Radiology

Characteristics of a First-Generation X-Ray System[1]

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Purpose: To compare the antiquated x-ray system of Hoffmans and van Kleef (circa 1896) with modern x-ray equipment in terms of radiation dose, x-ray beam properties, image quality, and electrical parameters.

Materials and Methods: The antiquated x-ray system consisted of a Ruhmkorff inductor, battery, and Crookes tube. The radiation dose rate, x-ray beam properties, and electrical characteristics of this system were determined. A modern computed radiography plate was used to compare images of a hand specimen obtained by using the antiquated system with images obtained by using the modern system.

Results: A peak voltage of 73 kV was obtained with an 8-V battery. With Crookes tube number 9, the half-value layer of the generated x-rays was 0.56 mm Al. Pinhole images showed that the x-rays originated from an extended area of the glass wall, causing image blurring. When measured on the skin of a hand specimen, the radiation dose of the antiquated system was about 10 times greater than that of the modern system for the same detector signal. The estimated skin dose was about 74 mGy for the antiquated system and 0.05 mGy for the modern system. The corresponding exposure times were 90 minutes and 21 msec.

Conclusion: Radiation dose and exposure time of the antiquated system were greater than those of the modern system by about three and five orders of magnitude, respectively. Images of the hand specimen obtained with the antiquated system were severely blurred but were still awe inspiring, considering the simplicity of the system.

Supplemental material: *http://radiology.rsna.org/lookup/suppl/doi:10.1148/radiol.11101899/-/DC1*

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On December 28, 1895, Wilhelm Conrad Röntgen reported his discovery of x-rays (1). Approximately 1 month later, Hoffmans and van Kleef used this new technology to acquire images of human anatomy in Maastricht, the Netherlands (2). Hoffmans was a physicist and high school director, and van Kleef was a medical doctor and director of the local hospital. More personal details are given in Appendix E1 and Figure E1 (online). The x-ray system they used was assembled with instruments that were part of the inventory of the high school.

Like many workers in the field, we were intrigued by these first imaging efforts that were performed with equipment that was not designed for such a purpose. What was it like to perform such experiments? What were the characteristics of the systems and the x-rays that they generated? What was the radiation dose? Adverse effects among users of x-ray systems and those who underwent imaging were reported within weeks of the experiments (3–5). Many excellent books and reviews that deal with the history of x-ray imaging are available (4–8); however, to our knowledge, no quantitative data about radiation dose and other properties of the first x-ray systems exist.

Since many of the instruments available to Hoffmans and van Kleef still work, permission was granted to repeat some of their first imaging studies with the original equipment. We performed experiments to compare the 1896 system with modern x-ray equipment in terms of radiation dose, x-ray beam properties, image quality, and some electrical parameters.

Advances in Knowledge

- The first-generation x-ray system produced soft radiation: the half-value layer was 0.56 mm Al for a pulsed high voltage of 73 kV.
- For the same radiation dose on the detector below the object, the skin dose needed to image a hand in 1896 was about 10 times higher than that needed with a modern system with use of 45 kV and a 3.5-mm Al filter.
- With use of the same exposure conditions used in 1896, the skin dose needed to image the hand was about 74 mGy; this was approximately 1500 times greater than that needed with a modern system.
- The exposure time needed to image the hand decreased from 90 minutes in 1896 to about 20 msec in 2010.

Materials and Methods

The setup shown in Figure 1 represents the first generation of x-ray imaging systems; later that year, several improvements had already been introduced (4,5,7). The 0.05-Ω resistor was inserted temporarily to measure the current drawn from the batteries. The transformer, capacitor, interrupter, and spark gap are part of one unit, the Ruhmkorff inductor (Appendix E2, Figure E2 [online]). The values of various electrical components (Fig 1b) were measured (Table 1).

We followed the example of Hoffmans and van Kleef (2) and used Crookes tube numbers 1 and 9 (9), as shown in Figure 1b. Both tubes had one electrode in the form of a disk (the cathode) and one or two electrodes in the form of a thin pin (the anode). The second anode present in Crookes tube number 1 was not used.

