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ORIGINAL ARTICLE

Secondary skull fractures in head wounds inflicted by captive bolt guns: autopsy findings and experimental simulation

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Abstract Apart from one article published by Rabl and Sigrist in 1992 (*Rechtsmedizin* 2:156–158), there are no further reports on secondary skull fractures in shots from captive bolt guns. Up to now, the pertinent literature places particular emphasis on the absence of indirect lesions away from the impact point, when dealing with the wounding capacity of slaughterer's guns. The recent observation of two suicidal head injuries accompanied by skull fractures far away from the bolt's path gave occasion to experimental studies using simulants (glycerin soap, balls from gelatin) and skull–brain models. As far as ballistic soap was concerned, the dimensions of the bolt's channel were assessed by multi-slice computed tomography before cutting the blocks open. The test shots to gelatin balls and to skull–brain models were documented by means of a high-speed motion camera. As expected, the typical temporary cavity effect of bullets fired from conventional guns could not be observed when captive bolt stunners were discharged. Nevertheless, the visualized transfer of kinetic energy justifies the assumption that the secondary fractures seen in thin parts of the skull were caused by a hydraulic burst effect.

Keywords Captive bolt stunning device · Slaughterer's gun · Secondary skull fractures · Ballistic simulants · Skull–brain model

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Introduction

In contrast to the German forensic literature, which is abundant in reports on fatalities caused by captive bolt guns [5, 7, 10, 15, 16, 18, 19, 22–26, 30, 31, 33, 34, 36, 47], only a few articles have been published on this topic in English-language journals or reference books [1, 2, 6, 9, 14, 20, 21, 28, 29, 38, 44–46]. This is probably attributable to the spreading of captive bolt livestock stunners mainly in central Europe where their purchase is quite liberal so that they are available to a wide range of users not only in abattoirs and butcher's shops but also in private farmer households [9]. The forensic relevance and topicality of injuries from such devices are apparent from the fact that in 2009 not less than four presentations have been dedicated to this subject at the 88th Annual Conference of the German Society of Legal Medicine [8, 11, 13, 35].

Most papers dealing with head wounds caused by "slaughterer's guns" focus on their epidemiologic, forensic, clinical, and imaging characteristics [4, 9, 14–16, 19–26, 29, 30, 36, 38, 40, 47]. As to the morphological signs, emphasis is placed on the typical skin wound (sharp-edged circular tissue defect often accompanied by two or four roundish soot depositions), on the entrance hole in underlying (flat) bone, and on the wound track which has a limited length of several centimetres containing the punched-out skin together with bone fragments, but no bullet. On the other hand, surprisingly, there was nearly no discussion of the intracranial pressure effects exerted by the entering bolt and affecting the encasing skull.

A review of the previous literature gives the impression that "no morphologic signs of indirect lesions away from the impact point, such as skull fractures, cortical contusions, or intracerebral haemorrhages" [38] have been observed up to now. Skull fractures found away from the wound channel in two recent fatalities from captive bolt humane killers induced us to reproduce the supposed indirect pressure effects in an experimental setup using simulants and a skull–brain model.

Case reports

Case 1

Suicide of a 55-year-old male butcher who had unsuccessfully attempted to kill his wife by manual strangulation and who afterwards went to his cellar where he shot himself in the head with a livestock stunner (Kerner type with two outlets for the explosion gases arranged symmetrically beside the central hole of the muzzle end; diameter of the bolt, 10 mm; Fig. 1a).

Body height 172 cm, body weight 105 kg. Contact entrance wound in the hairless parietal region: circular skin hole surrounded by a ring of powder soiling and accompanied by two roundish soot deposits corresponding to the openings of the smoke conduits (Fig. 1b). Sharp-edged circular bone defect on the outer table of the skull cap (diameter, 10 mm), bevelled out hole of the inner table (Fig. 1c).

