Does a Sixth Mechanism Exist to Explain Lightning Injuries? Investigating a Possible New Injury Mechanism to Determine the Cause of Injuries Related to Close Lightning Flashes

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Abstract:
Five mechanisms have been described in the literature regarding lightning injury mechanisms. A sixth mechanism is proposed in this article, namely, lightning barotrauma. A simple laboratory experiment was conducted using ordnance gelatin for ballistic studies. Lightning was simulated in a high-voltage laboratory using an 8/20-microsecond current impulse generator and discharged through ballistic gel. Temporary and permanent cavity formations were confirmed. The cavities formed were directly proportional to the currents used. Findings suggest that a sixth mechanism of lightning injury, namely, barotrauma, should be considered.

Key Words: lightning, barotrauma, ordnance gelatin, human tissue simulants, ballistic studies, wound profile, wounding mechanism, keraunopathology, keraunomedicine, current impulse generator, high voltage, temporary cavity formation, permanent cavity formation, explosive effects, explosion, shock wave

Introduction:

Five mechanisms have been described in the literature regarding lightning injury mechanisms. These mechanisms are primarily, first, a direct lightning strike and second, an indirect strike by contact with an object such as a pole or tree directly struck. A third mechanism is a side flash that could occur from a stricken object, such as a tree, to a nearby victim standing close by. Fourthly, a person or animal standing near a stricken object, or close to a close flash of lightning to ground, could be injured by so-called step voltages produced by lightning flowing through the resistance of the soil beneath. This earth current can then also flow in another pathway, namely, up one limb and down another of the victim, which could result in injury or even death. Finally, the so-called 'fifth mechanism', namely that the bodies could be sufficiently charged during the lightning leader process to cause upward streamers to be initiated from them[1].

Lightning is a multi-physics phenomenon requiring a multidisciplinary approach. Lightning injury models suggest that lightning injury is chiefly *electrical* and/or *thermal* in nature. While electrothermal phenomena explain the vast majority of injuries observed in lightning strike victims, including cardiac[2], electrothermal[3,4], and at least some of the neurological injuries observed, a review of the lightning literature shows an interesting injury phenomenon which is difficult to explain with the current electrical and thermal injury models and which has become the topic of controversy. The phenomenon includes torn and tattered clothing[5], fractures[6], rupture of shoes, traumatic perforation of tympanic membranes[7,8,9,10,11,12,13,14,15] lung contusion and haemorrhage and even pneumomediastinum[16,17].

These findings are similar to injuries seen in individuals who have been exposed to a bomb explosion and suggest explosive *barotrauma* as a mechanism of injury. To be injured by a blast, one has to be in the immediate vicinity of the explosion, about a meter or so. About 100 $lb/inch^2$ (690kPa) is the minimum threshold for serious damage to humans[18]. Blast lung, bowel contusion and tympanic membrane rupture, all of which may be found in some cases of lightning injury, are typically found in cases of direct transmission of a detonation shockwave as well[19].

It is customary to use Marshall’s Triad when considering the pathology of trauma of bomb explosions. The triad includes punctate-bruises, abrasions and small punctate lacerations all of which are typically found in an explosive bomb blast. Although many similarities exist between injury patterns seen in lightning and concussive injuries, Marshall's Triad findings are not typically found in lightning strike injuries.

A blast consists of a wave of compression passing through the air. The velocity of the shock wave depends on the distance from the epicenter, being many times the speed of sound at the start, but rapidly decreasing as it spreads out. The magnitude of the blast varies with the energy released and also the distance from the epicenter, the intensity obeying the inverse square law.

