Int J Legal Med (2012) 126:13–18
DOI 10.1007/s00414-011-0552-y

ORIGINAL ARTICLE

When backyard fun turns to trauma: risk assessment of blunt ballistic impact trauma due to potato cannons

Matthias Frank · Oliver Jobski · Britta Bockholdt · Rico Grossjohann · Dirk Stengel · Axel Ekkernkamp · Peter Hinz

Received: 16 November 2010 / Accepted: 10 January 2011 / Published online: 29 January 2011

Abstract Although potato cannons are an area of great interest among internet users, they are almost completely unknown in the medical community. These simple ballistic devices are made from plastic plumbing pipes and are powered with propellant gas from aerosol cans. By combustion of the gas–oxygen mixture, a high pressure is produced which propels the potato chunks through the barrel. It is the aim of this study to investigate the hazardous potential of these shooting devices. Test shots were performed using three illegally manufactured potato cannons that were confiscated by police authorities. Velocity, impulse, kinetic energy, and energy density were calculated. The risk of head and chest injuries was investigated by using Sturdivan's Blunt Criterion (BC), an energy based five parametric trauma model assessing the vulnerability to blunt weapons, projectile impacts, and behind-body-armor exposures. The probability of lethality due to blunt impact trauma to the chest was assessed using Sturdivan's lethality model. For potential head impacts, all test shots far exceeded the critical BC (head) value which corresponds to a 50% risk of skull fracture. The risk of injury with regard to chest impacts was similar. All but two test shots far exceeded the critical BC (chest) value corresponding to a 50% risk of sustaining a thoracic skeletal injury of Abbreviated Injury Scale 2 or 3. The probability of a lethal injury due to blunt chest impact was as high as 20%. To conclude, this work demonstrates that potato cannons should be considered dangerous weapons rather than as toys used by adventurous adolescents.

Keywords Trauma biomechanics · Blunt impact trauma · Trauma model · Blunt criterion · Spud gun

Ethical standards Ethical approval was not required for this experimental investigation.

M. Frank (✉) · R. Grossjohann · D. Stengel · A. Ekkernkamp
Department of Trauma and Orthopedic Surgery,
Ernst-Moritz-Arndt-University Greifswald,
Sauerbruchstrasse,
17475 Greifswald, Germany
e-mail: matthias.frank@uni-greifswald.de

M. Frank · D. Stengel · A. Ekkernkamp · P. Hinz
Department of Trauma and Orthopedic Surgery,
Unfallkrankenhaus Berlin,
Berlin, Germany

O. Jobski
Landeskriminalamt (LKA) Mecklenburg-Vorpommern,
Rampe, Germany

B. Bockholdt
Department of Legal Medicine,
Ernst-Moritz-Arndt-University Greifswald,
Greifswald, Germany

Introduction

The potato cannon (or spud gun) is one of the most popular self-made ballistic devices. A Google search for the phrases "potato cannon" or "spud gun," for example, reveals more than 353,000 and 418,000 hits respectively, including construction manuals and numerous video-files documenting their use. All over the world, mostly adolescent boys enjoy building and firing these combustion-powered guns launching chunks of potatoes into the environment. Their main appeal is their simple construction requiring only little craftsmanship. Their components, too, are easy to come by at the local hardware store [1].

A typical potato gun is constructed from standard polypropylene plumbing pipes (Fig. 1). The body of the device contains three basic elements: a barrel, a combustion chamber, and an ignition source. The potato is rammed into the barrel from the muzzle end. The sharp edge of the muzzle cuts the potato into a plug of the correct size to fit the bore size. A