Wide wound channel measuring 10 cm in length and filled with blood, running downwards from the top of the head along the medial aspects of the parietal lobes to the bottom of the brain's third ventricle with the punched-out skin (Fig. 1d) and a bone fragment left at the end of the track. Both orbital roofs were fractured although they were far away from the bolt's path and range (Fig. 2). The brain surface did not show any cerebral contusions.

Case 2

Suicide of a 47-year-old male butcher who had caused a traffic accident while under the influence of alcohol. One day later, he was found dead at home lying on a sofa in prone position with both hands over his head. The occipital region was penetrated by the bolt of a slaughterer's gun, which had got stuck within the cranium. The captive bolt stunner was a Schermer-type device (mod. Kaska; Fig. 3a) without additional smoke conduits so that the soot emerges only along the bolt's guide; diameter of the steel bolt, 13 mm.

Body height 168 cm, body weight 93 kg. Contact entrance wound in the occipital region thickly covered with hair: sharp-edged circular skin defect surrounded by an irregularly defined deposit of soot (Fig. 3b). In the

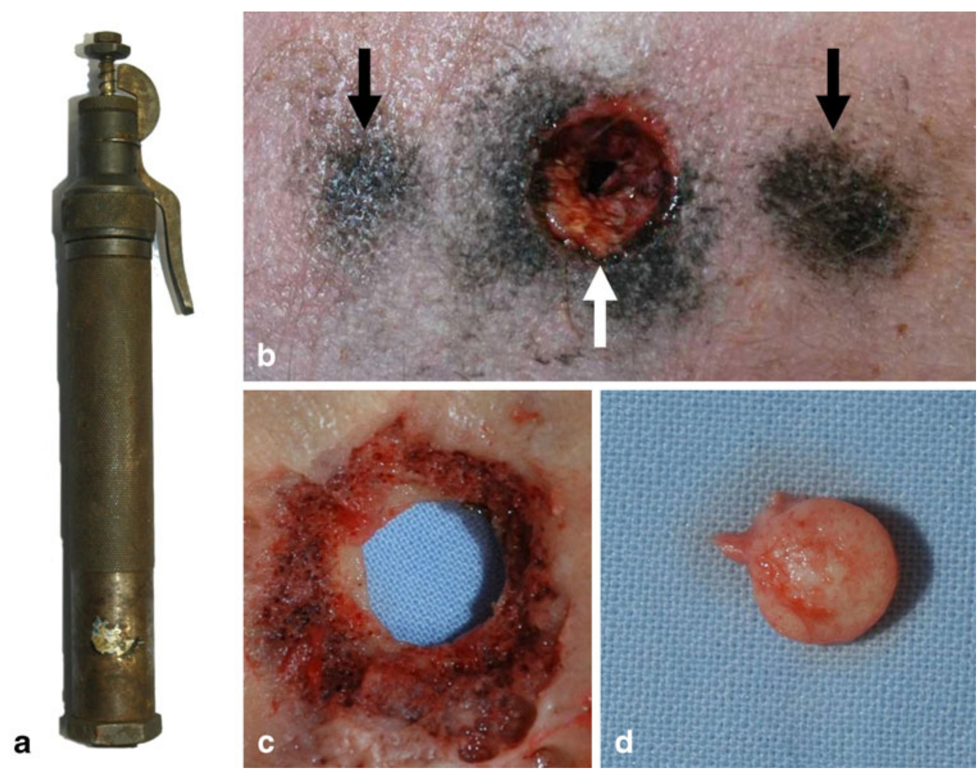

Fig. 1 Suicidal captive bolt injury to the parietal region (case 1) from a livestock stunner of the Kerner type (**a**). Entrance site showing a circular punch lesion (↑) accompanied by two roundish zones of powder soot blackening (↓↓) from the smoke conduits in the muzzle end (**b**). Inner aspect of the skull cap with cone-shaped widening of the hole in the direction of the shot (**c**). Punched out skin patch (**d**) from the depth of the wound channel

