Insights Imaging (2013) 4:513–523
DOI 10.1007/s13244-013-0238-8

ORIGINAL ARTICLE

Forgotten electrical accidents and the birth of shockproof X-ray systems

Gerrit J. Kemerink · Gerhard Kütterer · Andrew Wright · Frank Jones · Jeff Behary · Jan A. M. Hofman · Joachim E. Wildberger

Received: 30 January 2013 / Revised: 13 February 2013 / Accepted: 14 February 2013 / Published online: 29 May 2013

Abstract
Objectives To commemorate victims of electrical accidents that occurred in the first decades of radiology and relate these accidents to the evolution of the X-ray apparatus.
Methods Digitised newspapers, scientific journals, books and reports of legal procedures were searched for electrical accidents involving X-ray systems. Information on the historical systems was retrieved from the scientific literature and brochures from manufacturers.
Results We found 51 fatal and 62 non-fatal but serious electrical accidents. Most of them occurred between 1920 and 1940 and involved transformers that provided output currents well above the threshold for the induction of ventricular fibrillation. The accidents led to recommendations and regulations to improve safety for operators and patients, and spurred manufacturers to technical developments that culminated in fully electrically shockproof systems by 1935.
Conclusions Although largely forgotten, the development of the shockproof X-ray systems we take for granted today lasted about 4 decades and was associated with considerable human suffering. The complete solution of the problem is a success story of engineering realised by contributions from all parties involved.
Main messages
- *The development of electrically shockproof X-ray systems took about 4 decades (1895–1935).*
- *Between 1896 and 1920 electrical shocks from X-ray systems were common, but their consequences limited.*
- *After 1920, transformers killed by delivering currents above the ventricular fibrillation threshold.*
- *Inductors, static generators and high-frequency coils were generally low-current systems and safe.*
- *We found 51 fatal and 62 serious non-fatal electrical accidents, most occurring from 1920 to 1940.*

Keywords History of radiology · Electrical accidents · High-voltage power supplies · High-voltage conductor systems · Electrically shockproof X-ray systems

Electronic supplementary material The online version of this article (doi:10.1007/s13244-013-0238-8) contains supplementary material, which is available to authorised users.

Jan A. M. Hofman is a member of the International Society for the History of Radiology (ISHRAD)

G. J. Kemerink (✉) · G. Kütterer · A. Wright · F. Jones · J. A. M. Hofman · J. E. Wildberger
Departments of Radiology and Nuclear Medicine, Maastricht University Medical Center, P. Debijelaan 25, 6229 HX, Maastricht, The Netherlands
e-mail: gerrit.kemerink@mumc.nl

J. Behary
The Electrotherapy Museum, 627 36th Street, 33407, West Palm Beach, FL, USA
URL: http://www.electrotherapymuseum.com

Introduction

Electrical accidents with X-ray systems were responsible for a considerable number of injuries and deaths in a period that roughly extended from 1920 to 1940. This dark side of the early application of X-rays has received virtually no attention in the literature on the history of radiology and radiotherapy, in contrast to the consequences of poor radiation protection [1–3].

At the time of Röntgen's discovery of X-rays, and for many years thereafter, minimally insulated wires were used for connecting the high-voltage supply to the gas tube that generated X-rays, and all electrical contacts were generally bare. The ability of high-voltage to bridge considerable air gaps through electrical discharge increased the risk of receiving shocks. Gunther [4] wrote in 1919 that all users of these systems received electrical shocks at some time, and although the shocks were painful and could cause burns, the impact on the victim's health (and attitude) was minimal. The high-voltage generators of this period primarily consisted of induction coils, static generators and high-frequency coils of low electrical power. Apart from the danger of personal electrical shock, risk of fire existed in places where inflammable, volatile anaesthetics were used. Moreover, corona discharges around exposed high tension were responsible for the formation of noxious nitrogen oxides and ozone. Over time, wiring configurations received considerable attention, but wires and contacts still remained partially unprotected. The potential danger of X-ray machines increased after the development of high-voltage transformers, which allowed for an increase in electrical power. Ensuing fatal and serious non-fatal accidents incited several authors to formulate safety recommendations [4–6], which ultimately led to legislation [7, 8]. Though manufacturers developed many modifications to improve electrical safety, it was not until around 1935 that new X-ray systems might be considered electrically safe for the patient and operator (*see* Grigg [9] for many historical details).

In this work we present the lethal and serious non-lethal accidents we were able to retrieve from the literature. To provide a context for how the accidents occurred and how they contributed to the development of electrically shock-proof X-ray systems, the following subjects will be addressed: (1) electrical current and the human body, (2) high-voltage power supplies used in X-ray systems, (3) X-ray tubes, (4) wiring of X-ray systems, (5) safety recommendations and legislation, (6) victims of electrical shock, (7) types of electrical accidents.

Electrical current and the human body

The magnitude of the electrical current passing through human tissue is the main determinant of its effect. Therefore, it makes sense to first look at the effects of mains-like voltages, as these have been studied in great detail [10, 11].

Table 1 summarises some of the physiological effects from an alternating current (AC)—voltage applied between the left hand and both feet [10]. Unless stated otherwise, current is given as the effective or root mean square (rms) value. Induction of ventricular fibrillation forms the greatest risk for a fatal outcome of electrical shock.

Several factors affect the magnitude of the current and its physiological consequences [10–12]. Among them are the shape of the voltage (Table 2), its magnitude, its frequency, personal characteristics, the resistance of tissue and the path of the current (Appendix 1) [13].

Figure 1 shows the wound in the sole of the foot of a radiologist who came into contact with high-voltage while his foot was on an effectively earthed on/off switch. His boot was charred at the contact area. He was momentarily unconscious but recovered [14].

High-voltage power supplies used in X-ray systems

In the first decade of radiology, induction coils, static generators and high-frequency coils were commonly used as sources of high-voltage for an X-ray tube. The common static generators delivered currents far too weak to threaten life. High-frequency coils could cause serious burns, but stimulated nerves (and muscles) only to a very limited extent, making the induction of ventricular fibrillation unlikely. Induction coils generally provided currents well below the threshold for the induction of fibrillation, but high-power systems may have been dangerous. After 1907, high-voltage transformers came into use, slowly replacing the older systems [9, 15]. The waveforms of the various high-voltages used to excite an X-ray tube are shown in Fig. 2. More information on high-voltage power supplies is given in Appendix 2 [16–35].

