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| 論　文　名 | 「Establishment of radiation safety management guidelines for Crookes tubes used in the teaching of science（学校教育現場で用いられるクルックス管の放射線安全管理ガイドラインの確立）」 |
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# 論文要旨

Crookes tube is the oldest fundamental X-ray device that was used by Roentgen to start the study of radiation. It is a type of discharge tube, usually used with an induction coil as a power supply. By applying a voltage of several tens of kV between the cathode and the anode in the tube, the cations in the evacuated tube are accelerated to hit the cathode, which knock out secondary electrons. These electrons emitted by the cold cathode are accelerated to collide with the glass tube to create a bremsstrahlung X-ray.

In Japan, the curriculum guidelines demand to use Crookes tubes for observation of electricity and current in the second year of junior high school, and all five science textbooks contain information about Crookes tubes. In addition, due to the revision of the curriculum guidelines in March 2017, a content of understanding the nature of the radiation associated with the vacuum discharge was newly added, and further utilization of the Crookes tube has been required. Currently, many teachers are demonstrating on Crookes tube in a science class. But they do not know that the X-rays emitted from the Crookes tube owing to lack of radiation education in school for a long time. Practically, teachers and students may be exposed to X-ray radiation during a demonstration. Some studies showed that Crookes tubes emitted X-rays with very low energy (approximately 20 keV) but the 1 cm dose equivalent, $H_p(10)$, was remarkably high (up to 143 mSv/h at 5 cm). It caused a maximum dose ($H_p(10)$) of 0.15 mSv per experiment for students, which is higher than the recommended value in ICRP publication 36.

The X-rays emitted from the Crookes tube can be used as highly educational contents if it is used properly. Even if the Crookes tube is in such use, radiation safety must be ensured. However, radiation protection and safety guidelines have not yet been evaluated sufficiently to date. Basing on that urgency, the “Crookes tube project” has been launched nationwide in Japan by volunteer scientists since May 2017, and it is achieving the goal at a fast speed. The project aims to establish and promulgate the radiation safety management guidelines on Crookes tube at educational sites. This thesis involved a variety of tasks in the “Crookes tube project” and performed the following findings:

- Measurement: X-ray energy spectrum, electric operational parameters, dose spatial distribution,
- Evaluation: equivalent dose, the relevance between the dose and operating conditions.
- Protection: ALARA principle in radiation protection, improving operating conditions of equipment, improving in usage,
- Recommendation: provisional guidelines to manage radiation safety.

In Vietnam, although radiological education added to high school curricula tens of years ago, there was not a practical lesson of Crookes tube in the teaching of science. Practically, actual learning has a better learning effect than via video or theory. The research in the thesis is the premise for the application of the Crookes tube in teaching science in Vietnam future.

Chapter 1 introduced general information about the history of the Crookes tube, its applications in teaching science, and the "Crookes tube project" in Japan. The Crookes tube is a device that plays a prominent role in talking about the history of radiation in science class. This chapter also presented the essentials of the Crookes tube project, progressing works, and involving tasks.

Chapter 2 presented characteristics of low-energy X-ray radiated from a Crookes tube used in the teaching of science. This chapter investigated the following parts: (a) the X-ray energy emitted from the Crookes tube; (b) electrical parameters and the correlation of operation factors to the characteristics of output X-ray spectrum; (c) leakage dose; (d) transmission of X-rays. To estimate the effectiveness of operational conditions to the output X-ray spectrum, the Crookes tube operated with various applied voltages from the induction coil. Since the Crookes tube emitted very low energy X-rays, all X-ray spectra were acquired with a high-performance X-ray and gamma-ray CZT detector. A handcrafted collimator kit was used to reduce the pile-up effect due to the high intensity of X-rays. The induction coil generated unstable voltage with a pulse-shaped width of 20 μs. The inhomogeneous high-voltage pulses were measured by a digital oscilloscope, and a voltage divider circuit was used to avoid damaging the oscilloscope's probes. The effective energy of X-rays was approximately 20 keV, and the applied voltage was in the range of 16 kV – 40 kV. The distribution of the peak energy matched well with the distribution of the most frequent voltage. In addition, the attenuation measurement estimated the transmission of X-rays through Al layers. The effective energy was interpolated from the attenuation coefficient showed a good agreement with the results obtained by the CZT detector. The present results indicated that effective energy and exposure increased with the increase of the applied voltage. However, the energy and dose were limited when the in-air spark occurred between the electrodes on the induction coil. It was found that the distance between the discharge electrodes controlled the effective energy and also dose.

