Development of a new X-ray source system using ultraviolet laser for medical treatment

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1. Introduction

In 2009, the U.S. Food and Drug Administration (FDA) approved the use of Xoft Inc.'s Axxent® system for the treatment of early-stage breast cancer. The system uses a disposable microminiature X-ray tube to deliver electronically controlled radiation therapy [1]. This interstitial treatment is called electronic brachytherapy, and its objective is to reduce the risk of cancer recurrence [2-3]. Since the microminiature tube is inserted in the body in order to irradiate the affected area, there is minimum damage to normal tissue and it is easier to handle compared to brachytherapy using radioisotopes. However, the generation of X-rays using the Axxent® is accompanied by hazards, such as the risk of electric shock, due to the use of both water for cooling the hot X-ray source and external high voltage for the acceleration of thermal electrons.

Alternative systems using a pyroelectric crystal as the X-ray source have been studied and developed, but have not yet been used in the medical field. One of the reasons for the delay is the safety issue associated with high-temperature heating of the pyroelectric crystal to generate X-rays [4-6].

In this study, we developed a new X-ray source system that uses a pyroelectric crystal and ultraviolet (UV) laser, and considered the safety of its application to medical treatment.

2. Materials and Methods

2.1 X-ray source system

Figure 1 shows the proposed X-ray source system that combines a UV laser and pyroelectric crystal. The UV laser is a Quantel Nd:YAG laser operating at a wavelength of 266 nm, repetition rate of 10 Hz, pulse energy of 10–40 mJ and beam diameter of 5 mm. We used a cylindrical $LiNbO_3$ pyroelectric crystal with a thickness of 4 mm and diameter of 10 mm. Synthetic fused silica of 2.3 mm in thickness was attached to the UV laser irradiation side of the pyroelectric crystal, and a stainless steel tube was attached to the opposite side of the synthetic fused silica. The target metal was copper of 10 μm in thickness, and DuPont™ Kapton® polyimide film of 75 μm in thickness was bonded to the copper target on the atmosphere side. The pressure inside the vacuum chamber was set to 3.3 Pa (2.5×10^{-2} Torr). Isopropyl alcohol in the gas state could be introduced into the vacuum chamber by a variable leak valve.

