.

Effect of the site of explosion on the pattern of injury

The different injury patterns of indoor vs. outdoor explosions are well documented in the literature. Katz et al. [3] identified a distinctive increase in the morbidity and mortality when the same explosive was detonated in closed quarters compared to open-air explosion [Table 2]. The very high rate of mortality in bus explosions indicates a special pattern of blast behavior in ultra-confined spaces. In open-air explosions, a rapidly expanding sphere of gas at high pressure travels from the center of the explosion, propagates through and around the objects in its path, and is intensified by reflection of the shock wave from the ground to form the Mach stem. The quick dissipation and velocity decline of the shock front in an open space results in low immediate and late mortality and in predominantly non-critical injuries.

Indoor explosions are characterized by increased immediate and late mortality. The high incidence of blast lung [Figure 2] explains why mortality is so high in indoor explosions. In a confined space, the blast is bounced off the walls [Figure 6], increasing mortality and morbidity. In ultra-confined spaces like buses, the localized area of overpressure from the explosion is instantly amplified by reflections from the enclosing bus walls [Figure 7]. The high mortality in such explosions can be only partly attributed to the proximity of the victims to the explosion site, because the intense overpressure is the immediate cause of many other deaths.

Triage and over-triage

Triage, the art of sorting patients according to the severity of their injury, is the key for successful management of mass casualty events so frequently encountered after terrorist bombing. It is performed in the field and in the emergency department.

Field triage should identify the critically injured patients who need immediate care, providing them with lifesaving procedures and transporting them to the surrounding hospitals after considering their capabilities and avoiding overcrowding of any of them.

Mastering the art of field triage requires extensive education and training. One main concern in teaching triage to field medical care providers is the principle of over-triage.

Over-triage, namely the proportion of survivors assigned to immediate care who are eventually found to be not critically injured, is beneficial in regular trauma, because an over-triage of 50% is needed to keep under-triage below 10%. In mass casualty events, on the other hand, over-triage can be disastrous because it reduces the likelihood that patients considered non-critically injured in the field will receive treatment for hidden or delayed critical injuries.

Immediately after the explosion the chaos phase starts, when family members, bystanders and passing vehicles evacuate 6–10% of the injured to the nearest hospital. When trained medical personnel reach the scene, the medical command phase starts and triage principles are employed in the management of the remaining injured. Evacuation of the most severely injured patients by the medical forces to the nearest hospital can cause major problems, because at this point patients evacuated in the chaos phase crowd the nearest hospitals. Compounding this is the unavoidable process of over-triage, even by trained medical personnel, and it could lead to increased critical mortality – the death of patients who reach the hospital alive. The linear correlation between critical death and over-triage [2] indicates that in mass casualty events over-triage can increase the mortality of patients otherwise deemed salvageable.

In the hospital, the triage officer, a well-trained surgeon, is responsible for sorting the injured according to their severity of injury. The most severely injured should be transferred to a well-equipped area in the emergency department where lifesaving procedures and basic diagnostic steps are performed. All other patients should be directed to another designated area of the emergency department, where teams start their evaluation. The medical command officer, a surgeon responsible for the medical aspects of the event in the emergency department, will guide the medical teams as to the proper evaluation algorithms, considering the type of explosion (closed space vs. open space), explosive, and the metal projectiles. The medical command officer will also guide the medical teams on the proper use of auxiliary diagnostic modalities and the proper sequence of transferring patients to the operating rooms. Sequencing angiographies, tomographies, as well as plain skeletal X-rays are mandatory for the proper in-hospital management of mass casualty events.

Surgery of the injured from bomb explosion is challenging. Since we termed the injury *multidimensional*, damage control surgery is the logical concept governing the treatment of these patients. This strategy enables surgeons to deal with physiologic derangements and anatomic damage in a timely manner.

When the acute emergency department phase is over, a tertiary survey of all patients admitted is crucial. Missed injuries after bomb explosions are not uncommon and should be avoided by a systematic repeated examination by dedicated medical teams.

It must be remembered that although physical trauma is the main concern, some of the injured will suffer post-traumatic reactions that should be managed by specialized teams; these teams should also attend to family members who may suffer stress reactions. Physicians and nursing staff should be instructed on post-traumatic reactions and their diagnosis. Joint effort by all relevant authorities is required to alleviate the suffering of the victims and their families. Stress reactions of the medical personnel