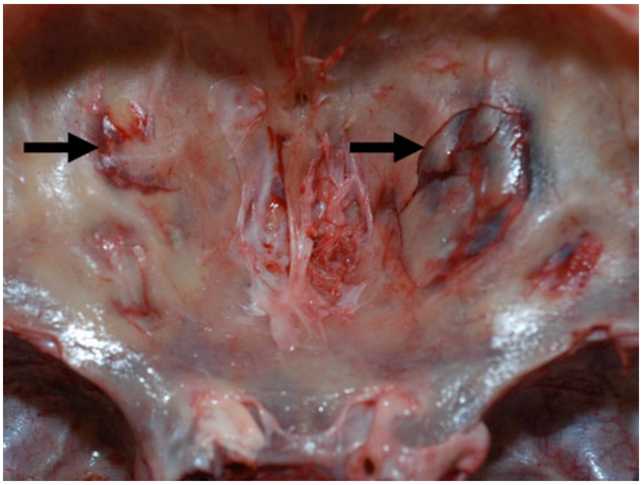

Fig. 2 Secondary fractures (→) of the orbital plates (case 1)

underlying cranial vault, the bone was punched out showing a clean-cut round hole on the outer table corresponding to the calibre of the bolt (13 mm) whereas the inner table was bevelled (Fig. 3c).

Hemorrhagic wound track in the sagittal plane with a total length of 8 cm along the medial aspects of the occipital lobes terminating in the brainstem (pons cerebelli) where a plug of bone with an adhering piece of hairy skin was lodged (Fig. 3d). The osseous clivus blumenbachii was unaffected. Far away from the bolt's path, there were two fracture lines in flat bones of the skull: one of them was running through the left temporal squama (Fig. 4) and the other through the middle cranial fossa of the right side. On the surface of the brain, no contusions could be detected at a distance from the wound channel.

Experiments

Materials and methods

Test shots were performed with a slaughterer's gun of the Schermer type (model "Kaska") discharging blank cartridges of cal. 10×11 mm (0.33 g nitro powder, with black colour marking on the case, meant for heavyweight cattle). The steel bolt has a diameter of 13 mm and a maximum length (outside the muzzle) of 78 mm. The distal end of the steel bolt is conically grooved forming a sharp-edged circular punching tool which is expelled with an initial velocity of about 45 m s^{-1}. There are no openings for the explosion gases in the muzzle plane.

At the time of discharge, the muzzle of the captive bolt gun was brought in contact with the surface of the simulants and the composite models, respectively, according to the procedure in pre-slaughter stunning. The experiments comprised the following series with three test shots each fired to:

– Blocks of *ballistic glycerin soap* measuring 38×25×25 cm (Permatin, Stein am Rhein, Switzerland)