Table 1 Effects at various currents[a] of 15–100 Hz voltage between left hand and feet. Current values in mA [10]

Duration of contact with source	Possibly perceived, no damage	Muscle contraction, difficulty breathing, freezing, reversible heart effects, no permanent damage	Heart stops, breathing stops, burns, risk of fibrillation	Persons with fibrillation[b]	
				5 %	50 %
10,000 ms	≤5	5–40	40–50	50	80
1,000 ms	≤15	15–50	50–70	70	130
100 ms[c]	≤50	50–400	400–800	800	1,200
10 ms[c]	≤200	200–500	500–1,000	1,000	1,500

[a] Effective or root mean square values

[b] Same figures for contact LH ↔ RF or LF, or of both hands ↔ both feet; figures have to be divided by 0.8 if RH ↔ LF, RF or both feet, and by 0.4 for LH ↔ RH (*L* left, *R* right, *H* hand, *F* foot)

[c] If duration of contact is less than 200 ms, fibrillation only occurs in vulnerable period of heart

Table 2 Thresholds for ventricular fibrillation due to normal, full- and half-wave rectified AC currents and current pulses from an inductor. Frequencies 15–100 Hz[a]

Rectification	Normal[b]	Full-wave[b]	Half-wave[b]	Pulse[c]
Conversion factor[d]		0.5	0.7	0.35[e]
Current at start fibrillation risk	36 mA	72 mA	51 mA	102
Current 5 % risk fibrillation	50 mA	100 mA	71 mA	141
Current 50 % risk fibrillation	84 mA	167 mA	118 mA	238

[a] Contact duration several seconds; currents between left hand and both feet, calculated according to [11]

[b] Currents are given as root mean square values (not rounded)

[c] Currents are peak-peak values

[d] Factor to convert value of root mean square current of rectified AC source into equivalent current of unrectified voltage with the same risk of introducing ventricular fibrillation [11]

[e] Similar factor for conversion of peak-peak value of current pulses from an inductor

An "ideal" transformer adjusts the primary current in real time to sustain any load of the secondary coil. It fails in practice because of finite resistances in the primary power supply and the transformer itself. There were very many models from many different manufacturers; Table 3 only gives an impression of the magnitude of the power available over time. Many low-power (and cheaper) systems, including mobile and dental units, were on the market. Around 1930, systems with a current rating of about 10–50 mA were rather common. Units specifically built for radiotherapy, both surface and deep therapy, were low-current systems (lower part of Table 3). The output of power supplies steadily increased over time.

When the transformer was used with gas tubes, mostly resistive networks (rheostats) were used to adjust the voltage and current for the tube, as was done with inductors. In case of a shortcut, these resistive networks limited the maximum current to some extent. After the introduction of the Coolidge tube, a considerably more dangerous situation arose. Coolidge tubes facilitated any current within its power limitations, independent of high voltage. This meant that the transformer could be made a low impedance device, i.e. a more ideal transformer, able to provide currents for a wide range of applications as the tube could take what was needed. The secondary voltage was set with an autotransformer on the primary side of the high-voltage transformer or with a primary with different taps for mains voltage connection.

Fig. 1 Wound at area of contact with foot switch, 17 days after electrical accident [14]

The autotransformer was introduced around 1909 [9]. Compared with the previously used resistive networks, the autotransformer, the tapped primary and the feeding mains voltage had low impedance. Together with the high current transformer, the complete power supply could provide a current that was several times larger than its nominal rating when it was short-circuited. As an overload of significant duration would destroy the transformer, this was prevented by a current interrupter or fuse in the primary circuit set to slightly above the maximum rated current.

If a person short-circuited the secondary tract, he would be shocked until the current interrupter or fuse tripped, or somebody switched off the system. According to Table 3, currents normally used for diagnostic systems would often be larger than the fibrillation thresholds shown in Tables 1 and 2. Also, smaller systems—designed for maximum currents of a few tens of mA—might have easily exceeded these thresholds when short-circuited [37]. The transformer current could be limited when a person came in series with a Coolidge tube or a hot cathode rectifying valve. In the first case, the maximum current was equal to that of the X-ray tube, in the second case the current would be likely slightly larger than the maximum current the system could deliver under normal circumstances.

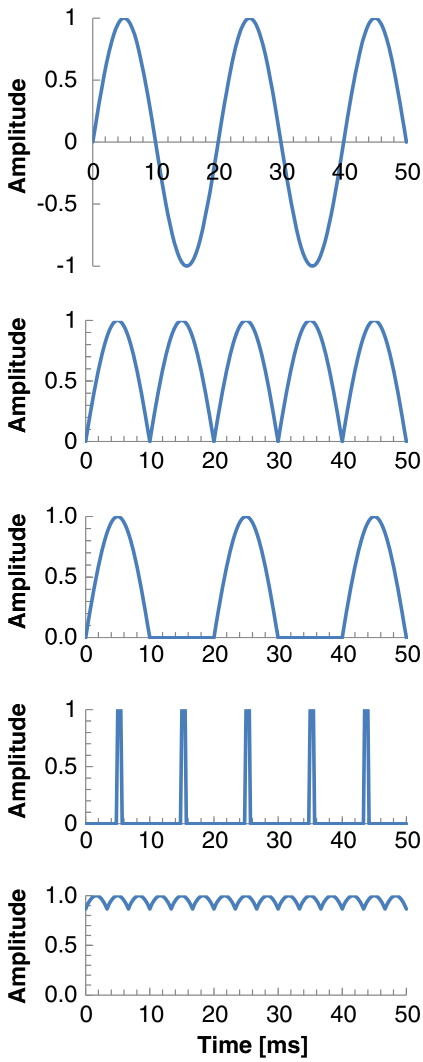

Fig. 2 Waveforms of high tension used for exciting X-ray tubes. *From top to bottom*: normal AC (50 Hz), full-wave rectified, half-wave rectified, idealised (rectified) inductor pulse and three phase rectified

In 1935 nearly all clinical X-ray systems advertised in *Radiology* and the *British Journal of Radiology* were of the shockproof type. However, it was well into the forties before all electrically unsafe systems were replaced by safe units. According to Grossmann [38, 39], the majority of deep-therapy systems and a considerable percentage of dental systems were shockproof around 1933, but the number of electrically safe surface-therapy and diagnostic X-ray systems was still small. More details on the development of X-ray apparatus are in Grigg's book [9].

