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The "Skin–skull–brain model": a new instrument for the study of gunshot effects

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Abstract

In order to create and study wound morphology, a "skin–skull–brain model" had to be designed which would make the laboratory reproduction of a real ballistic injury possible.

To simulate the human skin, an artificial skin (a silicon cap) is used. This silicon scalp contains synthetic fibers (artificial leather) to simulate the collagen and fat of the scalp. The artificial skull is a layered polyurethane sphere (19 cm o.d.; and 5, 6, or 7 mm thick) constructed in a specially designed form with a Tabula externa, Tabula interna, and a porous Diploe sandwiched in between. The periostium of the artificial skull is made of latex. This elastic latex layer prevents the bone fragments from scattering after the model has been struck by gunfire. The brain itself is simulated with ordnance gelatin, 10% at 4 °C, a material well known in wound ballistics. Gunshots were fired at a distance of 10 m from the model.

During the evaluation of the "skin–skull–brain model", it was possible to show that injuries inflicted to this model are fully comparable to the morphology of equivalent real gunshot injuries.

Using the "skin–skull–brain model" has some significant advantages: the model is inexpensive, easy to construct, instantly available for use, and eliminates ethics conflicts. The main advantage of such a model is, in comparison with biological substances, the high reproducibility of inflicted traumas.

Keywords: Skin–skull–brain model; Head model; Forensic science; Gunshot; Ballistic

1. Introduction

Firearms-related injuries are a leading cause of morbidity and mortality in the world. Gunshot wounds to the head are often seen in the emergency centers of hospitals, and in the autopsy rooms of forensic pathology departments. Among the most common causes of head injuries by gunshot are homicide and suicide. In Switzerland, for example, the self-inflicted gunshot is one of the most common methods of committing suicide.

The clinical accuracy of describing gunshot injuries is woefully inaccurate. One reason for this well-known fact is the general lack of understanding of the physical mechanisms behind the traumatic injuries caused by gunshots. Wound ballistics processes can only be fully understood when the physical laws of the motion of a bullet in air and in a dense medium are understood. "Terminal ballistics" describes the effects the projectile causes while striking the body, as well as the counter-effects produced upon the projectile.

Science incorporates two complimentary methods in order to study and solve a given problem. The first is the descriptive (result oriented) method: multiple observations of real cases are gathered together and then studied for the purpose of drawing a general conclusion; that is, forming an hypothesis. This hypothesis is then compared against new observations and, if necessary, modified by the results.

The second scientific method is the analytical (process oriented) method: this involves the experimental re-creation and careful observation, of the dynamic mechanism (the physical activity) that produced the end result. The analytical method requires experimentation (for example on a model) to prove or disprove the hypothesis derived from the

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descriptive method. The analytical method tests the hypothesis experimentally.

Naturally, both methods are necessary. Without a "framework theory", which is most often based on the descriptive summary of multiple case reports, we can neither ask revealing questions nor design suitable laboratory experiments.

So, wound ballistics is a science of experience and experiments. New data is mainly obtained by live firing, although the use of mathematical models, and consequently the possibility of making quantitative predictions, is increasing.

In order to create and study wound morphology, a physical head model had to be designed which would make the laboratory reproduction of a ballistic injury possible. In the past, experimental studies of head injuries utilized animals or human cadavers, and required expensive and time-consuming research. Another very important argument against the use of animals for such experiments is the inhomogeneity of the penetrated tissue. And, of course, tests on cadavers do not permit the determination of physiological reactions in living tissue. Furthermore, the use of live animals and biological tissue for experimentation is greatly limited by the guidelines of medical ethics. Consequently, both the engineering and the medical communities have expressed the need for biomechanical models that could be used to simulate and study traumatic head injuries.

The goal of this study was to develop a synthetic, non-biological "skin–skull–brain model" which would allow the simulation of gunshot wounds to the head in such a realistic manner as to reconstruct the specific physical characteristics of a given trauma, including its progressive formation. The essential point in the simulation was to produce a force similar to that of the original gunshot projectile(s) passing through the tissue. The highest and lowest damage potentials in the model tissue had to be in the same anatomical locations as in the human head. In a good model, the wound morphology of the skin, and the form and breadth of the bone fractures also had to be comparable with human traumas. Furthermore, the deformation and the penetration of the bullet had to be nearly the same in the model as in the human tissue.

It is known that in ballistic studies gelatin and glycerin soap are well-established substitutes for human soft-tissue [1–3].

Because gelatin and glycerin soap have approximately the same density as human tissue, the gunshot effects in them are comparable with those in human tissue. The experiments with these substitutes make it possible to understand what happens to the human body as the result of, for example, a penetrating gunshot.

The understanding of these end result requirements lays the groundwork for the expected simulated clinical wound patterns, and for the subsequent real case surgical procedures.