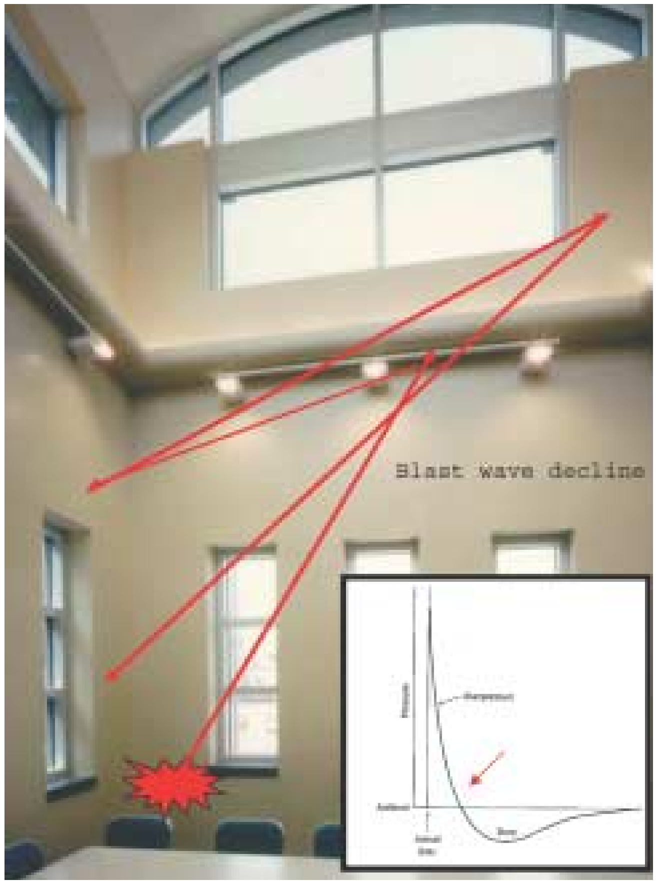

Figure 6. Blast wave decline occurs in confined space much slower than in outdoor explosions.

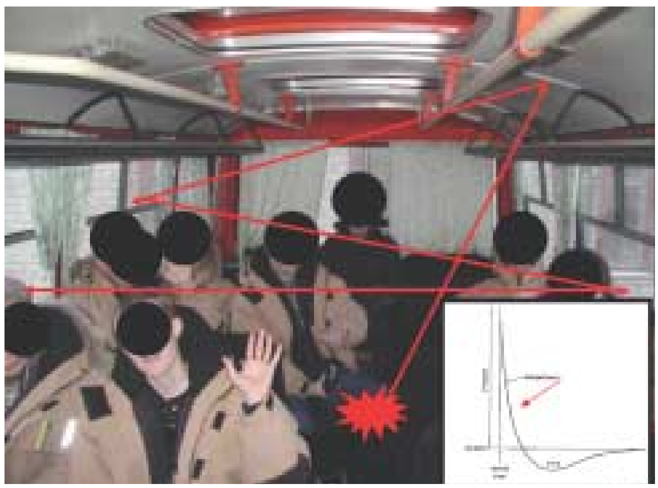

Figure 7. Inside the bus, the blast travels short distances and is reinforced from reflections off the walls, affecting many passengers. The graph representing the peak pressure indicates that blast reinforcement occurs long before the pressure declines.

are uncommon but should be minimized by holding debriefing sessions immediately after the acute event ends.

Only by repeated drills and extensive training that incorporate the experience gained by the medical personnel, and by assuring hospital preparedness, will victims of terror bombing be managed properly.

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References

1. Mellor SG, Cooper GJ. Analysis of 828 servicemen killed or injured by explosion in Northern Ireland 1970-84: the Hostile Action Casualty System. *Br J Surg* 1989;76:1006–10.
2. Frykberg ER. Medical management of disasters and mass casualties from terrorist bombings: how can we cope? *J Trauma* 2002;53:201–12.
3. Katz E, Ofek B, Adler J, Abramowitz HB, Krausz MM. Primary blast injury after a bomb explosion in a civilian bus. *Ann Surg* 1989;209: 484–8.

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Capsule

Higher retinoblastoma rate in IVF babies

A rare condition, occurring in about 1/15,000 live births in western countries, retinoblastoma is the most common eye tumor in children and the third most common cancer in children. It causes the growth of malignant tumors in the retinal cell layer of the eye. Moll et al. in the Netherlands noted an increased rate of retinoblastoma in babies born from in vitro fertilization. Between November 2000 and February 2002, retinoblastoma was diagnosed in five patients born after IVF. Assuming that 1.0–1.5% of children in the Netherlands are conceived by IVF, and that the five patients diagnosed with retinoblastoma represented all new cases in the Netherlands during that period, the authors calculated the relative risk of retinoblastoma to be 7.2 for an IVF rate of 1% (95% CI 2.4–17.0), or 4.9 for an IVF rate of 1.5% (95% CI 1.6–11.3). They recommend that future investigators consider the number of IVF treatments, other fertility drugs given before IVF, and the possibility that serious disorders in children conceived by IVF are diagnosed earlier than those in children without such close medical surveillance.

In an accompanying commentary, David BenEzra, from Hadassah Hebrew University Hospital in Jerusalem, warns about possible explanations other than causality. He notes that the five new cases of retinoblastoma could represent "clustering" of cases reported by interested observers, but advises a heightened awareness, a multidisciplinary approach and a closer follow-up of children conceived with assisted reproductive technologies.

Lancet 2003;361:273; 309

Capsule

P53 and apoptosis

Because many chemotherapeutic drugs kill tumor cells by inducing apoptosis (programmed cell death), cellular resistance to apoptosis is thought to be a major factor limiting drug efficacy. Elucidation of the molecular factors that determine whether a tumor will be sensitive or resistant to chemotherapy-induced apoptosis may ultimately enable oncologists to optimize therapies for individual cancer patients. Complementary laboratory and clinical studies by Bergamaschi et al. and Irwin et al. highlight the interactive role of the tumor suppressor protein p53 and its paralog p73 in the apoptotic response to chemotherapy. Their results reveal that specific mutations in p53, when present in combination with a common allelic variant at codon 72 of p53, can confer resistance to drug-induced apoptosis via inhibition of p73 function. Along with the implications for prediction of chemotherapeutic response, these findings raise the possibility that therapeutic modulation of p73 levels may offset the development of drug resistance in certain human cancers.

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