X-ray tubes

Because the development of high-voltage (HV) power supplies is intimately connected with the increase in the allowed loading of X-ray tubes, some attention to tubes seems in order (Appendix 3) [40, 41].

In the very first months of 1896, tubes with the glass wall functioning as anode were used, e.g. Crookes no. 9 tube, which was used in some recently replicated historical experiments [42]. The current in these tubes was well below 1 mA. Later that year, tubes with a metal anti-cathode (effectively the anode) and an electron-focusing cathode became the standard. The electrical power these tubes could dissipate was increased by changing the anode target material from platinum to tungsten, generally on a heavy copper backing. Water cooling was used for heavy-duty applications.

In 1913, the high-vacuum tube with a hot cathode was introduced by Coolidge of General Electric [43]. Great advantages of this new tube were that the tube current could be adjusted independently from the high-voltage and that the tube was very reliable. Over the years the heat capacity of the anode was increased, and higher currents became possible, requiring more powerful transformers. The advent of the rotating anode allowed for even higher peak currents with a smaller X-ray focal spot and a shorter exposure time than could be realised with the original Coolidge tube. In 1929 Philips introduced the rotating anode tube as we know it today, the Rotalix Metalix. Siemens developed the Pantix in 1933, and Machlett followed in 1938 [9].

Wiring of X-ray systems

Initially, simple wires were used for the electrical connection of a tube to the high-voltage generator (Fig. 3). A discharge between the two conductors was prevented with ample spacing. If the wires had isolation at the time, it did little to prevent discharges. With the increase in power of induction coils, and especially with the introduction of the more powerful high-voltage transformer after 1907, overhead electrical connections of increasing sophistication were introduced. Initially wires were used (Figs. 4 and 5); later, more stable tubing became the standard (Figs. 6 and 7). The use of tubes of a larger diameter, and other structures with a large radius of curvature, limited corona discharges at high-voltages as used in therapy, while large glass isolators were used to carry the metal conductor tubes and to provide good isolation from walls or ceiling.

The high-voltage for the X-ray tube was taken from the overhead system using spring-loaded cord reels, ensuring that no slacking loops of wire endangered workers. In addition, this system would warrant that wires which had been disconnected or got accidentally unhooked from the X-ray tube automatically moved to a safe height. Initially, small weights were also used to straighten wires (Fig. 8). Figure 9

Table 3 Power specifications of some transformers for X-ray systems[a]

Application/ manufacturer	Year	Primary power (max) [kW]	Secondary power [kW]	Secondary current (max.) [mA]	Corresponding high voltage [kV_P]
Diagnosis (& other purposes)					
Snook [9]	1907		10	100	100
Siemens & Halske[b]	1909	2–4	2–4		
Siemens & Halske[b]	1910	3–6	4	30–60	100–120
Meyer, Chicago [36]	1914–5			300	150
Reiniger, Gebbert & Schall[b]	1922	15.4	12	160	75
Reiniger, Gebbert & Schall[b]	1929		160	2,000	80
Therapy					
Reiniger, Gebbert & Schall[b]	1922	1.54	0.8	4	150–160
Siemens & Halske[b]	1923		1.75	10	175
Reiniger, Gebbert & Schall[b]	1924		2.4	8	300
Siemens-Reiniger-Veifa[b]	1929		0.72	6	120

[a] Systems from later than 1914 could be used with Coolidge tubes

[b] From Siemens MedArchiv (personal communication)

shows the wiring of a mobile system, Fig. 10 for a dental system.

The power supply was initially often found in the examination room on a table. In later years it was moved to a safer location, e.g. to a high place along the wall of the room, to another room or out of reach in a cage or cabinet. Some manufacturers built systems with two transformers and tubes, which, among other advantages, limited the amount of dangerous wiring (Fig. 11). Efforts were also made to improve the safety by electrically sensing whether one pole of the secondary of the transformer came into contact with earth or whether both poles were short-circuited, e.g. through a person. But devices such as the Securo [50] and the Salvator [51] did not find wide application. Notwithstanding, the Securo was favourably tested [52].

The dangerous high-voltage-carrying structures started to disappear after the development of electrically shockproof cables a few years before 1930 [9]. A cross-section of a modern shockproof cable is shown in Fig. 12. Figure 13 displays an early shockproof system developed by Philips.

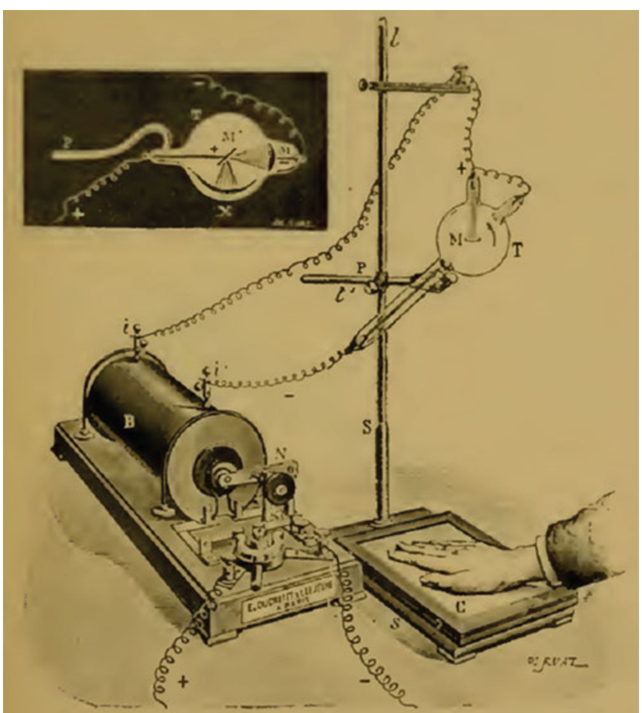

Fig. 7 — Dispositif pour la radiographie.