Kneubuehl and Oberli had the idea to simulate real hollow bones in gunshot experiments with artificial, polyurethane bones [3]. These synthetic bones have been used successfully in the past for student teaching and for training orthopedic and trauma surgeons [4].

One of the authors (BPK) then had the idea to simulate the human skull with a hollow, skull-sized polyurethane sphere.

Current literature describes no good substitute, for experimental purposes, for human skin.

And, no paper has yet been published regarding a qualitatively or quantitatively satisfactory model of the whole head (including skin, bone and brain), for the study of the mechanisms of cranial injuries by gunshot. The most recent investigations of gunshot wounds to the head have touched upon general analyses without providing any information on the morphology of the wound [5,6].

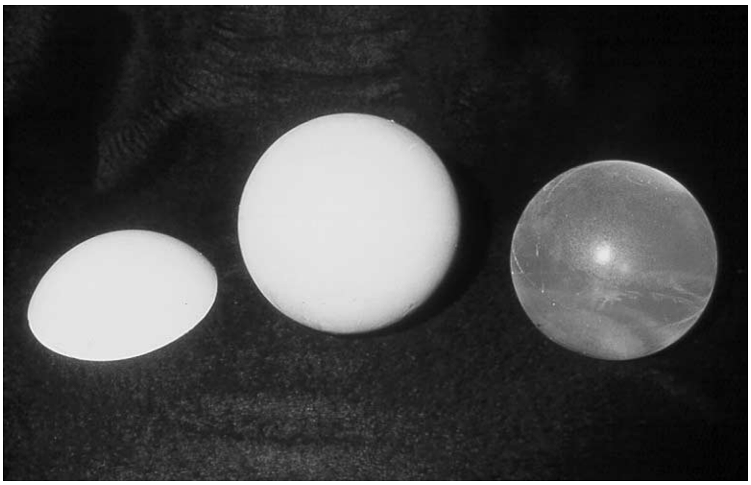

Fig. 1. Skin–skull–brain model. From left: Artificial scalp, hollow sphere of artificial bone (polyurethane), sphere of gelatin as a simulant of the brain.

2. Materials and methods

We developed a physical ‘‘skin–skull–brain model’’, which allows us to simulate gunshot wounds in such a realistic manner as to permit the reconstruction of the specific characteristics of a trauma.

The ‘‘skin–skull–brain model’’ is illustrated in Fig. 1.

To simulate the human skin, an artificial skin (a silicon cap) was used. This silicon scalp contains synthetic fibers (artificial leather) to simulate the collagen and fat of the scalp. The artificial skin was fastened to the skull model with modified suspender-straps (Fig. 2).

The artificial skull is a layered polyurethane sphere (19 cm o.d.; and 5, 6, or 7 mm thick) constructed in a specially designed form with a Tabula externa, Tabula interna, and a porous Diploe sandwiched in between. We chose the shape of a sphere because this geometric form gives much more reproducible and comparable results than does the complex form of a skull.

The periostium of the artificial skull is made of latex; an idea of Robin Coupland (surgeon for the International Committee of the Red Cross (ICRC) [7]. This elastic latex layer prevents the bone fragments from scattering after the model has been struck by gunfire.

The brain itself is simulated with ordnance gelatin, 10% at 4 °C, a material well known in wound ballistics. In liquid form, the gelatin was injected into the artificial skull through a 1 cm diameter borehole. The borehole is afterwards closed and sealed with a fitted plug.

Our live-fire experiments were performed with a broad variety, a representative spectrum, of ammunitions; for example following firearm types we used:

Pistol	9 mm Luger, FMJ-bullets, and Action 1 (DNAG)
Revolver	22 L.R., 38 Spl., 44 Rem. Mag.
Military Rifle	7.62 mm NATO and 7.62 × 39 (Kalashnikov) FMJ-Bullets
Shotgun	12/70 Brenneke Slug

The caliber ammunition most used in our experiments was the 9 mm Luger, with a muzzle velocity of about 350 m/s.

In this study gunshots were fired at a distance of 10 m from the model (Fig. 3).

High-speed photography was made with a Hadland Photonics IMACON 468, by experts from the Ballistics, Weapon and Ammunition Test Center, FA 26 Group ‘‘High-Speed Measurement Technique’’ in Thun, Switzerland.

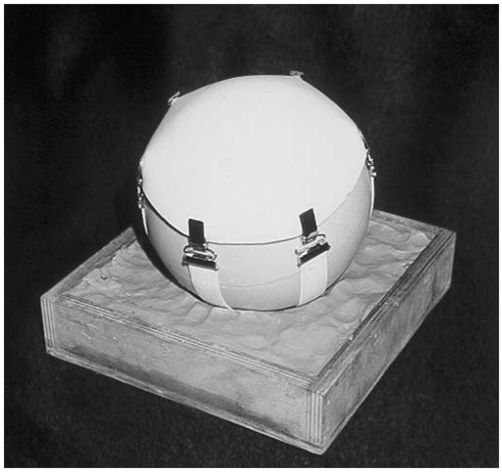

Fig. 2. The artificial skin is fastened to the skull model with modified suspender-straps.