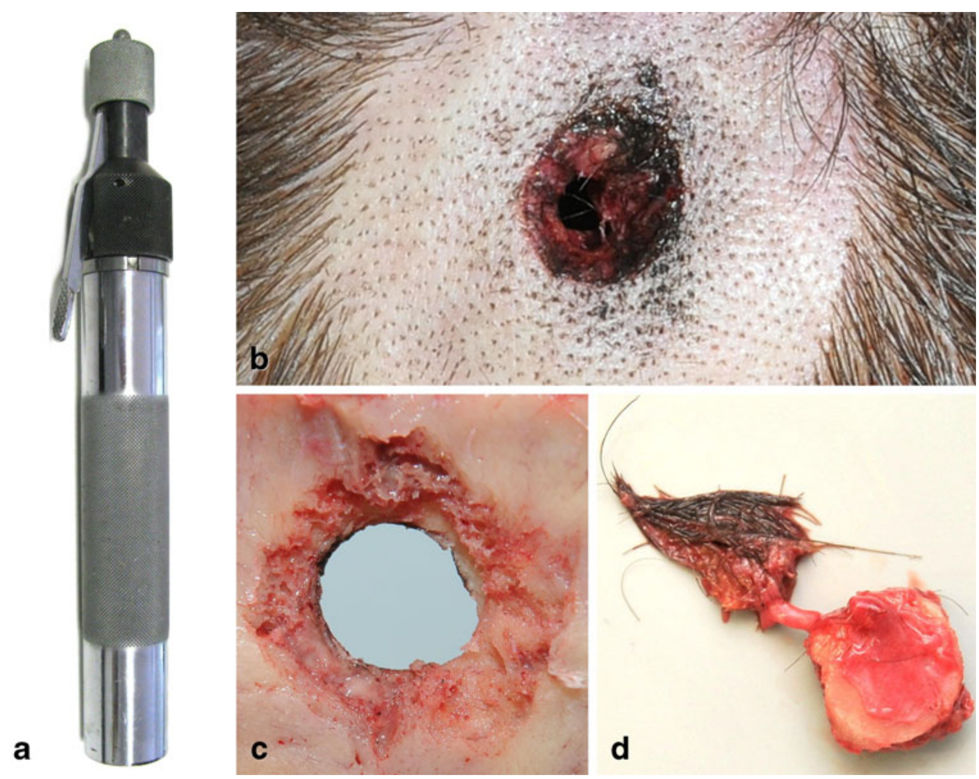

Fig. 3 Suicide with a stunning device of the Schermer type (**a**) fired into the occipital region (case 2). Entrance site (after pre-autopsy removal of the head hair) with a roundish skin hole surrounded by irregular soot deposits (**b**). Entrance defect in the skull (inner aspect, **c**). Punched-out patch of hairy skin connected with a round bone fragment (**d**) recovered from the end of the wound channel

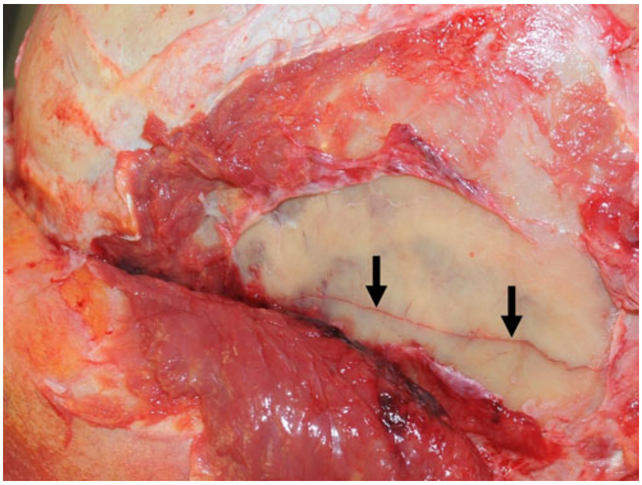

Fig. 4 Left temporal squama (after partial removal of the periosteum) with linear fracture (*arrows*, case 2)

– Spheres (diameter, 20 cm) consisting of *ballistic gelatin* in 10% concentration, made from gelatin powder (250 Bloom, type A, grain 20/60) from Naumann-Gelatine and Leim (Memmingen, Germany)
– *Skull–brain models* composed of a polyurethane sphere (artificial skull, o.d. 19 cm, 5-mm thick) and ordnance gelatin as brain surrogate [41–43]

To visualize the bolt's paths in the soap blocks and the extent of a possible temporary cavity, the soap blocks were examined by means of computed tomography (CT). The examinations were performed on a multislice CT scanner (Brilliance 16, Philips, Eindhoven, Netherlands) with the following parameters: 140 kV, 20 mAs, collimation 1 mm. Axial scans were reconstructed with 2- and 3-mm slice thickness. Multiplanar reformations in axial, sagittal and coronal orientation were reconstructed with 3-mm slice thickness. VRT were reconstructed using the in-built 3D-engine of Philips' software-suite.