Fig. 3 Wiring of an X-ray system as applied shortly after 1895 [44]

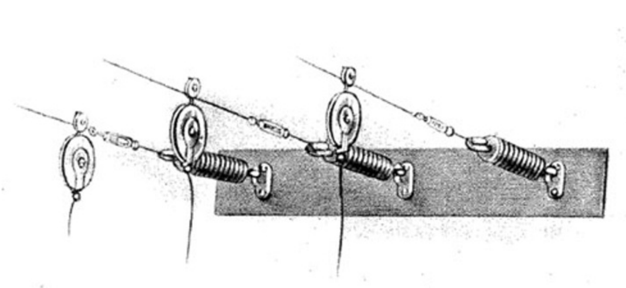

Fig. 4 Overhead wires with spring loaded self-winding reels for connecting the X-ray tube to the high-voltage power supply [45]

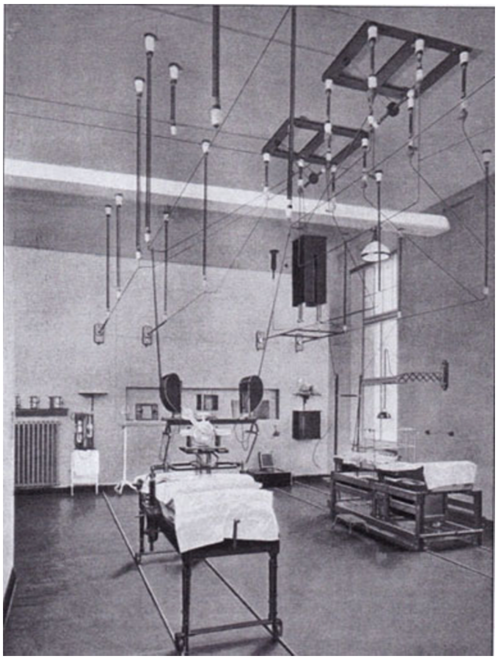

Fig. 5 Overhead wiring in the Allgemeines Krankenhaus St. Georg, Hamburg in 1914 [46]

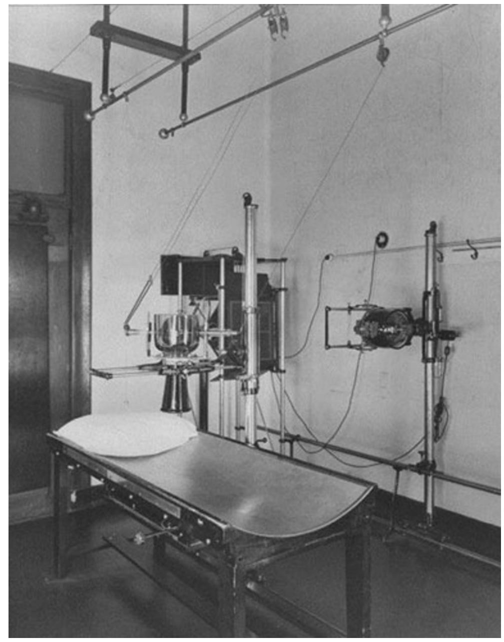

Fig. 7 The same setup as in Fig. 6, showing spheres on end of tubing and on isolators to limit corona discharges (Collection of Dr. D.O. Cuscela)

Safety recommendations and regulations

Initially, little attention was paid to preventing electrical shocks from X-ray systems. Many of the first books contained only casual warnings against electrical shocks. However, in 1913 Albers-Schönberg warned: "Even if at this time no injuries of patients and medical doctors have become known, there is no doubt that they can happen if unfortunate circumstances coincide" [53]. With the increase of the electrical power of the high-voltage supplies, shocks and their consequences were more severe, and electrical safety became an issue within the professional societies. It became a serious concern after the electrocution of a well-

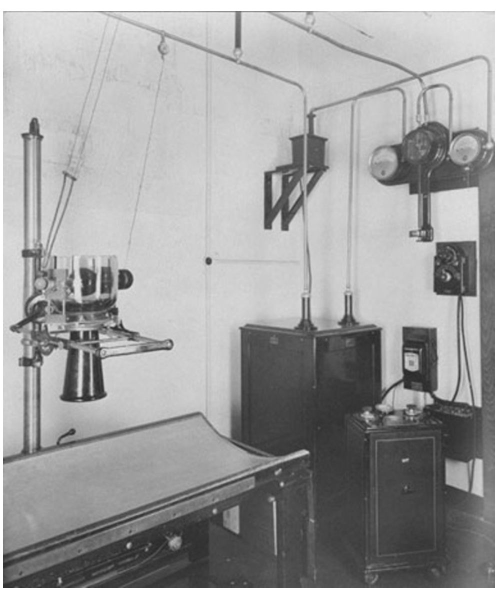

Fig. 6 Overhead tubing to excite Coolidge X-ray tube. Double wires to the left supply power for hot cathode and cathode potential, right wire for anode (Collection of Dr. D.O. Cuscela)

Fig. 8 Set-up showing small weights to straighten live wires to lower risk of accidental contact by operator or patient (Siemens-Halske, 1911) (Siemens MedArchiv, personal communication)

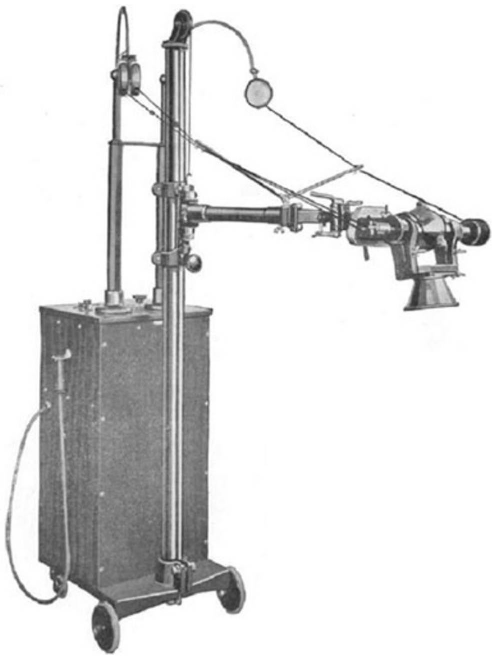

Fig. 9 Mobile X-ray system and its wiring (Wappler, 1923) [47]

known and experienced French radiologist, Jaugeas [54], in 1919. Electrical safety regulations were issued both in the USA and Germany (Appendix 4) [55–57]. Between 1920 and 1935, a few authors discussed aspects of electrical risks [5, 6, 38, 39], some to provide better recommendations [5, 6]