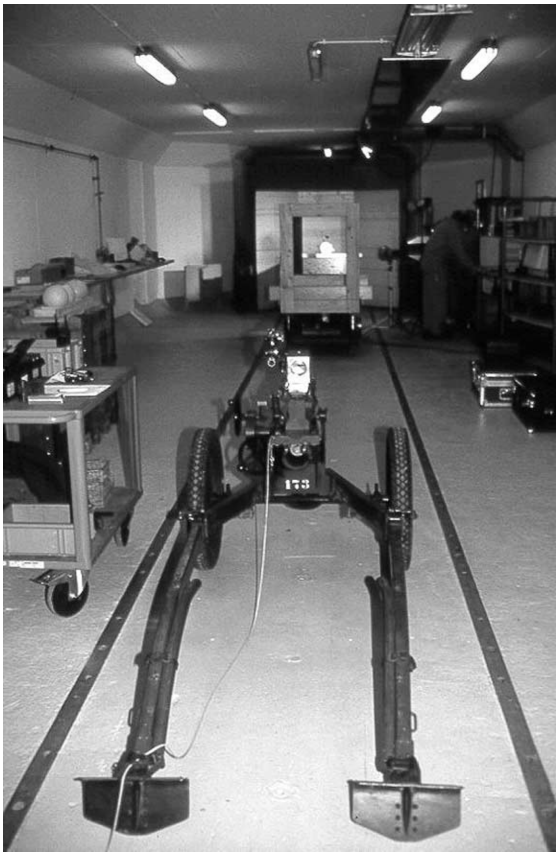

Fig. 3. Gunshots were fired at a distance of 10 m from the model.

3. Results

Various gunshot-trauma injuries were experimentally reproduced.

3.1. Head through-and-through gunshot

3.1.1. Skin

Around the entrance wounds in the artificial skin we found two significant signs of the distant, head-on (perpendicular to

Fig. 4. Experimental gunshot to the artificial *skin*.

skin surface) gunshot: the ''abrasion ring'', and the ''ring of dirt'' or ''grease ring'' [8–10] (Fig. 4). Both rings were created by the projectile, and looked like the morphology seen in real cases (Fig. 5). In the entrance wound itself the artificial leather, simulating the fat and collagen of the scalp, was visible, (Fig. 4).

The exit wounds in the artificial skin were also comparable to the human morphology.

It was also possible to reconstruct the semilunal abrasion of the glancing gunshot wound, which indicates from which direction the victim was shot.

The skin showed a cap-shaped abrasion to the left of the entrance wound. This indicates that the gunshot came from the left and that the projectile struck tangentially.

The same wound morphology is observed with real cases (Figs. 6 and 7).

3.1.2. Skull

Of particular note, it was possible to demonstrate the characteristic fracture lines of the bone at the entrance and exit wounds. Realistic wound morphology was obtained, with the synthetic bone reproducing the inward beveling of the bone at the inner margins of the entrance wound. This corresponds to the well-known effect of a larger lesion in the inner surface of the bone.

At the exit wound, the mechanism of outward beveling was also reproducible (Fig. 8).

Fig. 5. Gunshot entry wound from a real forensic case.

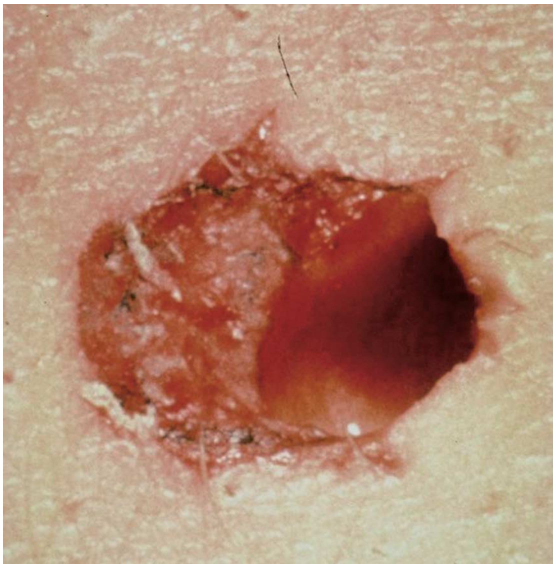

Fig. 6. Semilunal abrasion on the left side of this real forensic case gunshot entry wound indicates the projectile traveled from left to right.

The principle of ''interruption of fracture lines'' allowed us to determine the sequence of multiple gunshots in exactly the same way as in cadaver tissue. For example, the shot on the right came first, because the fracture lines radiating from the shot on the left are arrested (stopped) by those fracture lines that were already present (Figs. 9 and 10).