Vladimir A Rakov and Martin A Uman’s describe something similar in their book[20] *Lightning – physics and effect,* explaining little appreciated forces that can occur with lightning*:*

> ‘The return stroke heats the channel created by the preceding stepped or dart leader from nearly 10,000K to near 30,000K or more in several microseconds or less. Such a channel overpressure will result in an expansion of the luminous channel and the formation of a shock wave that propagates outward and eventually beyond the luminous channel, which attains pressure equilibrium with the surrounding atmosphere within tens of microseconds (Orville 1968). The shock wave differs from the acoustic wave (thunder) in that it compresses and heats the air and, as a result, propagates at supersonic speeds. The initial propagation speed of the shock wave is probably about 10 times the speed of sound (Few 1995). After the bulk (probably 99%) of the energy delivered to the shock wave has been expended in performing thermodynamic work on the surrounding atmosphere, the shock wave is transformed, within a few meters or less from the lightning channel, into an acoustic wave that propagates at the velocity of sound (Few 1975). Thus, the heated-channel thunder-generation mechanism involves the production and evolution of the shock wave, which is typically characterized by its pressure as a function or radial coordinate at different instants of time.’

A further review of the lightning literature reports that thunder consists of a roughly cylindrical initial pressure shock wave at the lightning channel in excess of 10 atmospheres. The shock wave rapidly decays to a sound wave within meters. The pressure wave – shock propagation – sometimes may cause exterior and interior damage to structures. There have been anecdotal reports of popping of nail-supported drywall away from horizontal and vertical wooden studs inside houses and broken glass windows.

It is not uncommon for a lightning flash to enter an unprotected building through a water pipe or wiring. The sometimes explosive effect may rip a hole in the wall where the flash passed through a ventilator, splintered the ceiling or blow off roof tiles. A case is on record where a lightning flash entered a small double-storied house and caused the complete collapse of one of the walls[21].

There are multiple well documented reports of trees being split asunder blast holes in the ground and flying masonry[5]. *The Physics of Lightning* by D.J. Malan[21] under the heading *Explosive Effect* notes:

> 'Should the heavy current of a lightning flash pass through a confined space, the heated air is not free to expand and will exert a pressure on the walls of the cavity. The larger the cavity, the smaller the excess pressure, since only part of the air in a large cavity will be heated. When a lightning flash is incident on rocky soil the electric current tends to follow the interstices between the rocks or cracks, which are filled with moist soil. Rocks may be split asunder or thrown aside with explosive violence

Muller Hillebrand carried out detailed studies of the effects produced by lightning on the rocky soils of Sweden. On one occasion investigated, lightning struck a pine tree and from there ploughed branching furrows in the ground. The total length of the furrows was 250m, and in one spot there was a crater-like hole 2 m in diameter and 750 mm deep. Rocks of up to half a ton in weight were dislodged and trees were uprooted. The total volume of stones and earth cast aside amounted to 25 m^3 or the equivalent of 70 tons. He estimated that about 200kg of high explosive T.N.T would have been required to produce the same effect as a lightning flash. Luckily, few lightning strikes are sufficiently high enough to produce such devastating effects.

Review of the otorhinological medical literature sometimes describes the tympanic membrane following lightning strike as 'a large tympanic membrane perforation with ossicular chain disruption' [7,8,9,10,11,12,13,14,15]. Proposed mechanisms of injury have included concussive "blast" effect on the ear, "direct" effect of electrical conduction, "splash" effect, "cylindrical shock wave of electrons" and/or direct "thermal burn"[17].

More research is therefore needed to investigate if there is a significant *concussive blast effect* or *lightning explosive barotrauma* immediately surrounding a lightning channel that could add to our understanding of some of these curious lightning injury patterns that have not been explained in the past.

Materials and Methods:

A simple experiment was conducted to test for the presence or absence of a blast wave surrounding lightning's luminous channel. The testing took place at the University of the Witwatersrand School of Electrical and Information Engineering High Voltage Laboratory utilizing an 8/20 microsecond Current Impulse Generator (Tektronix TDS 3014b oscilloscope) and an isolation transformer. The isolation transformer was there to protect the oscilloscope. Please note that this waveform does not represent that of Natural lightning which has a longer rise and fall time. Nevertheless, the 8/20 microsecond waveform is commonly used for electrical testing.

What made this experiment unique was the utilization of *ballistic gel* to determine whether or not a blast wave existed around the lightning channel or not.

There is sufficient data regarding tissue simulants such as gelatine with regards to projectile testing. Karl G Sellier and Beat P Kneubuehl in their book entitled Wound Ballistics and the Scientific Background give a good exposition of shooting tests through gelatine blocks[22], the premise being that when a projectile is shot through ballistic gel there is a 'crunch-punch-tear' effect which causes a permanent cavity and a 'stretch-splash' effect which causes a temporary cavity.