Fig. 10 Dental X-ray system from Ritter Dental with a Philips Metalix A tube. The cathode was grounded, but the radiator at the end of the tube had anode potential (system from around 1921–1924) [48]

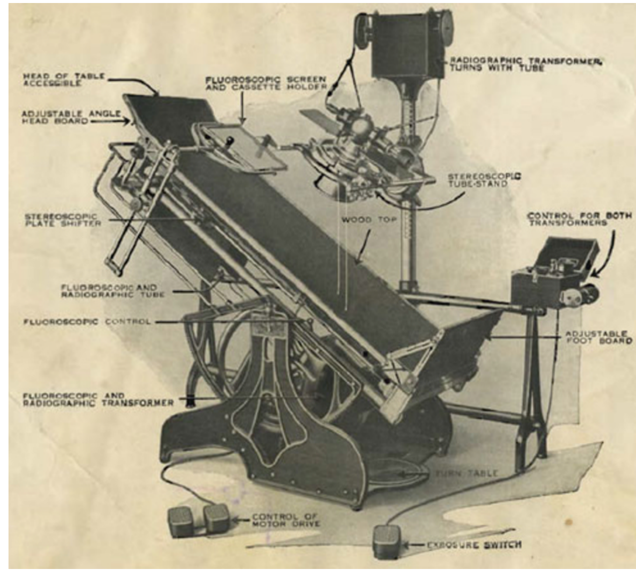

Fig. 11 The "trolleyless" Clinix from Campbell which had two transformers and two X-ray tubes limiting dangerous wiring (about 1920) [49]

and others to show how the new regulation "DIN RÖNT I" would have affected the accidents had these rules already been observed [38, 39].

Victims of electrical shock

Information on electrical accidents with X-ray systems was retrieved from newspapers in digital archives, scientific articles, reports of legal procedures and two books [1, 58]. We distinguished fatal and severe non-fatal accidents. To the latter category we attributed accidents that were deemed important enough at the time to report in writing or to be the subject of a legal procedure. Geographical coverage was limited and determined by accessibility of sources in English, German, French and Dutch. Countries for which accidents were found are: Australia, Austria, Denmark, Finland, France, Germany, Hungary, Italy, Spain, Switzerland, United Kingdom and the USA. A few articles contained

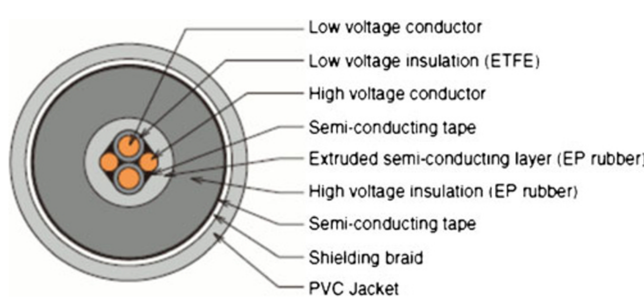

Fig. 12 Cross-section of a modern high-voltage cable (courtesy SWCC Showa Holdings Co., Ltd., Tokyo, Japan)

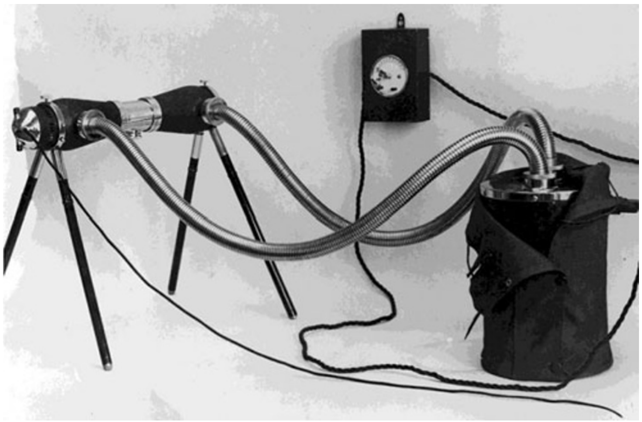

Fig. 13 Early electrically shockproof X-ray unit, the portable Philips Metalix Junior (1928) [48]

information on several accidents, e.g. the articles by Hemler (6 cases) [6] and Grossmann (25 cases) [38, 39], and a thesis by Kleibeler (16 cases) [59], though Grossmann included Hemler's data, and Kleibeler in turn those from Grossmann. The thesis by Kleibeler reported 20 fatal accidents; however, we found that four cases were mentioned twice (the following identities were found: Kleibeler case 1 [K1]=K12, K3=K14, K4=K13, K5=K6).

In total we found 51 persons who were killed in electrical accidents (Appendix 5). Most victims died instantly or after a very short time; two lived after the accident for 5 and 14 days, respectively. An induction coil was probably involved in a fatal case from 1906 as this preceded the transformer era. All other fatalities were likely due to transformer systems, but information on the type of apparatus was generally not provided. Three children were killed, an 8-year-old girl, a 10-year-old boy and a 6-year-old boy who put his hand into an X-ray shoe fitting machine in a shoe store. Deadly accidents after 1950 (n=6) involved one repair, three faulty systems, one demonstration and the shoe fitting machine accident mentioned above. For 17 cases there was only one source, and the maximum number of sources for a single case was six.

The number of serious non-fatal accidents we were able to trace numbered 62 (Appendix 6). For 49 cases there was only one source, and the maximum number of sources for a single case was five. The dependent cases in the works by Hemler, Grossmann and Kleibeler were counted as a single source. In one non-fatal case (from 1913) it was explicitly stated that an induction coil was involved. Twenty-six of the surviving victims (from 62) were reportedly unconscious after the accident.