3.1.3. Brain

We could clearly observe the gunshot channel and, as a result of the temporary wound cavity, cracks in the gelatin (Fig. 11).

We found bone fragments only in the area of the temporary wound cavity (Fig. 12).

Even the ''Kroenlein'' shot [11], caused by a high-velocity bullet, was reproducible with this new model (Fig. 13).

3.2. Glancing/tangential gunshot

We also fired glancing shots at the ''skin–skull–brain model'' and documented the results with high-speed photography (Fig. 14).

3.2.1. Skin

The wound morphology of the artificial skin (Fig. 15) looks like that of the real case. Visible at the beginning of the glancing bullet wound is a semilunal abrasion, which indicates that the bullet was fired from the left. Tears around the margin of the glancing wound point to the source of the gunshot, 180° opposite to the direction in which the bullet moved. These experimental results were comparable with the morphology seen in real cases [12].

3.2.2. Skull

Even though there was no fracture visible on the outer surface of the artificial skull, the Tabula interna was always depressed and bone fragments from the Tabula interna were found driven into the gelatin (Figs. 16–18). In more severe tangential gunshot injuries, the entire site-of-impact bone structure was fractured (Figs. 19 and 20).

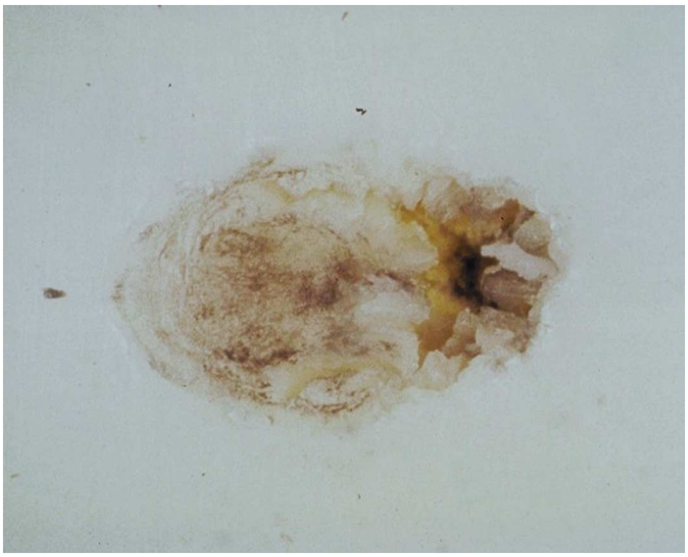

Fig. 7. Experimental gunshot to the artificial *skin*: same morphology as in Fig. 6.

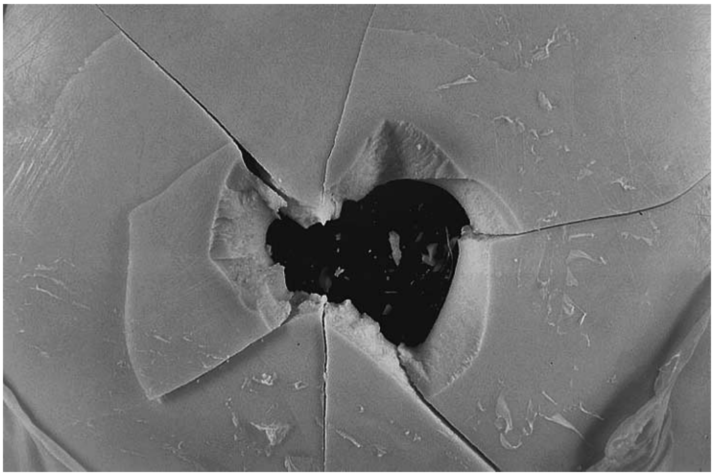

Fig. 8. Exit wound from the synthetic *bone*.

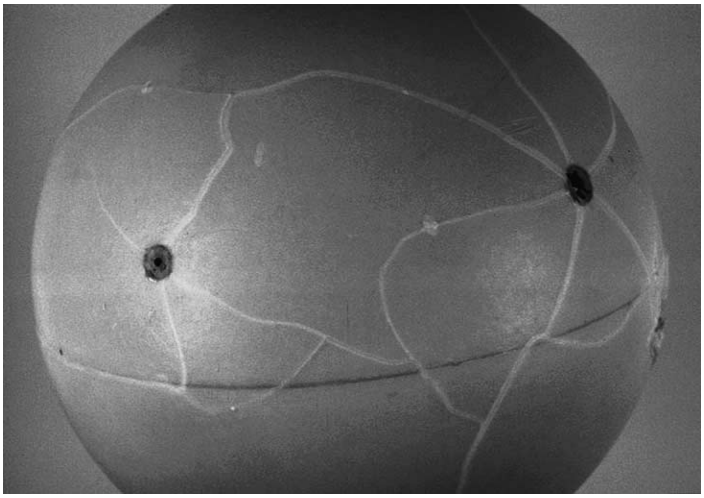

Fig. 9. Gunshots to the model: the fractures radiating from the gunshot injury on the left are arrested by the fractures from the gunshot injury on the right. This indicates that the gunshot injury to the right side had been inflicted first.