'When a high-velocity bullet enters the body and ploughs through tissue, it is obvious that material in its path will be thoroughly disintegrated. A permanent cavity, filled with blood and pulpated cells, is gouged out. In addition, immediately behind the moving missile, a large temporary cavity appears, many times the cross-sectional area of the missile itself. This temporary cavity quickly subsides, but tissue at its periphery has been greatly stretched and cells may be injured.'[23].

According to the ballistic literature, the pressure of the projectile shock wave may be as low as 4 atmospheres to as high as 60 atmospheres.

Tissue Simulants:

Normal Gelatine:
Normal gelatine was used initially to test the effects of the Current Impulse Generator. Gelatine is the protein produced from collagen when it is submitted to treatment to make it water-soluble. In general, gelatine is obtained from skin, bones and tendons. The jelly strength of gelatine is measured by the so-called *Bloom number*[24].

The Bloom number is a general measurement of the consistency of jellies. The unit is defined as the mass of a cylindrical stamp (diameter 12.7mm), necessary to penetrate 4mm into the jelly. For this, a jelly concentration of 6 and 2/3% and a temperature of 10 degrees Centigrade with a tolerance of 0.1 degree Centigrade are required.

Gelatine is available in consistencies of between 50 and 300 Bloom. For shooting tests type A with a Bloom number between 250 and 300 is usually used.

Corbin SIM-TEST[tm] ballistic test media:
SIM-TEST[tm] Ballistic Test Media was decided upon to be used as the test medium in our experiment. Corbin SIM-TEST[tm] ballistic test media is a stable, animal-protein based "simulated tissue" for consistent bullet performance tests. The material is a very close match to muscle tissue in density and consistency. The density is 1.3 gm/cc. (Density could be adjusted by controlling water content.)

SIM-TEST[tm] had advantages over wet newspaper, water, clay, conventional ballistic gelatine, and other test materials commonly used as a bullet expansion medium:
It was stable at room temperature. It was ready to use without mixing. No refrigeration was required. It was re-usable, re-castable. It was non-toxic, water

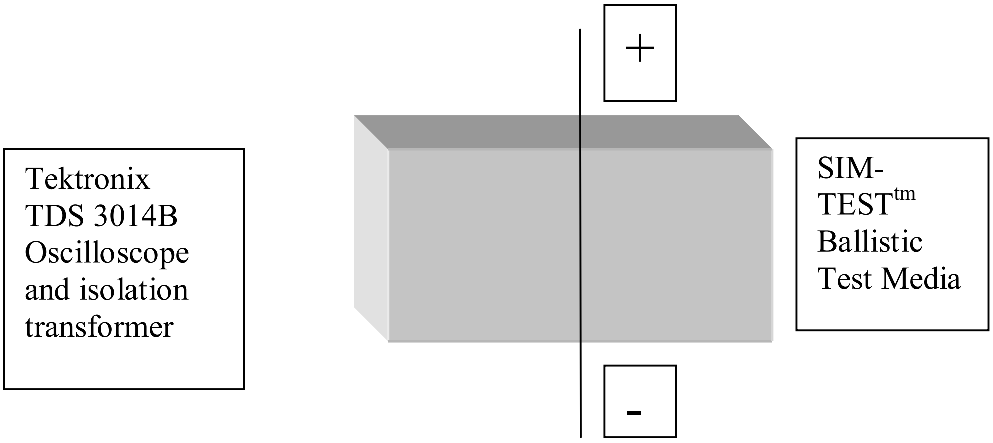
soluble with easy clean-up and had close simulation of actual tissue.

The lightning literature mentions four types of cloud-to-ground lightning discharges[20]

- Downward negative lightning (account for about 90% of global cloud-to-ground lightning)
- Upward negative lightning
- Downward positive lightning (account for 10% of global cloud-to-ground discharges)
- Upward positive lightning

This research chiefly focussed on the discharge itself and did not focus on the type of discharge, the leader-return-stroke sequences, the lighting continuing current or lightning M-components.