Apart from the generally present burns, pain and psychological shock, a dislocated shoulder, a shattered shoulder, torn muscles in a leg and a broken leg were reported. In many descriptions of accidents the involuntary and forceful hurling away of the body from the original position is stipulated.

We were interested in the accident rate as a function of time because this might allow investigation into a correlation with instrumental developments. The fatal accidents are shown in Fig. 14 and the non-fatal in Fig. 15. Unfortunately, not all sources specified the date of the accident; thus, two fatal accidents are omitted from Fig. 14. In Figure 15 there are 11 omitted cases.

Table 4 shows the distribution of victims on the basis of their profession or role in the X-ray procedure that caused the accident. Table 5 contains some information on the location of the body that came into contact with a live part of the system or was struck by a spark. Table 6 gives information on the procedures being performed during the accidents. Because it was often unclear whether the procedure during an accident was fluoroscopy or radiography, we combined both procedures in one group.

Types of electrical accidents

We will restrict our evaluation to accidents with transformers, as we assume that they were responsible for nearly

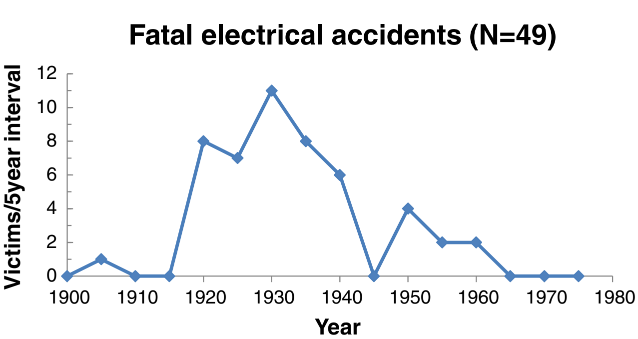

Fig. 14 Rate of fatal electrical accidents involving X-ray systems. Two cases, which occurred between 1919 and 1933, are not included

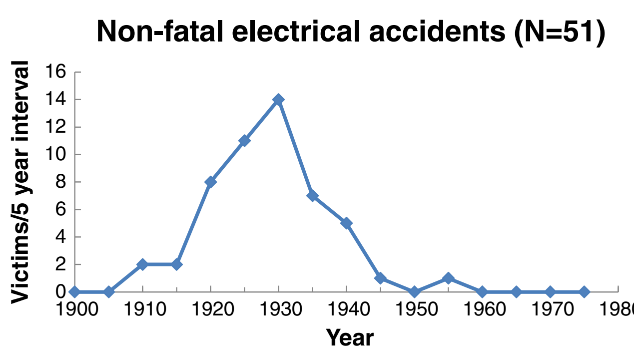

Fig. 15 Rate of non-fatal but serious electrical accidents involving X-ray systems. Eleven cases not included; seven of them occurred between 1919 and 1933, four before 1922

Table 4 Statistics on victims of electrical accidents

	Medical doctor	Helper[a]	Patient	Repair	Other	Total
Fatal accident						
Number	24	9	15	3	0	51
Average age [years][b]	40 (*n*=15)	25 (*n*=4)	32 (*n*=11)	24 (*n*=3)		
Percentage male	100 %	56 %	69 %	100 %	0	
Non-fatal accident[c]						
Number	29	14	17	0	2[d]	62
Percentage male	100 %	23 %	45 %		100 %	

[a] Helper: nurse, assistant, technician, physicist

[b] *Within parentheses* the number of times the age was specified

[c] Virtually no data on the age of this group were found; 26 persons (of 62) became unconscious

[d] One fireman and one unknown

all accidents (only two cases clearly involved inductors). The following situations of a person coming into electrical contact with a high-voltage power supply were most prevalent. These are discussed in more detail in Appendix 7 [60].

1. Person isolated, secondary coil of transformer floating. Negligible risk.
2. Person grounded, secondary of transformer floating. Small risk if not-grounded part of secondary can stand full output potential, generally the case for low high-voltages.
3. Person grounded, secondary of transformer floating, but voltage is now so high that insulation cannot stand full output potential and a shortcut in the apparatus results. High risk (possibly with fatal outcome).
4. Transformer has a secondary coil with a central tap that is grounded. Very high risk.
5. Person comes into contact with both poles of supply. Very high risk.

Discussion

This overview commemorates the human toll paid during the development of the electrically shockproof X-ray systems we take for granted today. This process lasted the first four decades after the inception of radiology. In this period, but also thereafter until all unsafe systems were replaced by shockproof units, many people died or were seriously injured by electrical accidents. A possible explanation for the complete lack of recent attention for this suffering is that X-ray systems have now been fully electrically shockproof for several decades.

The data on fatal and severe electrical accidents indicates that their rate increased sharply around 1920. It illustrates, therefore, that the introduction of the transformer in 1907, the autotransformer in 1909, and the introduction of the Coolidge tube in 1913 did not immediately lead to more serious hazards. Apparently, the increase in accidents involving the transformer-Coolidge tube combination beginning around 1920 was a function of its wider use and possibly some further increase in electrical power. Transformers with a connection of the secondary coil to ground were especially dangerous. The high risk of the more powerful transformer systems used for imaging becomes immediately evident upon comparison of the currents (Table 3) with the thresholds for ventricular fibrillation (Table 2). Note that during a short circuit the currents were even higher. After 1940 the accident rate diminished due to the more general introduction of electrically shockproof systems starting around 1935. New regulations stimulated this process. The risk of induction coils was generally small, but not zero, as a comparison of Supplementary Table S4 (Appendix 2) and Table 2 indicates.