The test shots of series 2 and 3 (to the gelatin spheres and the skull–brain models) were video-documented by means of a high-speed motion camera (Fastcam APX-R5, Photron, San Diego, CA, USA) with 15,000 fps from a 90° side view.

Results

The shots to the soap blocks left roughly cylindrical paths measuring about 7.8 cm in length corresponding to the maximum penetration length of the bolt. The initial parts of the channels were clearly wider than the distal parts. Consequently, longitudinal sections showed a progressive narrowing of the diameter which in the first section exceeded the bolt's calibre, whereas in the distal parts the cross-section was smaller than that of the bolt. As expected, the shape and dimensions of the cavities were identical when visualized either by CT imaging using axial slices or on direct examination after opening the blocks in a longitudinal plane (Fig. 5a, b). Not far away from the distal end of the bolt track, the channels were obstructed by a short plug of soap which was obviously sucked by the grooved tip of the bolt when drawn back into the barrel.

The shots to gelatin spheres resulted in a cylindrical destruction of the simulant with a diameter similar to the bolt. Due to the gelatin's elasticity, there was no permanent tubular cavity, but a channel filled with crushed material. When the spheres were laminated in thin layers, only some short slits ("cracks"), if any, were radiating from the bolt's path, especially in the layers close to the entrance site.

In the high-speed video documentation of the test shots to gelatin spheres, the rapid progress of the pressure wave originating from the entrance site of the bolt could be observed. It was perceptible in the form of a steep front on the sphere's surface extending centrifugally within several milliseconds (Fig. 6). In contrast to shots from real firearms, the penetrating bolt was not followed by a marked cavity or by pulsations of declining intensity.

The skull–brain models consisted of polyurethane spheres filled with ordnance gelatin. The spheres had been assembled by glueing together two halves. Therefore, along the circumferential connection line, an increased tendency

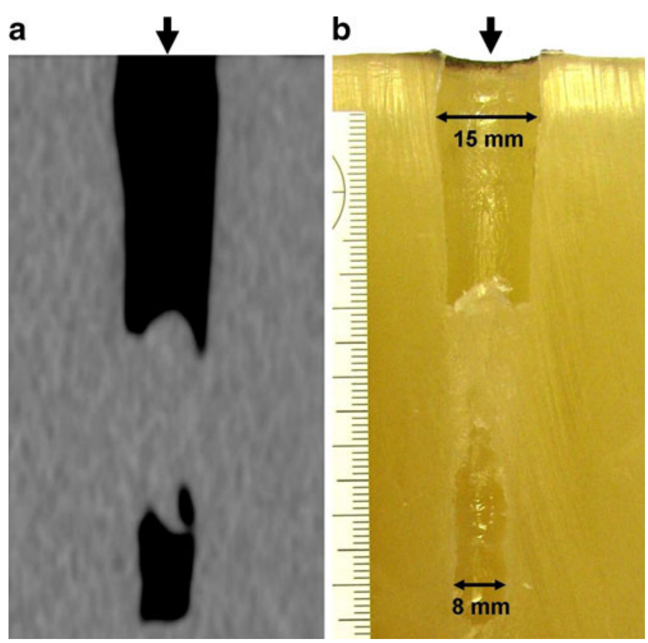

Fig. 5 Contact shot into ballistic soap. The entrance site is indicated by *arrows* (↓). The track of the bolt has been demonstrated by CT (**a**) and by cutting the block along the longitudinal axis of the channel (**b**). The soot deposition is confined to the margin of the entrance hole. In the initial section of the channel, the width of the cavity exceeds the diameter of the bolt