The experiment utilized normal Gelatine at the outset and SIM-TEST[tm] Ballistic Test Media, a thin-piece of conductive wire and an 8/20 microsecond Current Impulse Generator and an isolation transformer.



The experiment was repeated using incremental discharges beginning at 1kV to 20kV.

As with gunshot wound profiling[25,26], the following parameters were sought:

- Temporary cavity formation. The extent of the radial cracks in the gelatine approximates temporary cavity size.
- Permanent cavity formation.
- And the shape of the cavity formed (for example fusiform, cylindrical, etc)

Results:

At the outset of the experiment, normal cooking gelatine was used to determine the nature of the shock-wave phenomenon. Gelatine moulds were formed at various densities, viscosities and elasticities. The gelatine moulds were made to enable varying threshold velocities, variable threshold energies and various energy densities.

Gelatine proved an excellent medium to study the behaviour of the shock wave in that it was transparent and allowed for optical measurements. Since gelatine is made of natural substances, (water and proteins), disposal was also not a problem.

Findings were in keeping with the so-called "Wound Profile" of Fackler[26]. The size of the permanent cavity could easily be seen within the test gelatine. Fackler called the description of the totality of the projectile effects on gelatine, a "Wound Profile".

Initial testing with Gelatine blocks (50 to 300 Bloom). Showed the following results:

Current [kA]	**Wire intact**	**Wire disintegrates**	**Beading and/or Shrapnel**	**Node formation**	**Permanent cavity formation**
1.52	×				
2.21	×				
2.70		×		×	
3.22		×	×	×	
3.84		×		×	
4.32		×		×	
4.68		×		×	
5.06		×		×	
5.48		×		×	
6.14		×			×
9.0		×			×

Due to the fact that the protocol was designed to exclude the testing of projectiles, penetration depth of projectiles and the decomposition of projectiles, the classic 'wound profile' described in the wound ballistic literature could not be compared apples-with-apples, pears-with-pears, to that of the wound profile caused by a lightning discharge. The only similarity between the two would be the size of the temporary and permanent cavities. The temporary cavity was defined by fissure-fractures in the gelatine after testing. Axial views of the fissures-fractures were similar to those seen in projectile testing experiments.
The permanent cavity was defined by the permanent loss of gelatine surrounding the discharge.

As the current increased through the wire six situations were noted: Initially the wire was intact, at higher currents the wire was noted to disintegrate almost as a fuse would disintegrate. At higher currents beading and/or shrapnel formation was noted surrounding the permanent cavity. At higher currents 'smoke nodes' were identified (these were defined as caterpillar-like explosion defects in the gelatine surrounding the disintegrating wire). At higher currents there was directly proportional increasing permanent cavity formation surrounding the discharge. Furthermore; as the current increased through the wire, the size of the temporary cavity also increased in a directly proportional manner.

Having demonstrated permanent cavity formation within the softer gelatine media, experimentation progressed to the Corbin SIM-TEST^{tm} ballistic test media:
Fifteen centimetre (15cm^3) cubed blocks were utilized and a thin conductive wire was passed through the media from axial entrance to axial exit. Incremental currents were passed through the conductive wire beginning at 7,30kA progressing to 19,8kA. The diameters of the axial entrance and exit wounds were measured and plotted on a graph against the Current.

Experiment : Corbin's Gel

10kV = 7,30kA= (147mm) & (157mm) (x = 152mm) Fissure/fracture
12kV = 8,60kA= (273mm) & (190mm) (x = 2315mm) Fissure/fracture
14kV = 10,3kA= (320mm) & (410mm) (x = 365mm) Fissure/fracture
16kV = 14,8kA= (360mm) & (330mm) (x = 345mm) Fissure/fracture
18kV = 19,8kA= (540mm) & (41mm) (x = 470mm) Fissure/fracture

Discussion and Conclusion:

A shock wave is a special type of sound wave (acoustic wave) that runs through a medium at a certain velocity, depending upon the material and the temperature. The shock wave amplitude deceases approximately with 1/r (where r means the distance from the source). This is the result of a cylindrical expansion where the cylinder coincides with the projectile path. A point source causes a spherical propagation (e.g. an exploding mine in water), where the amplitude decreases with $1/r^2$. [22]

Preliminary research with a Current Impulse Generator and ballistic gel confirmed the presence of a destructive cylindrical shock wave surrounding the channel source, which propagated outwards and in a directly proportional manner to the amount of Current in the conductive wire.