Table 5 Body part touching high tension or sparked at by high tension

	Arm/hand	Head	Shoulder/body	Leg	Unknown	Total
Fatal accidents	20	3	6	0	22	51
Non-fatal accidents	21	10	2	7	22	62

Table 6 X-ray procedure performed during accident

	Fluoroscopy & radiography	Dental	Therapy	Other & unknown	Total
Fatal accidents	24	8	3	16	51
Non-fatal accidents	34	10	3	15	62

In total we succeeded in finding data on 51 fatal and 62 non-fatal accidents. The fact that nearly 33 % of the fatal and 79 % of the non-fatal accidents were only found in a single source indicates that the accidents were not greatly publicised. Grossmann noted in 1933 that of 26 (fatal and non-fatal) accidents known to him, 13 were mentioned in scientific journals and only five in newspapers. He blamed "a certain shyness for publicity" in the case of more severe incidents [38]. It seems safe to conclude that there must be many more cases, reported and otherwise, than we were able to recover.

Nearly half of all deaths and injured persons were medical doctors, all male. Only nine of the deaths are in the *Ehrenbuch*, the book of honour containing the names of people who died for the advancement of radiology [1]. The victims who lost their life were only 35 years old on average when all groups are taken together. Among the patients were three young children. Diagnostic imaging (excluding dental imaging), i.e. fluoroscopy, radiography or a combination of the two, comprised 71 % of cases of the group of accidents for which sufficient information was available. This is of no surprise as fluoroscopy had to be done in the dark and frequent adjustments in tube position and the setting of the diaphragm were required. Relatively few accidents occurred during therapy. The body parts that most often came into contact with a live part of the X-ray system were the hand and arm. Several shocks to the head resulted from bending towards the tube or its wires while supporting a patient. As discharges took place before a body part made physical contact with a live part of the system, many reports of accidents mentioned their occurrence. The improper training of X-ray operators was also frequently reported.

Electric shocks in the first 2 decades of radiology were not uncommon, but as there were no dire consequences of shocks at that time due to the limited electrical power of static machines and induction coils, the risk they posed was an accepted element of the profession [4, 38, 39]. Awareness grew with the rate of more severe accidents. A medical doctor, Pansdorf, who survived a severe electrical shock, reported his experience during fluoroscopy: "…suddenly I didn't see any more of the fluoroscopic image, but felt a contraction of the upper body and had the feeling that my thorax would be pulled apart. … I saw a flash at my left hand, with which I had operated the diaphragm, but could not let go, as my hand had closed convulsively. A metal taste developed on my tongue, and I had the feeling that I had to die that moment, without being able to call for help. A heavy load pushed me down, and I heard the rattling of my own breath. The whole lasted several seconds, and I still felt how I collapsed." A colleague switched off the system. Although Pansdorf was momentarily knocked unconscious and suffered for some time from injuries and physical shock, he recovered completely [61].

Such experiences, and fatal accidents, led to regulations to improve electrical safety. It also spurred X-ray manufacturers to improve their systems. By 1935 nearly all new systems were electrically shockproof. Two important developments that facilitated this transition were the introduction of the Coolidge hot cathode tube in 1913 and the development of flexible shielded high-voltage cable a few years before 1930. The first replaced the erratic gas tube that required more or less continuous surveillance, frequent tube exchanges and thus easy access. The Coolidge tube was more reliable and high-voltage and tube current could be adjusted independently. Ironically, it was also these latter characteristics and the higher loadability which had led to more dangerous systems. Later, the reliability of the Coolidge tube allowed its placement in a well-shielded housing, giving protection against radiation and electrical shock. The flexible high-voltage cable made the complicated and dangerous conducting system between power supply and X-ray tube obsolete.

To conclude, the development of completely electrically safe X-ray systems was a remarkable success of human endeavour in which all participants in the field played a role. It is astonishing from a modern perspective that the risks assumed by operators and patients and the many accidents they suffered were tolerated for decades. However, it speaks to the significant diagnostic and therapeutic advantages X-ray offered that their use was not suspended. The technology, procedures and legislation that resulted from the effort to eliminate electrical risks extended beyond the field and contributed to the growing culture of safe practices. The achievement of the electrically safe X-ray system served as reparation to the many martyrs in the history of radiology.

Acknowledgments The authors thank Mrs. M. Radau for help in retrieving historical material, Dr. D.O. Cuscela for providing illustrative photographs and Professor J. Grzywacz for information on electrical safety legislation in the USA.

References

1. Molineus W, Holthusen H, Meyer H (eds) (1992) Ehrenbuch der radiologen aller Nationen. Blackwell Wissenschaft, Berlin. Earlier editions appeared in 1937 and 1959
2. Meggitt G (2008) The early years of X-rays. In: Taming the rays: a history of radiation and protection. Lulu.com, Raleigh, pp 1–21
3. Herzig R (2001) Suffering, sacrifice, and the formation of American roentgenology. Am Q 53:563–589
4. Gunther ML (1919) Précautions à prendre dans les installations radiologiques intensives. J Radiol Electrologie 3:544–545
5. Shearer JS (1920) Electrical dangers in X-ray laboratories. AJR Am J Roentgenol 7:432–439
6. Hemler WF (1922) High tension electric shocks in roentgenologic practise. AJR Am J Roentgenol 9:365–370