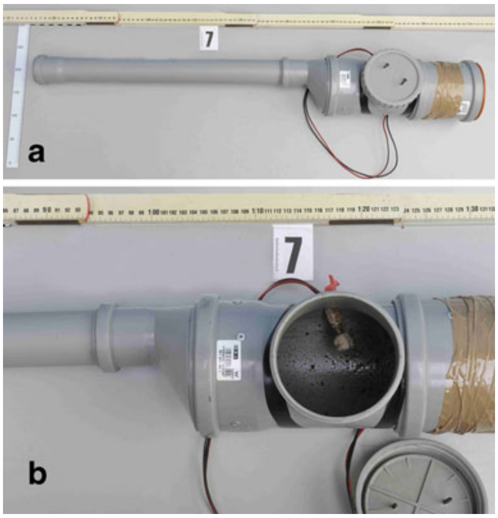

Fig. 1 Typical design of the potato cannon. A reducing bushing joins the combustion chamber (*right*) to the smaller-sized pipe of the barrel (*left*) (**a**). After the potato is rammed down the barrel from the muzzle end, the propellant is injected via the screw cap and the gas–oxygen mixture is ignited by the sparker (**b**)

ramrod is used to stuff the projectile down the barrel. Then, a stream of, for example, hairspray from an aerosol can is sprayed into the combustion chamber. After the chamber has been closed, the gas mixture is ignited by the sparker. The projectile is then propelled through the barrel by the high pressure created through combustion. The legal classification of potato guns as firearms varies among different countries and jurisdictions. In the US, legal assessment of spud guns varies greatly by state and county. On written request, the Bureau of Alcohol, Tobacco, Firearms, and Explosives of the US Department of Justice offers a classification of spud guns [2]. In many other countries (like Germany, for example), combustion-powered spud guns are generally considered firearms and their construction as well as their use is a criminal offense.

Although knowledge about these gadgets is very common and they are a topic of considerable interest among internet users, medical literature on these devices and their effects is very scarce. Except for two case reports on four facial injuries, the current medical literature contains no information (Table 1) [3, 4]. There are no studies investigating their hazardous potential. Therefore, it is the aim of this work to provide experimental data on the dangers of these popular shooting devices and make them more widely known in the medical community.

Methods

Test setup

Three illegally manufactured potato guns confiscated by police authorities were used during the tests. For technical specifications of the different devices, see Table 2. A commercially available hairspray can containing a propane/butane mixture was used as propellant gas. The gas was injected in one to two short bursts (each less than 1 s by instinct). Fresh potatoes and apples were used as projectiles. The cannons were loaded in the press-fit technique as described above.

For each projectile, mass (m) was measured. Velocity (v) of the projectiles was measured between 1.0 and 2.0 m from the muzzle using a photoelectric infrared light barrier [5]. Three measurements were taken in each subtest. Measurements were taken in a completely enclosed indoor shooting test stand to avoid any weather influences.

Kinetic energy (E) of each projectile was calculated as half the product of its mass (m) multiplied by square of its

Table 1 Literature review on documented injuries due to potato cannons

Age (years), sex	Projectile	Clinical findings	CT findings	Year
14, male	Potato	Multiple lacerations and ecchymosis of the lids; fragmentation of the right globe with no light perception	Displaced blowout fracture of the right orbital floor and medial wall; fractures of both cribriform plates; multiple nasal fractures; anterior basilar skull fracture; multiple orbital, ethmoidal, and maxillary sinus foreign bodies	1998 [3]
14, male	Potato	Left lid and facial edema, laceration of left cornea	None	1998 [3]
16, male	Frog	Right periorbital edema; foreign bodies (pieces of frog tissue) in the right eye globe and in the conjunctival space	Fractures of anterolateral sphenoid sinus wall, medial maxillary sinus wall, orbital floor with displacement of fragments into the maxillary sinus, and nasal septum	2007 [4]
16, male	Potato	Edema of the face; stellate laceration of the upper lip (4×2 cm); missing superior canine tooth	Le Fort I fracture of right maxilla; multiple complex fractures of right maxillary sinus; fracture of left frontal sinus; fracture of lateral wall of the left orbit	2007 [4]