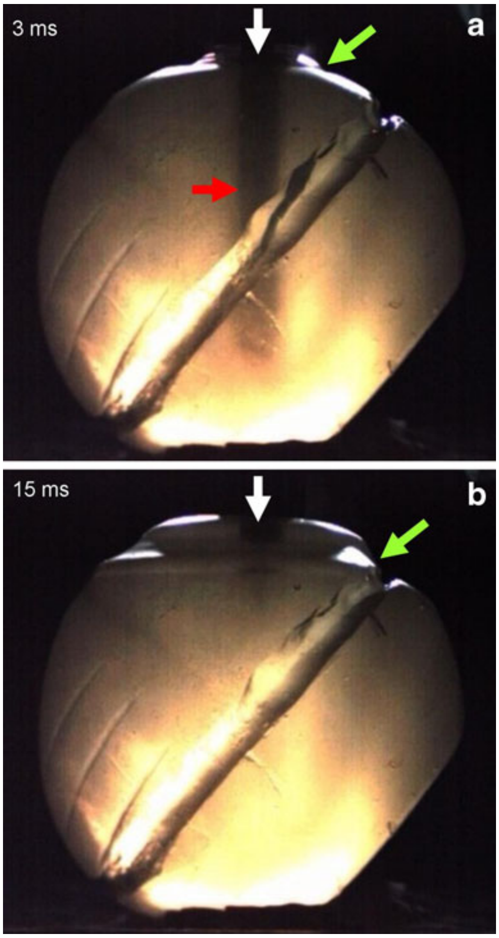

Fig. 6 High-speed motion camera documentation of a contact shot into a sphere made from gelatin. The entrance site is indicated by *white arrows* (↓). After 3 ms (**a**) the bolt can be seen through the translucent gelatin (*red arrow*); after 15 ms (**b**) it is already drawn back. A surface elevation with a steep front (*green arrows*) originating from the entrance hole propagates radially. The wide linear groove running diagonally around the sphere is due to the manufacturing method

of breaking apart was to be expected (similar to the sutures of the cranial vault). On the external surface of the artificial skulls, the entrance holes were circular in shape and had nearly the same diameter as the bolt, whereas the inner margins were bevelled. By means of the high-speed motion camera, it could be shown that the skull–brain model starts to disintegrate along the connection line of the two hemispheres already a few milliseconds after firing the bolt (Fig. 7), indicating a rapid increase of the intracranial pressure.

Discussion

In 1937, Czursiedel [5] was the first to publish a suicide committed with a slaughterer's gun of the Kerner type, which is still in use today [27]. Since then, fatalities caused by livestock stunners play an important role in forensic practice at least in the countries of continental Europe. Medicolegal literature mainly deals with the morphological features of injuries from slaughterer's guns, such as the punched-out wound in skin and bone, the different soot patterns depending on the type of device as well as in relation to the range and direction of fire, the manner of death (suicide/accident/homicide) in fatalities from humane killers, the common sites of entrance wounds, the possibly retained ability to act after a shot to the head, causes of death in cases with short or prolonged survival time and many others.

Captive bolt guns are usually counted among the "shooting devices", as a bolt is driven by the explosion gases of a (blank) cartridge. Nevertheless, in some respects, the wounding capacity differs from that of conventional bullets. The initial velocity of the bolt is rather low (~40–45 m s^{-1}) compared with projectiles fired from hand guns (~300–400 m s^{-1}). The distal end of the steel bolt is