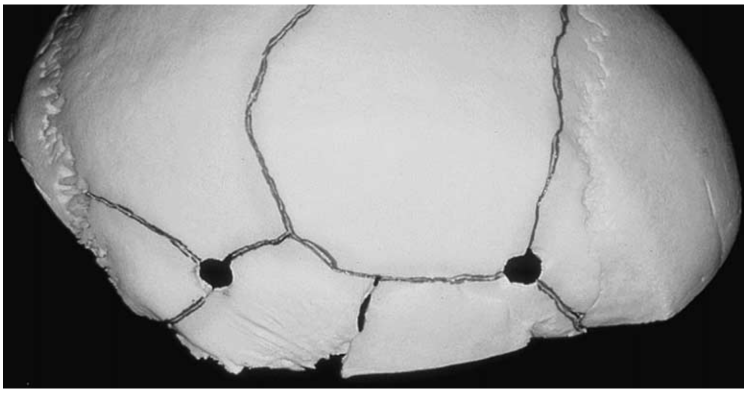

Fig. 10. Real forensic case of gunshot to the head: the fractures radiating from the gunshot injury on the left are arrested by the fractures from the gunshot injury on the right. This indicates that the gunshot injury to the right side has been inflicted first.

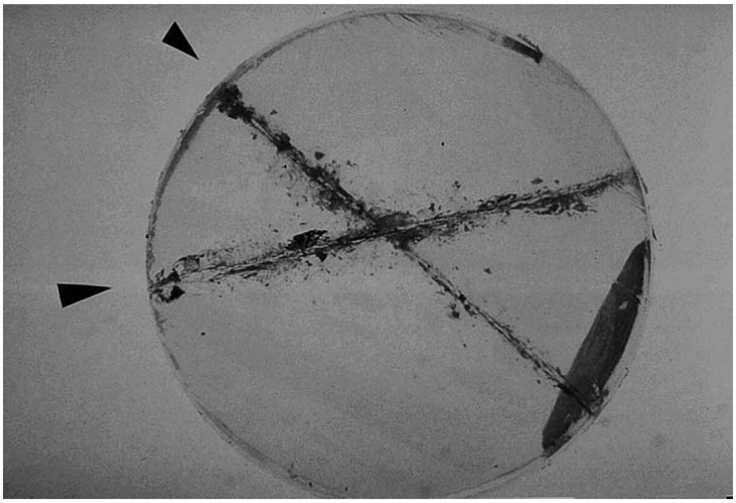

Fig. 11. Gunshot channels in gelatin as *brain simulant*.

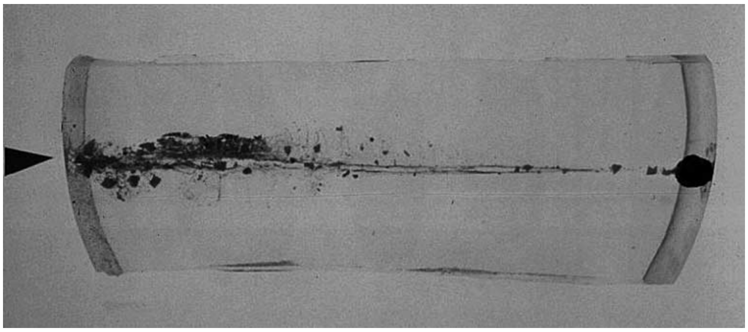

Fig. 12. Gunshot wound channel: bone fragments found only in the area of the temporary wound cavity.

Fig. 13. Kroenlein shot: total evisceration of the brain.

3.2.3. Brain

With these tangential gunshots, bone fragments were discovered driven into the gelatin. Also, these experimental results were comparable with the morphology seen in real cases [13–19]; (Figs. 18 and 21).

4. Discussion

During the evaluation of the ''skin–skull–brain model'', it was possible to show that injuries inflicted to this model are fully comparable to the morphology of equivalent real gunshot injuries.