Permanent cavity formation was demonstrated in the softer gelatine media, whereas temporary cavity formation was demonstrated in the harder gelatine media.

Based on aforementioned laboratory experiments, the existence of a sixth mechanism of lightning injury, namely barotrauma, should therefore strongly be considered.

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Figures:

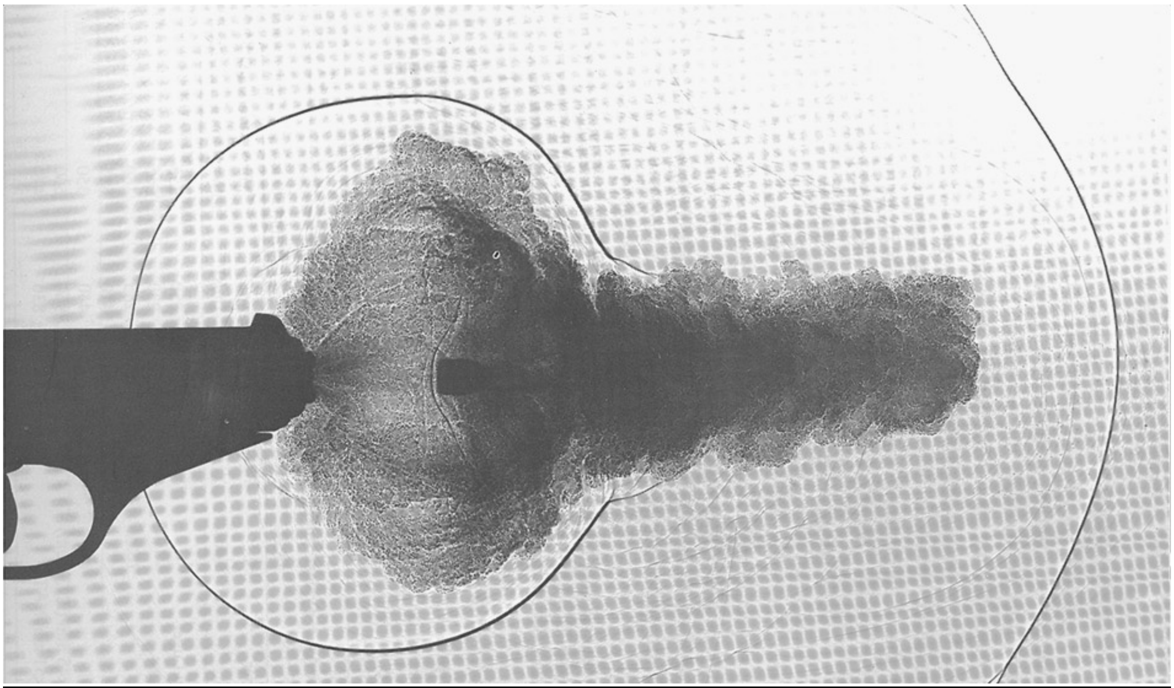

Figure 1: Gas flows at a muzzle having just fired a shot.
Note the shock wave at the tail of the bullet, showing the high gas velocity.

Figure 2: Axial view in the direction of the shot. Gelatine block with a shot. Original picture taken from the ballistic laboratory of Dynamit Nobel AG and published in the textbook *wound ballistics and the scientific background* by Karl G Sellier and Beat P Kneubuehl.