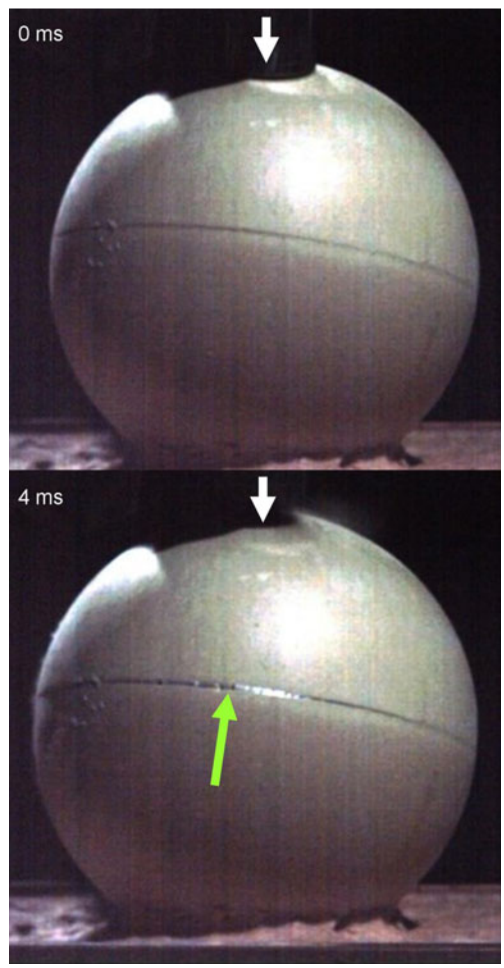

Fig. 7 High-speed motion camera documentation of a contact shot to a spherical skull–brain model. The entrance site is indicated by *white arrows*. Already after 4 ms, the two hemispheres dissociate from each other along the connecting line (*green arrow*)

grooved so that its front acts like a sharp-edged circular punching tool. The bolt is propelled only a few centimetres beyond the muzzle, and after firing it is drawn back into the barrel. Due to the limited length of the bolt, in shots to the head no exit wound is to be expected. At the end of the wound track, there is no bullet but punched-out pieces of skin and bone. It goes without saying that the steel bolt will not get deformed when passing through dense tissue and it has of course no tendency towards tumbling. Even in contact shots, no combustion gases are forced into the wound channel.

In captive bolt shots to the cerebral cranium, the following kinds of bone lesions may be found:

- An entrance hole at the site of penetration
- Punched-out bone fragments from the cranial vault at the end of the wound channel and along the bolt's path
- Bone fissures associated with the entrance hole (either radial or semicircular), mostly seen in angled shots [7, 9, 24, 38]
- Local bone destruction of the cranial basis if reached by the bolt (depending on its length, the entrance site and the direction of fire [45, 46])

In 1992, the possible occurrence of "secondary" skull fractures in shots from captive bolt guns was demonstrated by Rabl and Sigrist [31] for the first time. In the case presented by them, the left temporal bone and the lamina cribrosa were fractured far away from the bolt's path. Rabl and Sigrist assumed that the shock wave might have caused the fractures of the lamina cribrosa. The fracture line running through the left temporal bone was attributed to the hydraulic burst effect.

Apart from this single case report, to the best of our knowledge no further articles have been published concerning "indirect" skull fractures in captive bolt injuries. On the contrary, according to experienced authors, the absence of such indirect lesions is regarded as characteristic of the bolt's mere "punching" effect [38]. Therefore, it was surprising that two fatalities recently investigated by us were associated with secondary fractures caused by conventional slaughterer's guns.

In gunshots to the head, the common sites for secondary fractures are the orbital plates and other thin parts of the skull which are sensitive to a sudden increase of intracranial pressure [6]. Such indirect lesions can be seen both in contact and distant gunshot injuries. In the latter cases, the fractures are due to the temporary cavity and the concomitant rise in pressure resulting in a hydraulic burst effect exerted on the encasing skull [37]. In the fatalities reported by us, the fracture sites (orbital roofs, middle cranial fossa and temporal bone) belonged to the well-known spots of lessened resistance typically affected in gunshots to the head.

To elucidate the mechanism causing secondary skull fractures in captive bolt injuries, test shots were fired at two different simulants (glycerin soap, gelatin) and at skull–brain models. By means of simulants, the transfer of kinetic energy in biological soft tissue can be visualized. In contrast to elastic gelatin, ballistic soap shows an almost plastic deformation. The shot channel and the volume of the cavity are proportionate to the energy transferred [37]. Another useful instrument for the study of ballistic effects has been designed and tested by Thali et al. [41–43]: the (skin–)skull–brain model consisting of a polyurethane sphere (as artificial skull) and ordnance gelatin inside (as substitute for the brain). It turned out that the findings assessed after shots to the model were fully comparable to the morphology of equivalent injuries in real victims.