4.1. Skin

In literature, most gunshot studies were conducted with the skin of cadavers [2,3]. In our experiments, gunshot lesions produced in the artificial skin had the morphological

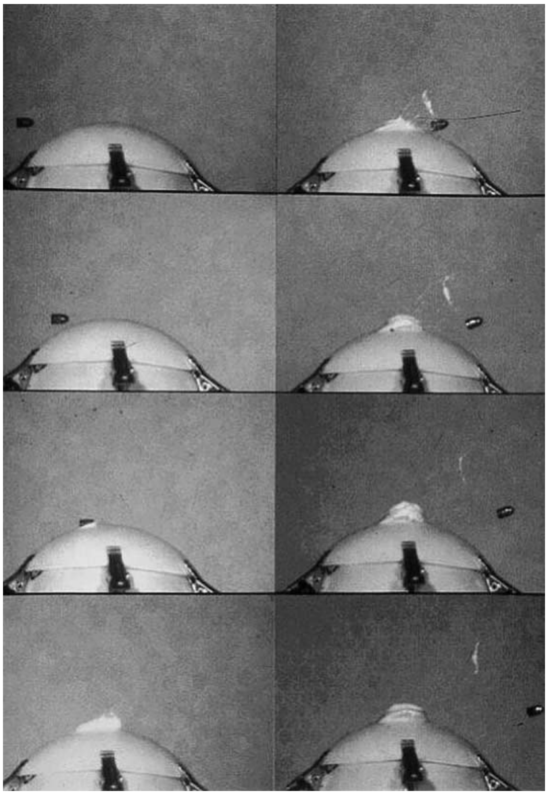

Fig. 14. High-speed photography of glancing gunshot fired at the skin–skull–brain model.

characteristics of real firearms wounds. Consequently, it was possible to reconstruct the morphology of distant gunshots, especially the characteristic signs for the entrance wound: the ''abrasion ring'' and the ''ring of dirt''.

It was also possible to reconstruct the semilunal abrasion of the gunshot wound specifically caused by tangentially striking projectiles, which abrasion also indicates the direction from which the gunshot came.

Furthermore, it was possible to study the development of a glancing gunshot wound. It is known that the direction from which a projectile is fired can be determined by a careful examination of the gunshot wound. Specifically, the observation was made that the ''skin tags'' [12], located along the lateral margins of the glancing wound, point toward the weapon, or, expressed in another way, point in the direction opposite the flight path of the projectile.

With the model, we could reproduce this morphology, and with the high-speed photography it was also possible to document the ricochet away from the skull. The physics of the ricochet is responsible for this special wound morphology [20].

4.2. Skull and brain

In the past, gunshot experiments done in order to study skull fractures used, for example, plastic mountain climbers' helmets, motorcycle crash helmets, and even ostrich eggshells as models [21]. Our skull model is the first ever built to incorporate a layered construction representing the human skull's compact bone layers, the Tabula externa and Tabula interna, as well as the porous bone layer in between.

The polyurethane skull allows us to reproduce characteristic fracture lines after gunshot trauma. For instance, the model allows us to reproduce the characteristically concentric and radiating fracture lines. In the gunshot wound channel—and only in the tissue affected by the temporary cavity in the gelatin—we found small artificial bone fragments. It is well known that the same fragmentation pattern is found in autopsies. Moreover, from the measurements of

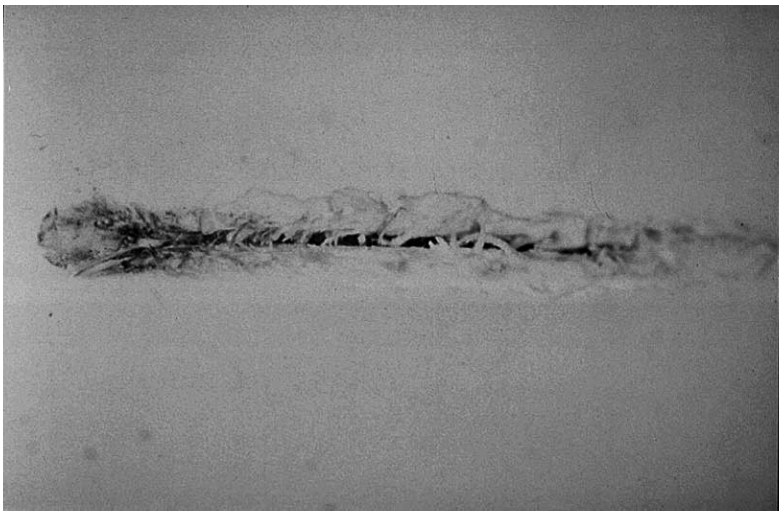

Fig. 15. Glancing gunshot: morphology of the artificial *skin*.

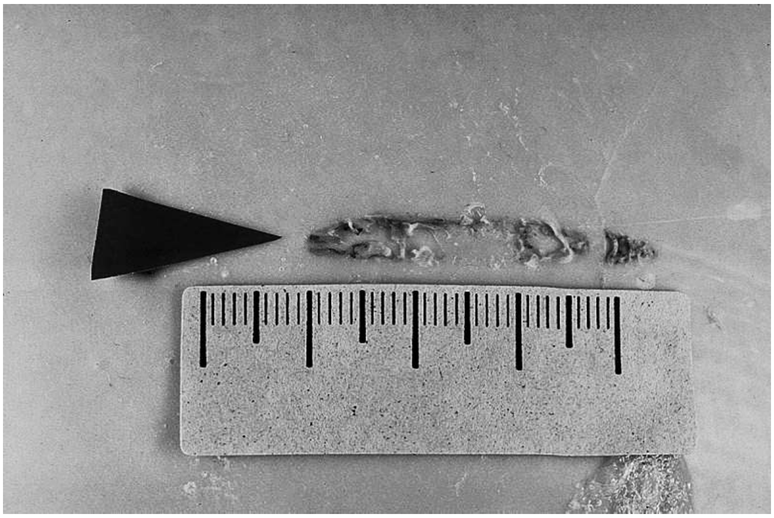

Fig. 16. Glancing gunshot: damaged *periostium* but no visible fracture on the outer surface of the artificial *skull*.