Table 2 Technical specifications of the illegally home-built potato cannons

Device	Barrel calibre (mm)	Barrel length (mm)	Combustion chamber diameter (mm)	Combustion chamber length (mm)	Combustion chamber volume (cm^3)
A	46	680	110	350	3,300
B	46	560	110	300	2,800
C	46	700	110	330	3,100

velocity (v). Impulse (p) of the projectile was calculated by the product of its mass multiplied by its velocity. The energy density (ED) was calculated using energy and surface of the projectile's head. Assuming that the threshold energy density (ED_{tsh}) required for skin penetration is 0.1 J/mm^2, the threshold velocity (v_{tsh}) which causes penetrating wounds as a function of cross-sectional density (S) was calculated according to Sellier and Kneubuehl by the following formula [6]:

$$v_{tsh} = \sqrt{\frac{2,000 \times ED_{tsh}}{S}} \quad (1)$$

The cross-sectional density (S) was calculated by the formula $S=m/A$ (m projectile's mass, A projectile's face area) [6].

Blunt Criterion for injury risk assessment of head and chest impacts

The Blunt Criterion (BC) is a five parametric trauma model which is used to assess vulnerability to blunt weapons, projectile impacts, and behind-body-armor exposures. It was originally developed by Sturdivan at the Army's Biophysics Lab at Aberdeen Proving Ground, Maryland [7].

The Blunt Criterion is determined by the formula:

$$BC = \ln\left(\frac{\frac{1}{2} \times M \times v^2}{W^{1/3} \times T \times D}\right) \quad (2)$$

where M is the mass of the projectile in kilograms, v the velocity of the projectile in meters per second, W the mass of the struck individual in kilograms, T the combined thickness of the body wall at the impact location of the struck individual in centimeters, and D is the diameter of the projectile in centimeters [7].

The application of the Blunt Criterion for assessing potential blunt ballistic impacts to the head and chest as well as the derivation of the biological values characterizing the properties (weight of body part, thickness of body wall) of the body parts struck by the impactor have previously been described in detail [8]. For calculating the Blunt Criterion for head impacts, W_{head}=4.9 kg [9] and T_{head}=1 cm [10–12] were used. For calculating the Blunt Criterion for chest impacts, W_{body}=77.0 kg [13] and T_{chest}=3 cm [14] were used.

In order to include the diameter of the impactor in relation to the thickness of the body wall struck by the impactor into the Blunt Criterion equation, Sturdivan et al. introduced a correction for the effective diameter (D) of the projectile when D' is greater than twice the thickness of the body wall ($2\times T$) [7]. Geometry gives the area of contact, A:

$$A = \pi \times T \times (D' - T);\ D' \ 2 \times T \quad (3)$$

The effective diameter (D) to be used in Eq. 2 is:

$$D = 2 \times \sqrt{\frac{A}{\pi}} \quad (4)$$

This correction (Eq. 4) is used only when D' is greater than $2\times T$. Otherwise, the actual diameter ($D'=D$) is used. Therefore, the effective diameter was only used when calculating the Blunt Criterion for head impacts. For chest impacts, the actual diameter of the projectiles was used.

Probability of lethality due to blunt ballistic impact trauma to the chest

The probability of lethal blunt trauma due to non-penetrating impact of the projectiles launched by the potato cannons was assessed according to the model created by Sturdivan. In the late 1970s, Sturdivan developed a multi-parametric lethality model to estimate the probability of a non-penetrating projectile causing lethal blunt trauma to the thorax [15]. The Sturdivan model was based upon a compilation of empirical databases derived from live-animal tests. Kneubuehl transferred the Sturdivan model into basic metric units (meter, kilogram, second) and introduced the following equation [16]:

$$P(L) = \frac{1}{1 + \exp\left[39.9192 - 3.597 \times \ln\left(\frac{E}{W^{1/3} \times D \times T}\right)\right]} \quad (5)$$

where E denotes the kinetic energy of the projectile, W the victim's body mass, T the thickness of the victim's body wall at the impact location, and D the diameter of the impactor (all values in basic units meter, kilogram, second). This multiparameter lethality model was used to assess the probability of lethal blunt trauma to the thorax of a 50th percentile male struck by a non-penetrating projectile launched by a potato cannon.