Recently, computed tomography has been introduced into ballistic research as a non-invasive tool for visualization and numerical analysis of the permanent and temporary cavity in glycerin soap [12, 17, 32]. Sectional measurements can be performed without manipulating the soap block and allow exact conclusions as to the energy released along the bullet's and bolt's path, respectively. In clinical neuroradiology, CT scans of head injuries from captive bolt guns have been an essential part of routine diagnostic measures for a long time already. The hyperdense wound channel within the brain is typically wider near the entry site and contains bone fragments [9]. Multi-slice computed tomography has also been applied to pre-autopsy imaging both in gunshot and captive bolt injuries [3, 4, 39, 45].

Our test shots into ballistic soap produced channels with a length corresponding to that part of the bolt which leaves the barrel. The width of the initial section clearly exceeded the diameter of the bolt without having the dimensions or the spindle-like shape of a temporary cavity typical of gunshots. The conical shape resembled the cavity produced by a spherical bullet or a splinter [37]. As expected, CT imaging and direct measurement after cutting open the soap blocks provided identical results as to the channel's dimensions. The marked narrowing of the channel far off the entrance site can be explained by the suction effect of the bolt's end when drawn back into the barrel.

The test shots into spheres made of ballistic gelatin were documented by means of a high-speed motion camera. The picture sequence did not show the formation of a temporary cavity of significant extent (cf. Fig. 6). In agreement with Schyma et al. [35], there was no indication that combustion gases were propelled into the depth of the bolt's track. When laminating the gelatin at right angles to the longitudinal axis of the bolt's path, only short radial cracks (measuring several millimetres in length) could be found in the initial section. Therefore, a slight radial displacement of the simulant could be demonstrated, but its scale was not comparable with the cavity seen in shots from conventional handguns and rifles. High-speed photography of the spheres revealed the early appearance of a marked surface elevation originating from the entry site and proceeding in the direction of the shot (cf. Fig. 6). The steepness of the front running through the gelatin medium resembles the propagation of a pressure wave caused by the sudden displacement of tissue along the shot channel.

Within the human head, the pressure gradient is reduced with increasing distance from the point of origin as the wave is reflected and strayed at the interfaces of the inhomogenous anatomic structures with the consequence of a longer lasting wave mix. According to experimental studies, the traumatological effects of shock waves in wound ballistics seem to be confined to reversible functional changes (e. g. mechanical stimulation of nerves) and to subcellular damage whereas macroscopic lesions could not be observed up to now [37].

On the other hand, the kinetic energy released by the bolt has been demonstrated to bring about a (at least moderate) radial acceleration of the target medium. This could be recognized by our test shots into simulants. The soap blocks showed a widening of the bolt path after the entrance. In gelatin, short cracks were radiating from the first section of the bolt channel. If the expansion of the temporary cavity is limited by a firm encasement (as in shots to the head), the intracranial pressure will build up considerably and potentially exert a hydraulic burst effect on the covering skull. This well-known phenomenon adequately explains the occurrence of secondary fractures away from the bolt's path and preferably located in thin bones such as the orbital roofs. Referring to our skull–brain model, the connection line between the two hemispheres represented a pre-existing weakness with an increased tendency to break.

Conclusions

- Head injuries from captive bolt stunners may be associated with secondary fractures of the skull away from the path of the bolt.
- These fractures are typically located in especially thin and therefore vulnerable parts of the skull such as the orbital plates, the temporal bones, the lamina cribrosa and the middle cranial fossae.
- The occurrence of indirect bone lesions can be explained by the shot-induced displacement of the brain associated with a polydirectional pressure exerted on the skull.

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