7. National Electrical Code (NEC) Regulations. National Board of Fire Underwriters, New York (1931)
8. DIN RÖNT 1. Vorschriften für den Hochspannungsschutz in medizinischen Röntgenanlagen. Deutsche Röntgen-Gesellschaft, Fachnormenausschuβ Krankenhaus, Verband Deutscher Elektrotechniker E.V. (1930) Beuth, Berlin
9. Grigg ERN (1965) The trail of the invisible light. Charles C Thomas, Springfield
10. International Electrotechnical Commission. Effects of current on human beings and livestock. Part 1. General aspects. IEC/TS 60479–1. Edition 4 2005–7
11. International Electrotechnical Commission. Effects of current on human beings and livestock. Part 2. Special aspects. IEC/TS 60479–2. Edition 3 2005–7
12. Olson W (1998) Electrical safety (Chapter 14). In: Webster JG (ed) Medical instrumentation, 3rd edn. John Wiley & Sons, New York
13. Chemical Rubber Company (1969) Spark gap voltages. In: CRC handbook of chemistry and physics, 50th edn. Chemical Rubber Company, Cleveland, p E61
14. Nisbet AT (1929) A case of burn from high-voltage current. AJR Am J Roentgenol 22:158
15. Eisenberg RL (1992) Radiology: an illustrated history. Mosby, St Louis
16. Gray J (1890) Electrical influence machines. Whittaker, London
17. Graetz L (1918) Handbuch der Elektrizität und des Magnetismus. Band I. Elektrizitätserregung und Elektrostatik. Barth, Leipzig
18. Wehrsen A (1913) Neue Starkstrommaschinen. Catalog, Berlin
19. Wagner RV (1907) Catalogue of electrical instruments for physicians and surgeons. Chicago
20. Kassabian MK (1910) Röntgen rays and electro-therapeutics, 2nd edn. JB Lippincott, Philadelphia
21. Kaye GWC (1922) The practical applications of X-rays. Chapman & Hall, London
22. Wommelsdorf H (1912) Verbesserungen an Kondensatormaschinen. Ann Phys 39:1201–1206
23. Armagnat H (1908) The theory, design and construction of induction coils. McGraw Publishing, New York
24. Salomonson W (1920) Discussion on the papers by Morton, Phillips and Wright. J Inst Electr Eng 58:732–735
25. Morton ER (1915) A text-book of radiology. EB Treat & Co, New York, p 111
26. Morton R (1920) The efficiency of high-tension transformers as used for X-ray purposes. J Inst Electr Eng 58:719–726
27. Phillips CES (1920) Problems of interrupted and fluctuating currents. J Inst Electr Eng 58:727–729
28. Crowther JA (1922) The principles of radiography. J & A Churchill, London, p 100
29. Donath B (1903) Die Einrichtungen zur Erzeugung der Roentgenstrahlen, 2nd edn. Von Reuther & Reichard, Berlin
30. Dessauer F, Wiesner B (1905) Kompendium der Röntgenographie. Otto Nemnich, Leipzig
31. Albers-Schönberg HE (1906) Die Röntgentechnik, 2nd edn. Lucas Gräfe & Sillem, Hamburg
32. Ruhmer EW (1904) Konstruktion, Bau und Betrieb von Funkeninduktoren und deren Anwendung, mit besonderer Berücksichtigung der Röntgenstrahlentechnik. Hachmeister & Thal, Leipzig
33. Taylor JE (1932) Induction coil—theory and applications. Pitman & Sons, London
34. Coolidge WD (1920) Oil-immersed X-ray generating outfits. AJR Am J Roentgenol 7:181–190
35. Bouwers A (1928) A new X-ray apparatus with complete X-ray and electrical protection. Acta Radiol 9:600–605
36. Meyer WM (ca. 1914–1915) Meyer interrupterless apparatus. WM Meyer, Chicago
37. Grashey G (1941) In: Grashey G (ed) Röntgendiagnostische Geräte und Anlagen, Chapter 4, Albers-Schönberg HE—Die Röntgentechnik, vol I, 6th edn. Thieme, Leipzig
38. Grossmann G (1933) Elektrische Unfälle. Röntgen praxis 5:269–286
39. Grossmann G (1933) Elektrische Unfälle (Schluβ). Röntgen praxis 5:354–363
40. Green H (1910) Clover leaf tube pointers. Green & Bauer, Hartford
41. General Electric Company (1924) Coolidge X-ray tube. Instruction book 89136B. General Electric Company, Schenectady, NY, 1920. Additional information. In: Jerman C (ed) (1928) Modern X-ray technic. Bruce Publishing, St. Paul-Minneapolis
42. Kemerink M, Dierichs TJ, Dierichs J, Huynen HJ, Wildberger JE, van Engelshoven JM, Kemerink GJ (2011) Characteristics of a first-generation X-ray system. Radiology 259:534–539
43. Coolidge WD (1913) A powerful Röntgen ray tube with a pure electron discharge. Phys Rev 2:409–430
44. Aubert L (1898) La photographie de l'invisible—les rayons X. Schleicher Frères, Paris
45. American X-Ray Equipment Co. Catalogue A (1915) Dental X-ray apparatus and accessories. American X-Ray Equipment Co., New York Chicago
46. Albers-Schönberg HE, Seeger F, Lasser I (1915) Das Röntgenhaus des Allgemeinen Krankenhauses St. Georg-Hamburg, errichtet 1914/1915. Von F. Leineweber, Leipzig
47. Wappler Mobile Unit, advertisement (1923) Radiology 1:XX
48. Hofman JAM (2010) The art of medical imaging. Koninklijke Philips Electronics NV, Eindhoven
49. Campbell Electric Co. (1920) Trolleyless Clinix X-ray plant. Lynn, Mass
50. Fritsch E (1928) Die Beseitigung der Hochspannungsgefahr im Röntgenbetriebe durch den "Securo". Strahlentherapie 28:810
51. Sarsfield LGH (1934) Safety measures in X-ray work, including high-voltage flexible cables. J Inst Electr Eng 75:253–270
52. Levy DM (1929) Eenige opmerkingen over de beveiliging tegen hoogspanningsgevaar in het röntgenlaboratorium. Ned Tijdschr Geneeskd 73:3206–3211
53. Albers-Schönberg HE (1913) Die Röntgentechnik, 4th edn. Lucas Gräfe & Sillem, Hamburg
54. Case JT (1921) Death of Dr. F. Jaugeas. AJR Am J Roentgenol 7:167–168
55. Christie AC (1921) New committees. AJR Am J Roentgenol 8:204
56. Imboden HM (1923) Report of the safety committee presented at the Los Angeles Meeting of the A.R.R.S. Am J Roentgenol Radium Ther 10:246–247
57. Warnshuis FC (1936) Concerning an imaginary law demanding shockproof X-ray rooms. Cal West Med 44:136
58. Jellinek S (1931) Der elektrische Unfall, 3rd edn. Franz Deuticke, Leipzig
59. Kleibeler B (1965) Tödliche Hochspannungsunfälle beim Umgang mit Röntgenapparaten für medizinische Zwecke, Inaugural-Dissertation an der Medizinischen Fakultät der Freien Universität, Berlin
60. Wetterstrand GA (1925) A roentgen accident with a fatal result through the short-circuiting of the secondary current. Acta Radiol 5:105–108
61. Pansdorf H (1930) Starkstrom- und Hochspannungsschäden im Röntgenbetriebe. Roentgenpraxis 2:359–366