the projectile's loss of velocity while penetrating the bone we know that bone fragments did not possess enough energy to produce their own wound channels [2,3].

In our model, the bone lesions created by glancing gunshots also resemble those lesions in real cases. Glancing wounds to the skull were first reported by Cushing [17]. Like Dodge et al. [18], he presented the following types of gunshot skull injuries: the Tabula interna was always depressed, but in some instances the Tabula externa was linearly fractured. In severe injuries, the Tabula externa fracture was stellate and depressed. These lesions were produced by a projectile glancing off the skull. The bullet strikes the skull at an angle too acute for penetration, but nevertheless transfers part of its energy at the point of impact [16]. Berg et al. [16] reported that in most severe head injuries, bone fragments from the Tabula interna were driven deeply into the brain; and that usually the fragments were clustered. In glancing gunshot wounds to the skull, scattered bone fragments were driven intracranially and lacerated blood vessels and brain tissue over a much wider area than that which the size of the shallow scalp wound would lead one to expect. Published observations were confirmed in our experimental series [13–15].

We could produce exactly the same results in our experiments: we had the same types of fractures of the Tabulae interna and externa, and the clustered fragments of the

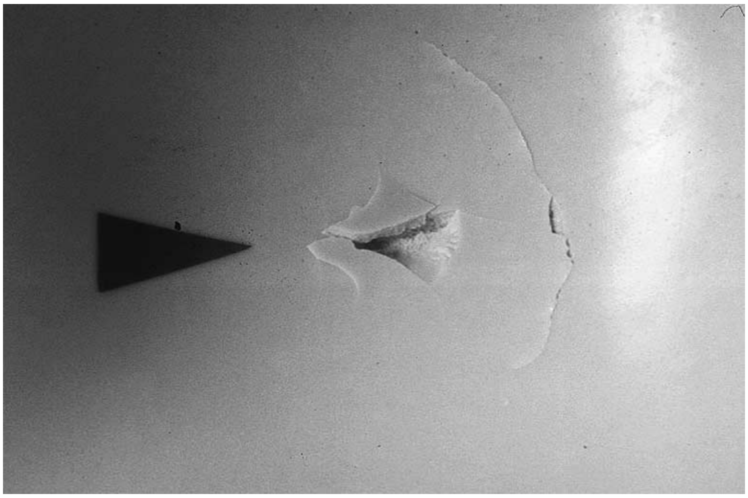

Fig. 17. Glancing gunshot (view from inside the head): depressed *tabula interna*.

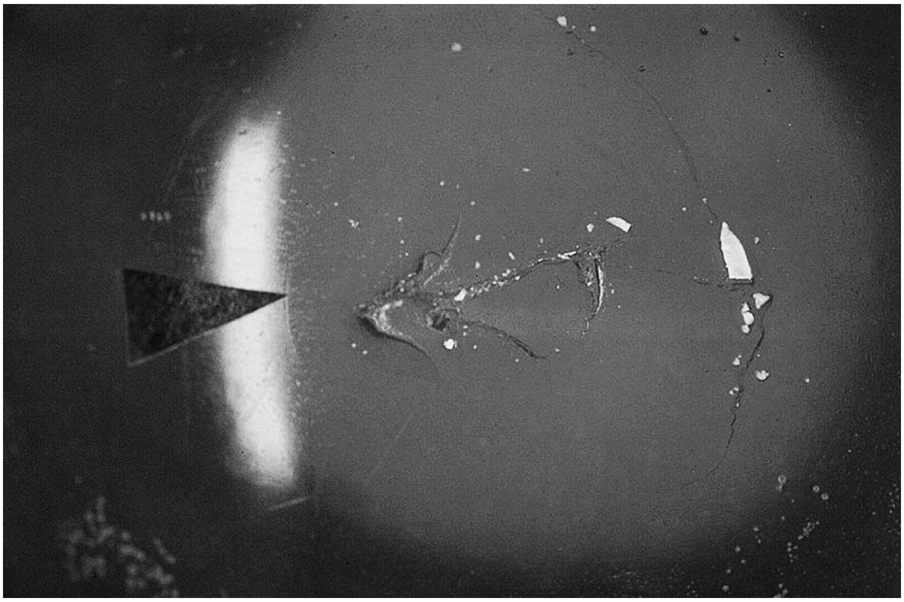

Fig. 18. Glancing gunshot: Bone fragments from the *tabula interna* were found driven into the gelatin *brain*.

polyurethane bone were also deeply driven into the gelatin brain. In our study, real and experimental lesions had the same morphological characteristics.