Results

The average velocity of the potatoes/apples was measured as being v=59.34 m/s (range 39.18–82.60 m/s) exerting an average impulse of p=4.77 Ns (range 2.71–6.72 Ns). The average kinetic energy of the projectiles was calculated as being 148.8 J (range 53.4–263.7 J).

For the head impact, average Blunt Criterion value was calculated to be BC_{head}=3.014 (range 2.114–3.710) while an average Blunt Criterion for the chest impact was calculated to be BC_{chest}=0.806 (range −0.094–1.502).

Probability of lethality ($P(L)$) due to blunt ballistic impact trauma to the chest ranged from 0.1% to 20%.

Development of the Blunt Criterion for head and chest impacts and energy density as a function of the projectiles' energy is diagrammed in Fig. 2. For detailed experimental data, see Table 3.

Discussion

While the combustion of an explosive propellant gas is the most common power source for potato cannons, they can also be actuated by compressed gas (pneumatic cannons) or by a sudden vacuum breaking (dry ice bomb cannon) [17–19]. In combustion-powered potato guns, an exothermic chemical reaction of a gaseous hydrocarbon fuel (propane or butane) with an oxidizer (atmospheric oxygen) creates a pressure gradient which propels the projectile down the barrel. Propane and butane are widely available aerosol propellants in hairspray or deodorant cans. For butane and propane, the explosive limit of the gas–oxygen mixture ranges from approximately 2% (lower explosive limit) to 10% (upper explosive limit, UEL) [20, 21]. Below the explosive limit, the mixture is too lean to burn and above the UEL, it is too rich to burn. During explosive combustion of the potato cannon, approximately 0.5–1.5% of the calculated chemical energy potential is actually transferred into kinetic energy of the projectile [22].

The ballistic parameters of the potato cannons show a very broad spectrum. A consistent firing capacity is impossible, because many different factors affect the combustion and launching process, e.g., the design of the device, shape and weight of the projectile, the position of the projectile in the barrel, the tightness of the projectile in the barrel, the concentration of the gas–oxygen mixture, and the time passing from injecting to igniting the gaseous fuel. The significance of the results is limited, however, due to the small number of three test shots per cannon during the test. But, even three shots allow an adequate assessment of the minimum and maximum risk values involved and provide insight into the injury patterns that might be expected.

Predicting the potential risks of injury of non-penetrating projectiles on the basis of ballistic experiments is difficult. Threshold values determined by the US Army Land Warfare Laboratory, which considers impact energies between 40 and 120 J to cause "dangerous" injuries (like

Fig. 2 Blunt Criterion for head and chest impact and energy density as a function of the kinetic energy of the cal. 46-mm potato/apple