Chapter 3 investigated the dose distribution from the Crookes tube using thermoluminescent dosimeters. During the demonstration, the leakage dose might cause exposure to participants, but the characteristics of dose distribution was an ambiguous factor. In this chapter, the dose spatial distribution of X-rays surrounding the Crookes tube was estimated using thermoluminescent dosimeters (TLDs) and obtained the 70 μm dose equivalent, $H_p(0.07)$. The results in the present study characterize and map the spatial dose distribution of the Crookes tube. It indicates where is the minimum exposure position to prevent radiation hazards. To evaluate sufficiently the inhomogeneous radiation field, 2-D measurement of the dose distribution was performed. TLDs were attached to 2-D human body shape, in which the size was fitted to a junior-high-school student. The 2-D human body shape was placed at four aspects of the tube (front, back, right, and left) for the dose assessment. $H_p(0.07)$ doses on the body were in the range of 0.23 ± 0.01 – 0.46 ± 0.02 mSv/h at 1 m. The highest dose distributed on the aligned direction to the head of the Crookes tube (central-upper portions of the body) and declined on the lower parts. On the other hand, the doses were severely low for the back side and the left side, and they distributed in the range of 0.07 ± 0.01 – 0.16 ± 0.01 mSv/h, and 0.10 ± 0.01 – 0.23 ± 0.01 mSv/h, respectively. At the highest output, the maximum $H_p(0.07)$ dose was 0.08 ± 0.01 mSv for 10 minutes at the distance of 1 m from the front of the tube.

Chapter 4 estimated the transmission of X-rays through the popular materials to collect workable materials for radiation shielding. According to the ALARA principle, exposure is possible to minimize by distance, time, and shielding. For teaching science, radiation shielding material must attenuate radiation intensity effectively, and its light-transmittance ensures to observe the behavior of the electron beam inside the Crookes tube. The present study concentrated on investigating the transmission properties of transparent such as acrylic, lead acrylic, glass materials, and pure aluminum used as the compared material. The lead acrylic had the same transmission factor with aluminum, while that of acrylic was greatly higher. The glass aquarium covered the whole Crookes tube with the transmission factor of 30% that showed the good effect of radiation shielding. In addition, the transmitted dose for each demonstration (for 10 min) was below the limited dose of the ICRP 36. These results revealed that lead acrylic and the glass aquarium were suitable to protect participants against exposure to X-ray radiation irradiated from Crookes tubes in the science class.

Chapter 5 included the conclusion of the thesis, the summary of the previous chapters, and guidelines of radiation safety management for the Crookes tubes. The major output of the Crookes tube was the front surface of the tube, and this side was also the highest dose distribution. From the present results, the participants should keep a distance of 1m from the tube. It strictly avoids the position facing the front of the tube. On the induction coil, the distance of discharge electrodes should be set shorter than 20 mm and never remove them. A demonstration should conduct within 10 minutes with low output power to keep the minimum radiation exposure. Besides, it is effective in reducing radiation exposure using transparent shields such as lead acrylic or glass aquarium during demonstrations.

# 審査結果の要旨

本論文は、主に中学校の教育現場で用いられるクルックス管を安全に取り扱うためのガイドラインの確立の基礎となる低エネルギーX 線のエネルギー分布、空間線量分布、遮蔽特性の実験的研究を行ったものである。クルックス管は陰極線管とも呼ばれ、中学校学習指導要領において、電流、放電、放射線に関連した単元での授業での実演が進められている。他方、古い製品の一部には、非常に高い強度のX線が漏洩してくるものがあることが指摘されている。しかるに、生成されるX線のエネルギーは極めて低く、通常の放射線サーベイメーターなどでは正確な線量測定もできない。本研究では、クルックス管から漏洩してくるX線の基礎特性を正確に測定し、その成果を中学校の理科教育のためのガイドライン制定に還元している。特に、注目すべき成果は以下のとおりである。

(1)クルックス管に印加する誘導コイルの出力電圧は一定ではなく、振幅の異なるパルス状である。パルスピークの高電圧で加速された電子は管壁を容易に透過する高エネルギーX線を生じる。本研究では、クルックス管外部に漏洩するX線のエネルギースペクトルおよび被ばく線量と運転条件の関係を初めて明らかにすることができた。

(2)クルックス管ではビーム状の電子がガラス壁に衝突してX線を発生するため、X線の放射には強い異方性があると予想される。本研究では被ばく線量の空間分布を詳細に測定し、被ばくのリスクを最小限にするための重要な知見を得ることができた。

(3)低エネルギーX 線は金属板で容易に遮蔽できるが、教育現場の利用を考えると身の回りにある透明な材料の使用が望ましい。本研究では市販のガラス水槽がかなりの遮蔽効果を示すことができ、ガイドラインにも反映させることができた。

以上の諸成果は、教育現場でのクルックス管使用にとどまらず、同じく低エネルギーX線を日常的に使用している医療現場の看護師の被ばく低減に重要な知見を与える。本研究はこのようにX線の発生の物理機構のみならず、放射線案管理の上からも有益な情報を提供したものであり、関連分野の学術的・産業的な発展に貢献するところ大である。また、申請者が自立して研究活動を行うのに必要な能力と学識を有することを証したものである。
学位論文審査委員会は、本論文の審査および最終試験の結果から、博士（工学）の学位を授与することを適当と認める。