The batteries were new and of the lead acid variety, and they gave off about 2 V per cell; in the original experiments, Bunsen elements of 1.9 V per cell were used (2). We used four cells in series, as in the original report (about 8 V in total). The unloaded secondary high voltage was estimated by using the integrated needle-plate spark gap, as well as the more accurate version with spheres. In all experiments, we set the integrated spark gap at 110 mm, just as Hoffmans and van Kleef had done.

We measured the attenuation of x-rays in Al to characterize beam hardness by half-value layer thickness. We used thin MCP-N thermoluminescence dosimeters (TLD Poland, Krakow, Poland) to ensure that we correctly measured the contribution of the soft components of the x-rays. We also measured the high-energy part of the x-ray spectrum with an NaI(Tl) scintillation detector (Thyroid Uptake System; Canberra, Zellik, Belgium) and a beam filter of 0.3 mm Cu and 0.5 mm Al.

To estimate the clinical radiation dose and to evaluate image quality, we repeated Hoffman and van Kleef's test number 8 from January 31, 1896, in which they imaged the hand of "a young lady" (2) who was in fact the 21-year-old daughter of van Kleef. We used a hand specimen instead. During this test and several other experiments, we assessed the dose rate by using MCP-N thermoluminescence dosimeters, TLD-100 dosimeters (Harshaw, Solon, Ohio), and electronic personal dosimeters (EPD Mk2; Thermo Scientific, Waltham, Mass). We also used the TLD-100 and electronic personal dosimeters for occupational dosimetry during the experiments.

The x-ray focus was imaged with a 2.5- or 5-mm-diameter pinhole in a 2-mm-thick sheet of Pb. We used images of the hand specimen to qualitatively compare image quality of the 1896 system with that of the modern equipment (Bucky Diagnost with Optimus Generator; Philips, Best, the Netherlands). With the modern system, we used our standard x-ray protocol for a hand (45 kV; filtration, 3.5 mm Al; 5 mAs; focus-detector distance, 1 m). The entrance dose was determined with TLD-100 dosimeters. The image receptor was, in all

Published online before print
10.1148/radiol.11101899

Radiology 2011; 259:534–539

Author contributions:
Guarantors of integrity of entire study, M.K., J.M.A.v.E., G.J.K.; study concepts/study design or data acquisition or data analysis/interpretation, all authors; manuscript drafting or manuscript revision for important intellectual content, all authors; manuscript final version approval, all authors; literature research, T.J.D., J.M.A.v.E., G.J.K.; experimental studies, M.K., T.J.D., J.D., H.J.M.H., J.M.A.v.E., G.J.K.; statistical analysis, T.J.D., G.J.K.; and manuscript editing, all authors

Potential conflicts of interest are listed at the end of this article.

See also the editorial by Gunderman and Tritle in this issue.

cases, a modern storage phosphor plate (Kodak GP Direct View digitized on a Kodak CR 975 reader; Carestream Health, Rochester, NY).

The x-ray experiments in the hospital were performed in an electrically shielded room (Faraday cage) because a sparking Ruhmkorff coil emits a broad spectrum of electromagnetic radiation that might affect sensitive patient monitoring systems and other equipment. The x-ray tube was placed behind a shield (Fig 1a).

Table 1

Values of the Electrical Components of the 1896 Ruhmkorff Inductor

Component	Capacity (μF)	Inductance (H)	Resistance (Ω)
Capacitor	7.3	NA	386×10^3
Primary coil transformer	NA	6.8×10^{-3}	0.20
Secondary coil transformer*	NA	1900	66×10^3

Note.—NA = not applicable.

* Only for order of magnitude. These values are for a slightly newer Ruhmkorff coil (F Ernecke, Berlin, Germany). Values for original unit could not be measured because of a bad internal contact, which had a negligible effect at high voltage.