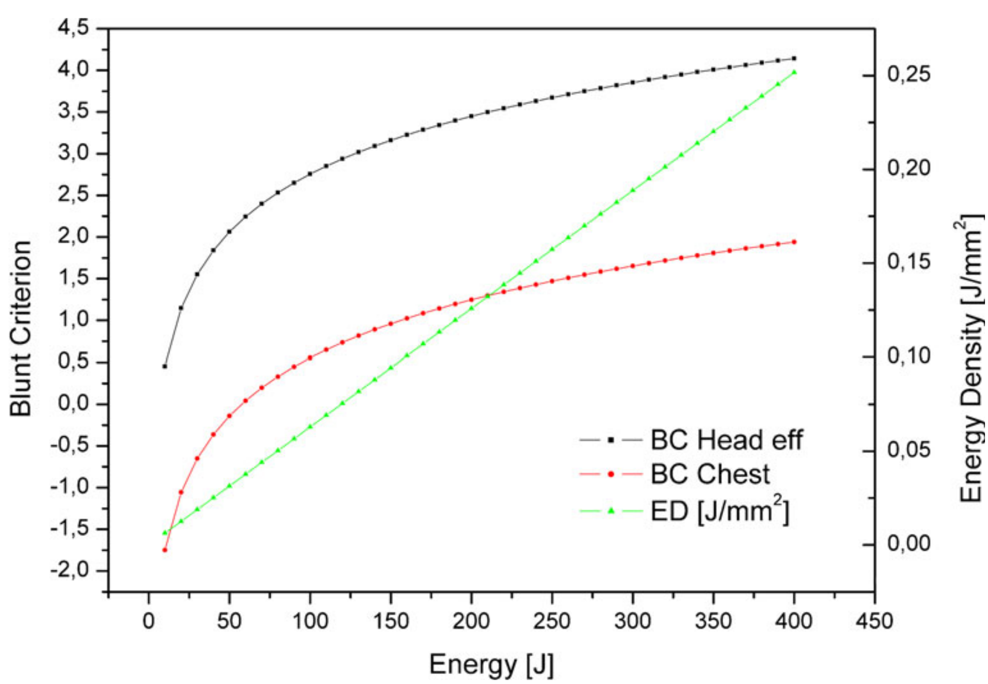

Table 3 Ballistic parameters of the discharged calibre 46-mm projectiles

Shot	Projectile	Mass, m (g)	Sectional density, S (g/mm^2)	Threshold velocity, v_{tsh} (m/s)[a]	Velocity, v (m/s)	Impulse, p (N s)	Energy, E (J)	ED (J/mm^2)	BC head[b]	BC chest	Lethality, $P(L)$[c]
A.1	Potato	95.5	0.0574	59.0	65.9	6.290	207.3	0.125	3.469	1.261	0.095
A.2	Potato	117.9	0.0709	53.2	45.5	5.370	122.3	0.074	2.941	0.733	0.015
A.3	Potato	87.2	0.0525	61.7	39.2	3.416	66.9	0.040	2.339	0.131	0.002
B.1	Potato	78.0	0.0469	65.3	63.0	4.915	155.1	0.093	3.179	0.972	0.036
B.2	Potato	77.0	0.0463	65.7	53.0	4.081	110.1	0.066	2.837	0.629	0.011
B.3	Potato	68.6	0.0413	69.6	39.5	2.709	53.4	0.032	2.114	−0.094	0.001
C.1	Apple	85.6	0.0515	62.3	78.5	6.720	263.7	0.159	3.710	1.502	0.200
C.2	Apple	70.5	0.0424	68.7	82.6	5.823	240.5	0.145	3.618	1.410	0.152
C.3	Apple	53.5	0.0322	78.8	66.8	3.574	119.4	0.072	2.917	0.710	0.014

ED energy density

[a] Calculated threshold velocity for skin-penetrating injury

[b] As $D > 2 \times T$, the effective diameter of the projectiles was adjusted according to Eqs. 3 and 4

[c] Lethality probability for chest impacts

abrasions, cracked ribs, cerebral concussion) and impact energies exceeding 120 J to cause "severe damage" (like massive skull fractures, rupture of the heart and kidney, fragmentation of the liver, hemorrhages), may serve as orientation values [16].

Among a number of other criteria formulated to predict impact injury, the applicability of the Blunt Criterion for a very broad range of blunt impacts has repeatedly been demonstrated [7]. With regard to the injury risk of head impacts, every test shot far exceeded the critical value of $BC_{head}=1.61$ which corresponds to a 50% risk of skull fracture after blunt ballistic impact to the head [23]. Every single test shot surpassed even the BC_{head} value which corresponds to a 90% risk of skull fracture on the logistic regression curve proposed by Raymond et al. [23].