In conclusion, a new artificial ''skin–skull–brain model'' has been developed, which is highly suitable for the scientific simulation of gunshot wounds to the head. This inexpensive and easy-to-assemble device is a valuable tool for studying the mechanisms of head injuries, and in the process high-speed filming their formation.

We agree with Sellier and Kneubuehl [2,3] who say there is a marked difference between observations and experimental tests, because observed data (case reports) are fraught with many uncontrolled variables. Experiments hold the crucial advantage in that the scientist can control most of the variables except the one he or she happens to be particularly interested in.

Use of the ''skin–skull–brain model'' presents some significant advantages: the model is inexpensive, easy to construct, instantly available for use, and eliminates ethics conflicts. The main advantage of such a model is, in comparison with biological substances, the high reproducibility of inflicted traumas.

Fig. 19. Severe tangential gunshot injury: fracture system.

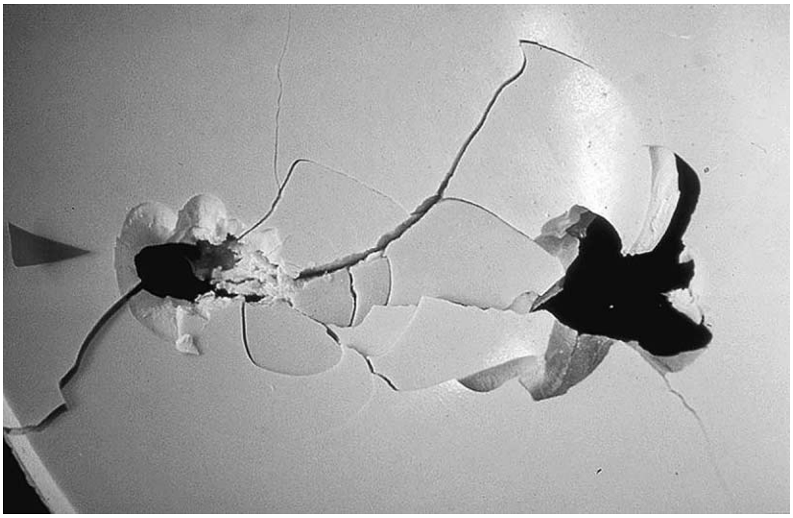

Fig. 20. Fracture system (view from inside the head): inward beveling of the bone at the inner margin of the entrance wound and outward beveling at the exits wound.

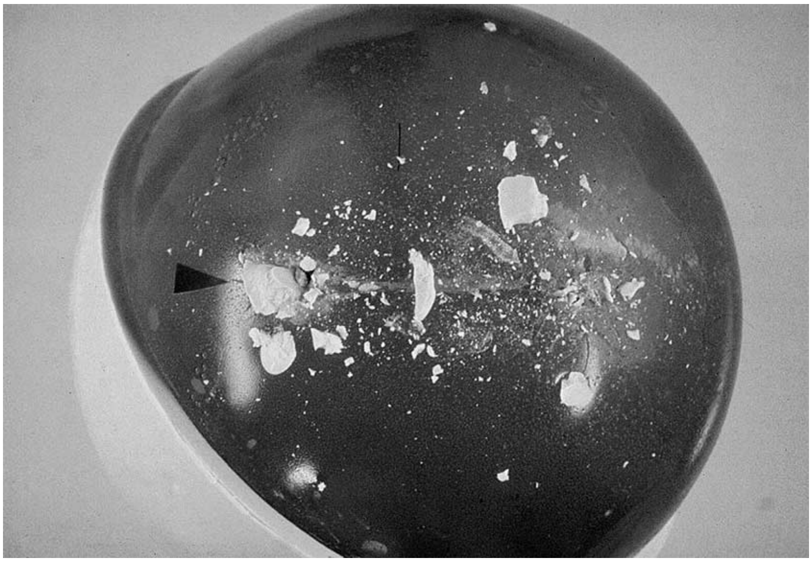

Fig. 21. Same gunshot injury as in Figs. 19 and 20: *bone* fragments deeply driven into the gelatin *brain*.

For comparative studies the use of models is quite satisfactory, and all the more so when the materials are homogeneous, as the effects we want to study can be observed more easily and more precisely.

One area of application for the ‘‘skin–skull–brain model’’ will be for the experimental recreation of real forensic cases in order to answer reconstructive questions about the step-by-step process of the criminal act.

This model is furthermore an instrument ideally designed and constructed (a) for the study of devastating head injuries, and (b) to assist in the development of surgical procedures and legislative processes.

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