Figure 1

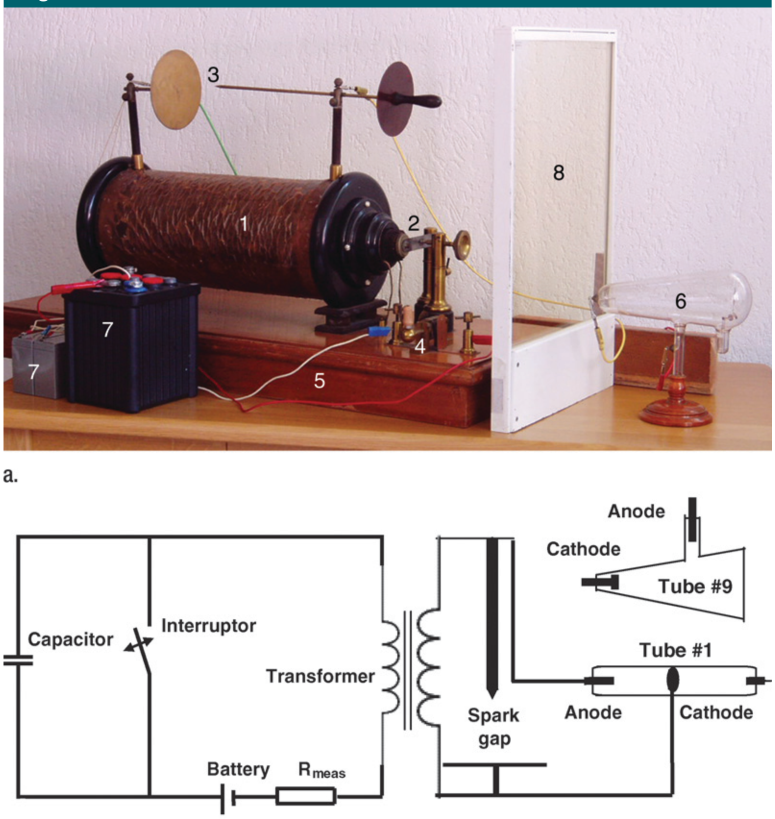

Figure 1: **(a)** Photograph of the x-ray system as it appeared in January 1896, including the Ruhmkorff inductor (C Gerhardt, Bonn, Germany), and consisting of the transformer *(1)*, interruptor *(2)*, spark gap *(3)*, switch *(4)*, and large foil capacitor integrated in the instrument base *(5)*. Also shown are Crookes tube number 9 *(6)*, modern batteries *(7)*, and the transparent lead shield *(8)* we used. **(b)** Schematic drawing shows simplified electrical scheme of Ruhmkorff inductor with Crookes tubes number 1 and number 9 (9). R_{meas} = 0.05-Ω resistor.

Results

For a battery voltage of 8.4 V, the maximum spark length in air was measured with 90-mm-diameter spheres, yielding a length of 26 mm. From this measurement, a peak voltage of 73 kVp was calculated (10). Discharges between the plate-needle spark gap of the system started slightly below 110 mm, corresponding to approximately 80 kV (10). The high voltage is not sharply defined by the latter method; nevertheless, this spark length was initially the standard way of specifying the high tension of the system. Figure 2 shows some discharges within the plate-pin spark gap.

The loaded circuit consumed 20 W of power. Figure 3 shows the voltage over the primary coil of the transformer. The transformation ratio (R_t) of approximately 500 (73 kV/150 V ≈ 500) corresponds well to the value obtained from the estimated inductances of the secondary (L_s) and primary (L_p) coils as $R_t = \sqrt{(L_s/L_p)}$. The x-ray pulse frequency was approximately 20 Hz, and the duration was approximately 2 msec. The damped oscillation of the primary circuit current is the common behavior of a resonance circuit and has the expected frequency of approximately 700 Hz ($2\pi/\sqrt{[LC]} \approx 700$ Hz), with L being the inductance and C being the capitance given in Table 1.