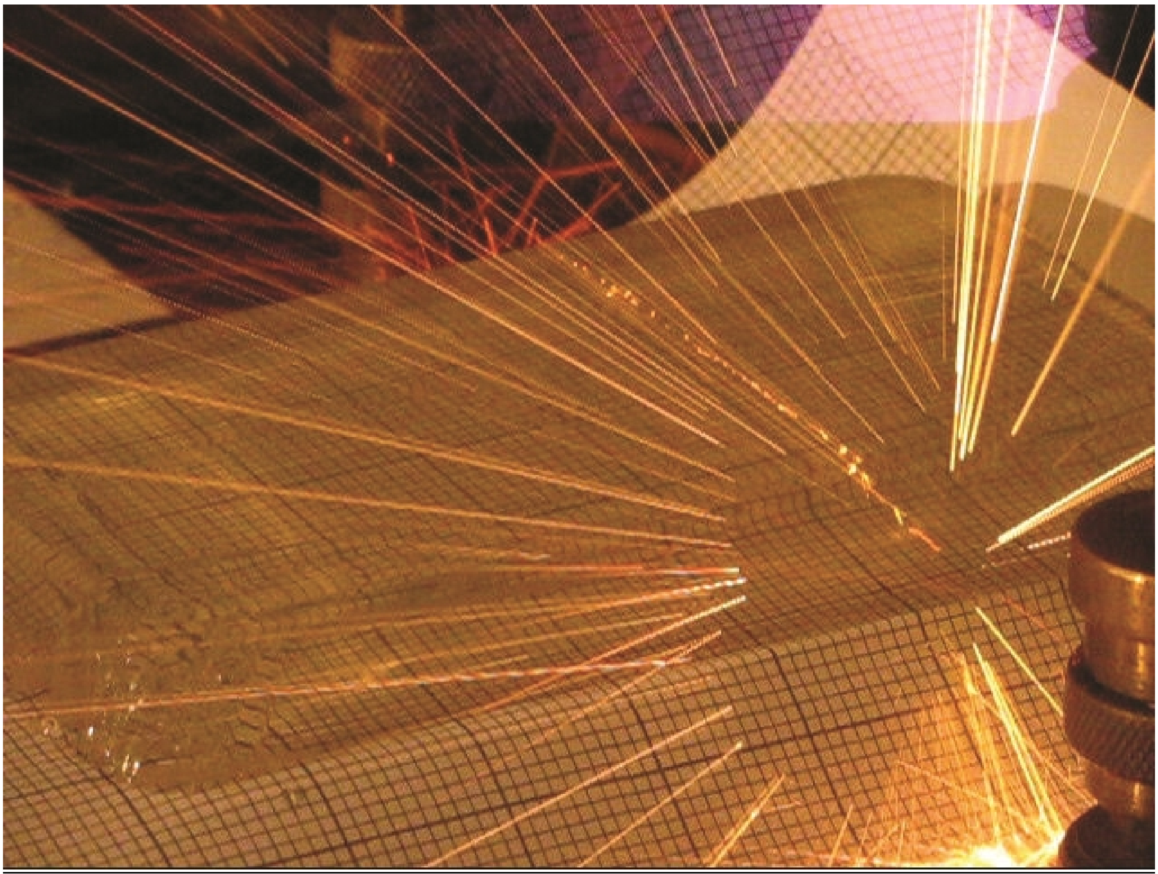

Figure 3: Current impulse generated through gel showing radial explosion. High-speed camera footage showing the moment of impulse generation. Note the radial explosion.