With regard to the injury risk of chest impacts, all test shots except two also far exceeded the critical threshold value of $BC_{chest}=0.37$ which corresponds to a 50% risk of sustaining a thoracic skeletal injury of Abbreviated Injury Scale (AIS) 2 or 3 (moderate to serious injury like rib fractures with flail chest, fracture of the sternum) [13, 14]. The highest BC_{chest} value was found to be 1.502 which corresponds to a thoracic injury of AIS 5 (critical injuries like major lung lacerations, hemopericardium, aortic rupture, major tracheal laceration) [7].

Previous investigations on blunt ballistic impact have shown that the presence or absence of skin penetration is not a significant predictor for underlying bone fracture [24]. Regarding only the energy density of the potatoes would mean underestimating the danger of these devices. For example, the threshold energy density for perforating injuries ($ED_{tsh}=0.1$ J/mm^2) corresponds to the potato's energy of 166.2 J. On the other hand, the energy threshold of 166.2 J corresponds to a BC_{head} of 3.264 and to a BC_{chest} of 1.582 (Fig. 2). These Blunt Criterion values correspond to a risk of skull fracture of more than 90% and to a thoracic injury of AIS 5 (critical injuries), respectively [7, 23].

A comparison of the muzzle energy between these potato cannons (53.4–263.7 J, Table 3) and well-known air guns, which develop approximately 7.5 J, might also emphasize their hazardous potential [16].

In the Blunt Criterion trauma model, the numerator represents the energy deforming the body and excludes the energy remaining in the impactor and transferred to the body as whole body motion [7, 13]. However, the kinetic energy of the potatoes or apples launched by these guns is not entirely available to do damage at their impact location as the energy is partly spent on deformation of the potato at the time of impact.

In general, using more parameters provides more information and may improve predictive ability of the multiparametric trauma models in comparison to kinetic energy as single parameter, but it may also mean an increased error-proneness. While the ballistic parameters (diameter, mass, and velocity of the projectile) of the Blunt Criterion trauma model can be measured easily, the thickness of the body wall cannot, plus the fact that it is subject to both intraindividual and interindividual variation.

Potato cannons are also a popular construction project for physics demonstrations and science fairs [17]. Courtney and Courtney determined the muzzle velocity of a spud gun by using an acoustic measurement. By analyzing the sound waveform of the time delay between the ignition of the propellant gas and the target strike, they determined that the muzzle velocity is 57.8 m/s [25]. Applying the basic laws of thermodynamics and mechanics, Mungan numerically analyzed the limiting muzzle velocity of a compressed air-powered potato cannon to launch a 100-g potato to be approximately 78 m/s [17].

Conclusion

The results show that potato cannons should be considered as dangerous weapons rather than as toys for adolescent boys. Life-threatening and potentially lethal injuries must be expected when an individual is struck by their projectiles. Trauma and forensic experts as well as legal authorities should be alerted to their hazardous potential and the inherent lethal dangers of these home-built shooting devices.

Conflict of interest The authors declare that they have no conflict of interest.