Figure 4 shows the broad-beam transmission of x-rays through Al. The transmission (T) was determined from the ratio of the entrance and exit doses measured with the MCP-N thermoluminescence dosimeters. The logarithm of the transmission (ln[T]) could be fitted with the expression $\alpha(e^{-\beta d}-1)$, where d is the thickness of Al, resulting in α of 6.38 and β of 0.21 mm^{-1}. The logarithm of the transmission does not decrease linearly with distance due to beam hardening and build-up. The first half-value layer was 0.56 mm Al, corresponding to a monoenergetic (effective) energy of about 18 keV. Thus, the x-rays were soft. The x-ray spectrum measured with the scintillator detector showed that nearly all x-rays had

Figure 2

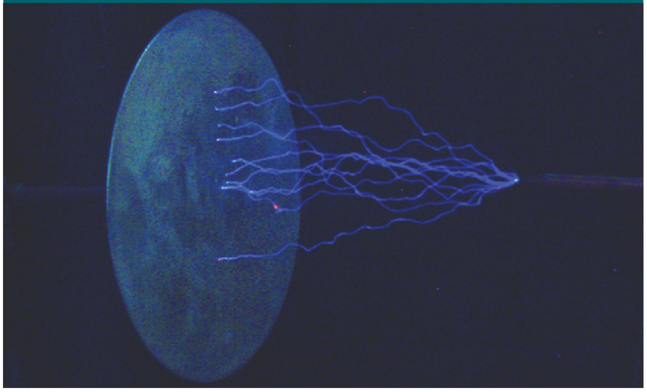

Figure 2: Photograph with a long exposure time shows disruptive discharges over the spark gap. This spark gap is used as a simple high-voltage meter and voltage limiter.

Figure 3

Figure 3: Signal trace on a cathode ray tube of an oscilloscope shows voltage over the primary coil during imaging. Horizontal axis scale is 10 msec per division, while the vertical axis scale is 50 V per division. Interruption of the primary coil occurs just before the large negative peaks; the transformer amplifies these approximately 150-V peaks to approximately 73 kV.

less than 40 keV of energy (Appendix E3, Figure E3 [online]). However, a low-intensity tail extended to about 70 keV, which corresponded well to the estimated high voltage of 73 kV. The power consumption of the system (20 W) limits the time-averaged tube current at 73 kV to a theoretical maximum value of about 0.3 mA; however, due to various losses, it is likely to be considerably lower.

Figure 5 shows pinhole images and photographs of the operational x-ray sources. The alligator clip marked the orientation of the symmetrical Crookes tube number 1. As already known to Röntgen and Hoffmans and van Kleef, the x-rays originate mainly from the greenly fluorescing glass wall. Reversal of battery polarity stopped x-ray generation.

Images obtained with the hand specimen placed directly on the computed radiography plate are shown in Figure 6. The exposures are compared in Table 2. Experiments in which we used the slightly newer Ruhmkorff coil together with Crookes tube number 1 yielded similar results (Appendix E4; Figures E4, E5 [online]).

The average dose rate in air during our experiments was 0.86 mGy/min ± 0.08 (standard deviation) at 10 cm from the tube center; our occupational dose was zero.

Discussion

Besides x-rays, there have been few, if any, discoveries in physics that have resulted in practical applications with an enormous societal impact within months of the discovery. The rapid introduction of this technology was made possible by the presence of the tools

Figure 4

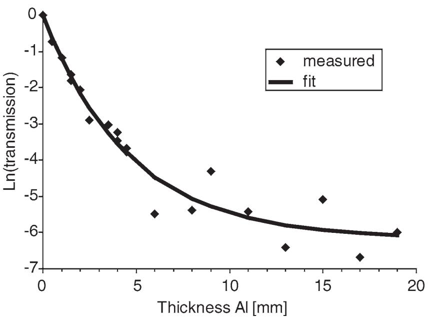

Figure 4: Graph shows broad-beam transmission of x-rays generated by Crookes tube number 9 through Al.

required to produce x-rays in many schools and universities, where they were used to study cathode rays, canal rays, gas discharges, fluorescence, phosphorescence, and—at times—for simple amusement.