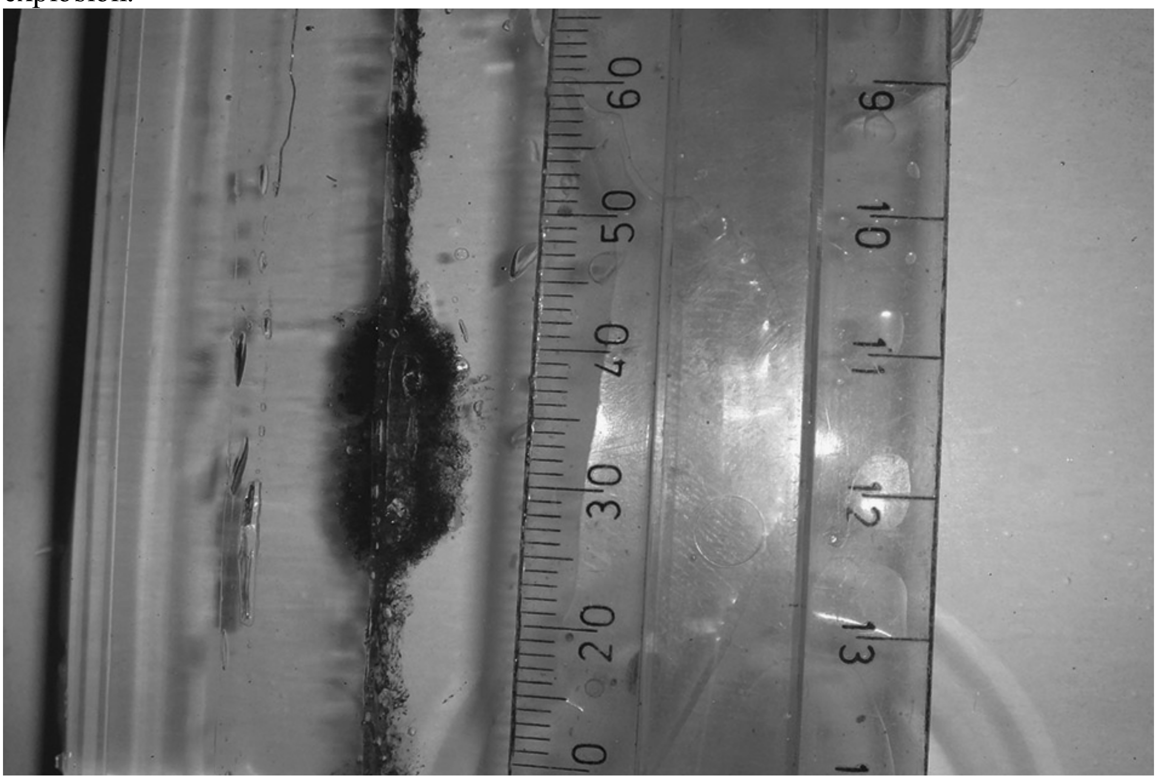

Figure 4: Permanent cavity formation. A ‘smoke node’. Permanent cavity formation noted in the softer gelatine media. Caterpillar-like explosion defect noted in the gelatine surrounding the disintegrating wire.

Figure 5: Incremental permanent cavity formation. Incremental destruction of surrounding gelatine as demonstrated from left-to-right at increasing voltages. The voltages were increased incrementally from 1kV to 6 kV. This represented a serial increase in current from 1,52kA to 9,0kA. The gelatine/water ratio represented a 30mg/500ml mix. Notice no visible reaction within the wire at 1kV (1,52kA). Notice complete wire disintegration with cylindrical smoke node formation at 6,0Kv (9,0kA).