References

1. Gurstelle W (2001) Backyard ballistics. Chicago Review Press, Chicago
2. Bureau of Alcohol, Tobacco, Firearms, and Explosives (ATF). US Department of Justice Web site. http://www.atf.gov/firearms/faq/unlicensed-persons.html#potato-gun-classification. Accessed 13 November 2010
3. Barker-Griffith AE, Streeten BW, Abraham JL, Schaefer DP, Norton SW (1998) Potato gun ocular injury. Ophthalmology 105:535–538
4. Skavysh A, Wojcik R, Murphy RX, Kazahaya M, Pasquale MD, Barraco RD (2007) Facial injuries by potato gun: spuds as scuds. Inj Extra 38:81–83
5. Franke E (1981) Ermittlung der Bewegungsenergie der Geschosse. In: Zobel KF (ed) PTB-Bericht W-19 Gesetzliche Munitionsprüfung. Physikalisch-Technische Bundesanstalt, Braunschweig und Berlin, pp 27–31
6. Sellier K, Kneubuehl BP (1994) Wound ballistics and the scientific background. Elsevier Science B.V, Amsterdam
7. Sturdivan LM, Viano DC, Champion HR (2004) Analysis of injury criteria to assess chest and abdominal injury risks in blunt ballistic impacts. J Trauma 56:651–663
8. Frank M, Bockholdt B, Peters D, Lange J, Grossjohann R, Ekkernkamp A, Hinz P (2010) Blunt Criterion trauma model for head and chest injury risk assessment of cal. 380 R and cal. 22 long blank cartridge actuated gundog retrieval devices. Forensic Sci Int. doi:10.1016/j.forsciint.2010.10.023
9. Pignolet F, Guillion F, Duval-Beaupere G, Guezard B, Tarriere C (1990) In vivo measurement of human weight supported by the successive anatomical level from C4 to the femoral head, SAE (Society of Automotive Engineers) Technical Paper 902306 13-21
10. Lynnerup N (2001) Cranial thickness in relation to age, sex and general body build in a Danish forensic sample. Forensic Sci Int 117:45–51
11. Hatipoglu HG, Ozcan HN, Hatipoglu US, Yuksel E (2008) Age, sex and body mass index in relation to calvarial diploe thickness and craniometric data on MRI. Forensic Sci Int 182:46–51
12. Tilotta F, Richard F, Glaunes J, Berar M, Gey S, Verdeille S, Rozenholc Y, Gaudy JF (2009) Construction and analysis of a head CT-scan database for craniofacial reconstruction. Forensic Sci Int 191:e111–e112
13. Bir C, Viano DC (2004) Design and injury assessment criteria for blunt ballistic impacts. J Trauma 57:1218–1224
14. Bir C, Viano D, King A (2004) Development of biomechanical response corridors of the thorax to blunt ballistic impacts. J Biomech 37:73–79
15. Hoxha S, Elliott JE (1985) Simulation of area weapons effects (SAWE) safety criteria. US Army Armament Research and Development Center, Dover
16. Kneubuehl BP, Coupland RM, Rothschild MA, Thali MJ (2008) Wundballistik. Grundlagen und Anwendungen. Springer, Heidelberg
17. Mungan CE (2009) Internal ballistics of a pneumatic potato cannon. Eur J Phys 30:453–457
18. Ayars E, Buchholtz L (2004) Analysis of the vacuum cannon. Am J Phys 72:961–963
19. Gorrin NR, Moore TC, Asch MJ (1990) Glass shrapnel injuries to children resulting from “dry ice bomb” explosions: a report of three cases. J Pediatr Surg 25:296
20. European chemical Substances Information System (2000) IUCLID Chemical Data Sheet Butane. http://ecb.jrc.ec.europa.eu/esis/index.php?LANG=de&GENRE=CASNO&ENTREE=106-97-8. Accessed 13 November 2010.
21. European chemical Substances Information System (2000) IUCLID Chemical Data Sheet Propane. http://ecb.jrc.ec.europa.eu/esis/index.php?LANG=de&GENRE=CASNO&ENTREE=74-98-6. Accessed 13 November 2000.
22. Pierson HM, Price D (2005) The potato cannon. Determination of combustion principles for engineering freshmen. Chem Eng Ed 39:156–159
23. Raymond D, Van Ee C, Crawford G, Bir C (2009) Tolerance of the skull to blunt ballistic temporo-parietal impact. J Biomech 42:2479–2485
24. de Freminville H, Prat N, Rongieras F, Voiglio EJ (2010) Less-lethal hybrid ammunition wounds: a forensic assessment introducing bullet-skin-bone entity. J Forensic Sci. doi:10.1111/j.1556-4029.2010.01431.x
25. Courtney M, Courtney A (2007) Acoustic measurement of potato cannon velocity. Phys Teach 45:496–497