We found that setting up the x-ray system was easy, as was generating spectacular sparks in air. Crookes tube number 9 produced x-rays from the start; however, Crookes tube number 1 did not, despite the presence of a gas discharge. However, we slowly increased the primary voltage over the Ruhmkorff coil to 18 V, at which point there was suddenly some flashing in the tube; thereafter, x-ray generation started. It turned out that a small part of the top of the anode pin had unintentionally melted. The molten metal, probably Al, will have gettered part of the gas. It is likely that the vacuum in the tube had worsened over the years by degassing of the glass, leading to a too-short mean free path for electrons to accumulate the energy necessary to generate bremsstrahlung. It was a known and serious problem to maintain a usable gas pressure (approximately 0.01–0.1 Pa) in these tubes (Appendix E5 [online]) that was solved only with introduction of the hot cathode in 1913.

In the tubes of the first-generation x-ray systems, radiation originated mainly from the glass wall, and this x-ray focus was large. For the tubes in our recreation, this was evidenced by the pinhole images in Figure 5. The large focus and the fact that the hand had stiffened with the fingers in adduction, thereby resulting in a relatively large distance of most bones to the computed radiography plate, led to an unsharp image of the hand. With the clinical system, this was not a problem because the focus was much smaller, of the order of 1 mm^2, and much farther away.

X-rays produced with the first-generation system were found to be soft, with a half-value layer of 0.56 mm Al, as compared with a measured value of 3.2 mm Al for the modern system at 73 kVp with a nominal filter of 3.5 mm Al. The softness can be explained by the lack of additional filtration, the distribution of electron energies toward lower values due to the finite free electron path length, the tube potential taking all values between zero and the peak voltage, and a somewhat lower terminal voltage due to loading. This interpretation appears to be consistent with the measured x-ray spectrum. The softness of the x-rays led to a relatively high skin dose, which was approximately 10 times higher than that of the modern system. In addition, the use of photographic plates in the early days of radiography required a further increase in the radiation dose, resulting in a total increase of about 1500 (Table 2). A modern image receptor like the storage phosphor plate is thus more than 100 times more sensitive than the photographic plate from 1896. It should be noted, however, that the x-ray output and radiation quality could vary greatly because of unpredictable variations in the gas pressure. Hence, there was always the risk of under- or overexposing the photographic plate.

Doses at which deterministic skin effects might start were not readily reached with this first-generation system: at 10 cm, it would take nearly 400 hours to incur a dose of 2 Gy. However, soon thereafter, a metal (Pt) anode was used in combination with more powerful generators, and unfortunate incidents became all too common (3–5).

Figure 7 summarizes the characteristics of x-ray systems of 1896 and 2010. Typical characteristics of the first-generation x-ray system are a large focus, the emission of radiation with a soft component, and a low output. The most noticeable property of a modern

Figure 5

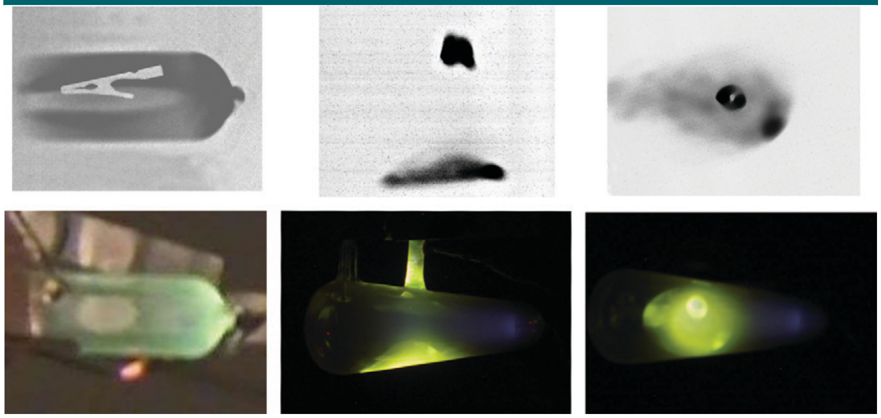

Figure 5: Pinhole radiographs (top) and photographs (bottom) of Crookes tubes number 1 (left) and number 9 seen from the side (middle) and top (right). Note the similarity between the regions with fluorescence and x-ray emission. Imaged objects were below the tubes, as shown in the bottom left and bottom middle images.