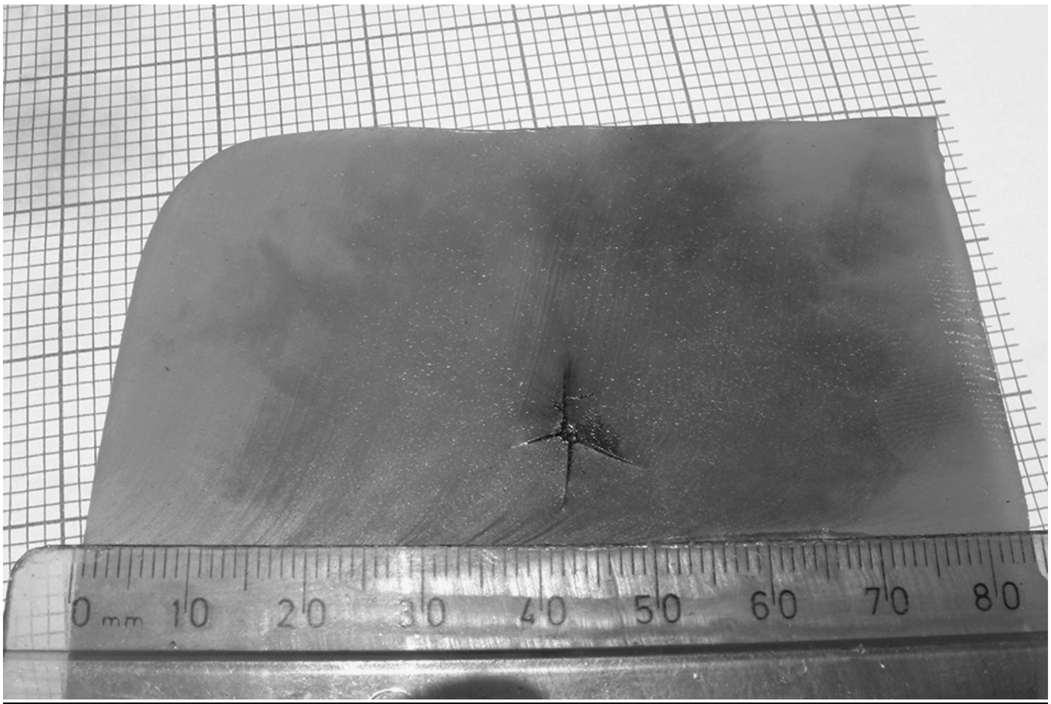

Figure 6: Axial view. Corbins gel. 10kV. Temporary cavity formation demonstrated in the harder gelatine media. Small fissure-fracture similar to that seen in projectile testing experiments. The current strength measured 7,30kA.

Figure 7: Axial view. Corbins gel. 18kV. Temporary cavity formation demonstrated in the harder gelatine media. Large fissure-fracture similar to that seen in projectile testing experiments. The current strength measured 19,80kA.

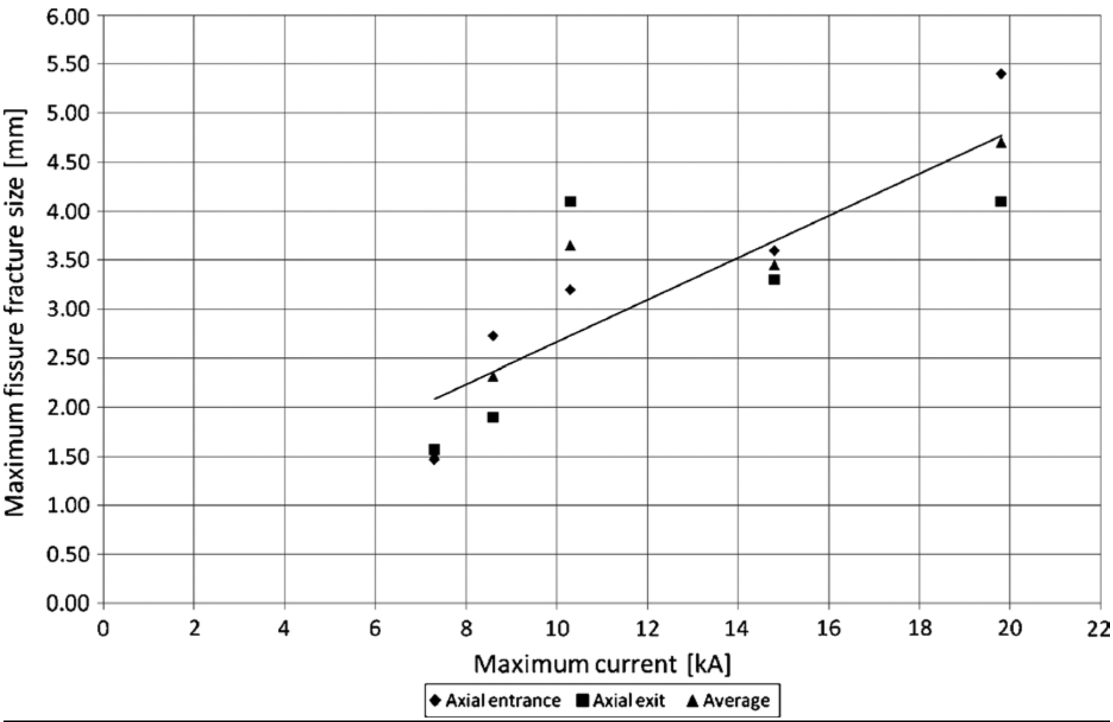

Figure 8: Table demonstrating incremental cracks in Corbins gel. As the current increased through the wire, the size of the temporary cavity also increased in a directly proportional manner.