Figure 6

Figure 6: Images of the hand specimen of an 86-year-old woman obtained with Crookes tube number 9 (left) and a modern x-ray system (right). In both cases, the image receptor was a modern computed radiography plate. The exposure time with the 1896 system was 21 minutes, and the distance from the imager to the hand was 46 cm. With the modern system we used the following settings: 45 kV, 3.5-mm Al filtration, 5 mAs (225 mA, 21 msec), and 1 m between the hand specimen and the imager.

Table 2

Comparison of Exposure Parameters Used to Obtain a Radiograph of a Human Hand

Parameter	1896 System	Modern System	Ratio
Skin dose (mGy)			
Storage phosphor plate on both systems*	0.6	0.05	12
Original conditions (including photographic plate)†	74	…	1472
Exposure time	90 min	21 msec	257000

* Normalized to same average detector signal below hand (11).

† Calculated from present exposure correcting for distance and exposure time in Hoffmans' experiment number 8 (2).

Figure 7

January 1896	December 2010
Tube	
Evacuated glass bulb with some residual gas	High vacuum
Gas discharge generates free electrons and ions	Electrons come from heated filament
X-rays from glass wall surrounding anode	Anode is tungsten disk
X-ray focus is 10–100 cm^2	X-ray focus is approximately 1 mm^2
Permissible load of the order of watts	Permissible load of the order of kilowatts
No filtering of x-rays, except by glass wall	Typically ≥2.5-mm-thick aluminum filter
Exposure time of minutes to hours	Exposure time of milliseconds to seconds
High-Voltage Generator	
Battery and Ruhmkorff inductor	Main and medium-frequency generator
High voltage in the form of short spikes	High voltage that is nearly constant
Power consumption of 20 W	Power consumption up to 100 kW
High voltage estimated from spark length	High voltage measured electronically
Detector	
Screenless photographic plate	Flat panel detector/storage phosphor plate

Figure 7: Chart shows comparison of the 1896 x-ray system with a modern x-ray system.

system is the extremely high power density the focus of the x-ray tube can withstand, enabling one to obtain sharp images with a short exposure time.

Our experience with this machine, which had a buzzing interruptor, crackling lightning within a spark gap, and a greenish light flashing in a tube; which spread the smell of ozone; and which revealed internal structures in the human body was, even today, little less than magical. Clearly, this technique left ample room for improvement. In the following century, the image quality and nearly all components of the x-ray system were greatly improved. Simultaneously, radiation dose and exposure time were lowered by three and five orders of magnitude, respectively, turning x-ray imaging into a convenient and safe modality.

Acknowledgments: The authors dedicate this study to the Museum Club Maastrichtse Nutsbedrijven of retired electrical engineers who maintained a large collection of historic instruments, including those used in this study. They further thank the city of Maastricht for making the equipment available; A. Lataster, MSc, from the Department of Anatomy and Embryology, Maastricht University Medical Center, for use of the hand specimen; and H. Kingma, PhD, M.J. Frantzen, and G. Mulkens for their highly appreciated help.

Disclosures of Potential Conflicts of Interest: M.K. No potential conflicts of interest to disclose. **T.J.D.** No potential conflicts of interest to disclose. **J.D.** No potential conflicts of interest to disclose. **H.J.M.H.** No potential conflicts of interest to disclose. **J.E.W.** Financial activities related to the present article: none to disclose. Financial activities not related to the present article: received payment for lectures and scientific courses from Bayer Schering Pharma, Boston Scientific, and GE Healthcare; institution received payment for lectures and scientific courses from Bayer Schering Pharma, Boston Scientific, and GE Healthcare. Other relationships: none to disclose. **J.M.A.v.E.** No potential conflicts of interest to disclose. **G.J.K.** No potential conflicts of interest to disclose.

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