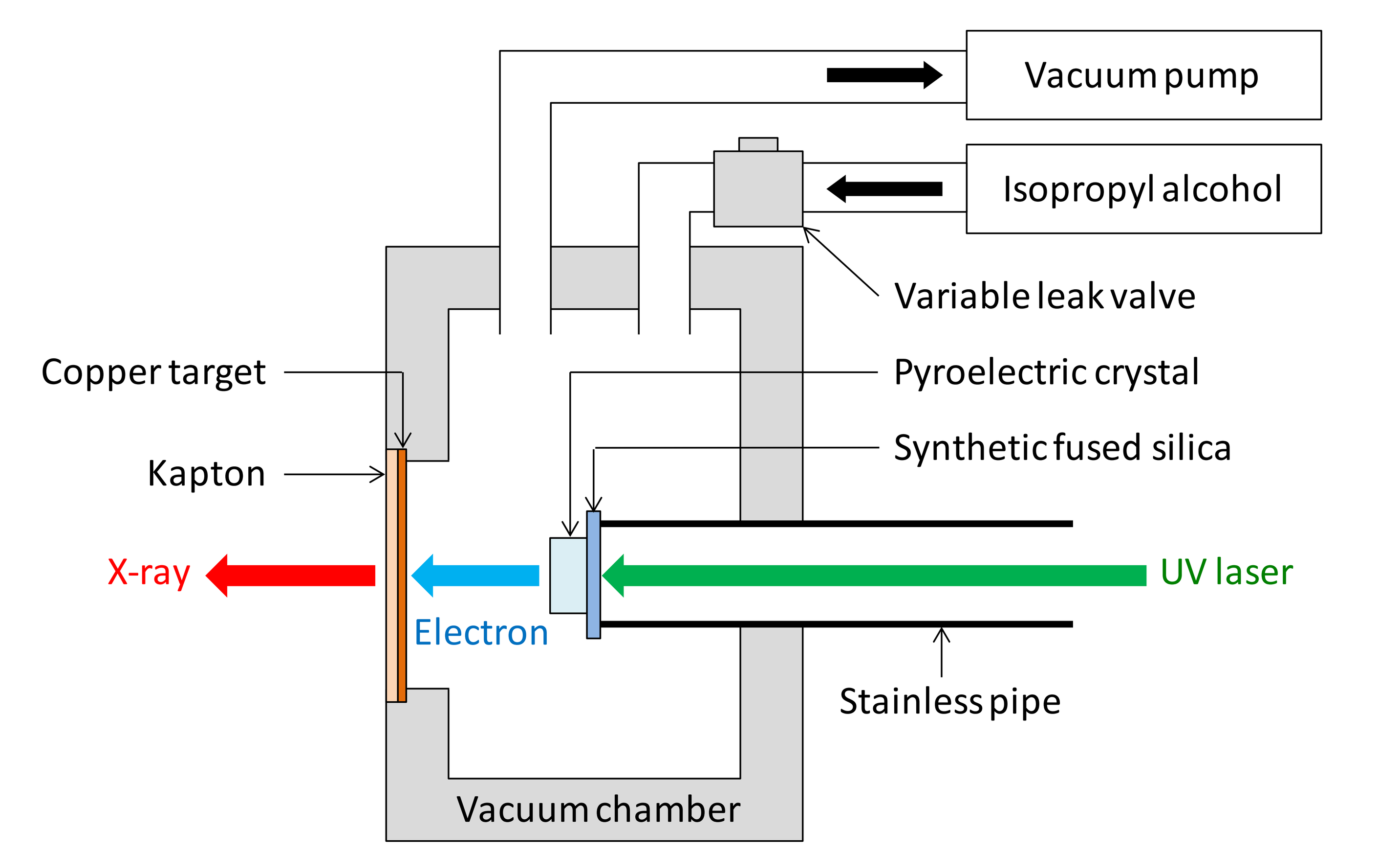

Figure 1: Proposed system in which X-rays are generated by UV laser irradiation of the pyroelectric crystal, which then emits electrons that collide with the copper target.

2.2 Measurement of X-ray energy

The energy of the generated X-rays was measured using a RAMTEC 413 X-ray spectrum analyzer (Toyo Medic Co., Ltd.). The analyzer was set at a position about 1 cm from the Kapton® film in the X-ray source system.

2.3 Experimental introduction of isopropyl alcohol

Temporal changes in the X-ray count were measured by introducing the isopropyl alcohol gas into the vacuum chamber. Measurement was performed using the Inspector+ (S.E. International, Inc.) set at a position about 1 cm from the Kapton® film in the X-ray source system.

2.4 Measurement of temperature of pyroelectric crystal

The temperature of the pyroelectric crystal excited by UV laser light was measured temporally. Measurement was performed using a thermometer with a thermocouple connected to the pyroelectric crystal. The pulse energy of the UV laser light was 10–40 mJ.

3. Results

3.1 X-ray energy spectrum

Figure 2 shows the X-ray energy spectrum when the UV laser was irradiated for 300 s. Characteristic X-ray peaks of K_α and K_β from the copper were observed near the energy levels of 8 and 9 keV, respectively. Moreover, bremsstrahlung X-rays were observed up to about 30 keV. The absorbed dose of the generated X-rays was 4.7 μGy for 300 s.

3.2 Temporal response of X-ray count

Figure 3 shows the temporal response of the X-ray counts by the presence of isopropyl alcohol gas in the vacuum chamber. Regardless of the presence or not of isopropyl alcohol gas, X-rays were detected starting at about 1 min after UV laser irradiation, and the count distribution took on the appearance of a mountain. When isopropyl alcohol gas was not present, the peak count was about 40 cps, and the X-ray generation duration was about 5 min.

On the other hand, when isopropyl alcohol gas was present, the peak count was about 4500 cps, an increase of more than 100-fold compared to the case without isopropyl alcohol gas. Moreover, the X-ray generation duration also increased significantly.

3.3 Temperature change of pyroelectric crystal by UV laser

Figure 4 shows the temporal change in temperature of the pyroelectric crystal during UV laser irradiation. For UV laser irradiation of about 9 min, the increase in temperature from room temperature by laser energy of 10, 20, 30 and 40 mJ/pulse was 0.9, 1.5, 2.5 and 4.3 K, respectively.

4. Discussion

4.1 X-ray source system using UV laser and pyroelectric crystal

To induce the emission of electrons from a pyroelectric crystal to generate X-rays, it is usually necessary to heat the pyroelectric crystal to a temperature of about 353–373 K [3-6]. In this study, UV laser light was successfully used to induce electron emission and generate X-rays. Electron emission from a pyroelectric crystal using UV laser has been reported [7], but we did not find any reports on the generation of X-rays using this technology.

The synthetic fused silica was used on the pyroelectric crystal in order to decrease the pulse energy from the UV laser. When the pyroelectric crystal was directly irradiated by the UV laser, without using the synthetic fused silica, the irradiation side of the crystal was carbonized. This phenomenon is thought to be the result of the UV laser pulse energy of mJ order. However, when a rental UV laser of μJ/pulse order was used, X-rays were successfully generated without using the synthetic fused silica. It is also possible to apply optical fiber technology when using UV laser of μJ/pulse order.

4.2 Terrestrial gamma ray dose rates in Shiga Prefecture

The X-ray energy spectrum results well reflected the characteristics of the copper target. However, it is necessary to increase the X-ray dose for use in medical treatment, and so the bremsstrahlung X-ray will need to be increased by using a larger pyroelectric crystal or a higher repetition rate of the UV laser.

4.3 Temporal response of X-ray count

Since the count of X-rays emitted from the pyroelectric crystal changed with time, the stability of the X-ray output and the increase in the X-ray dose will be important factors for medical applications. The isopropyl alcohol gas experimentally used in this study greatly contributed to the increase in the X-ray count. It is considered that the electrons were supplied to the surface of the pyroelectric crystal because of the reduction of isopropyl alcohol. Therefore, it is important to examine the method of supplying electrons to the pyroelectric crystal in order to increase the dose of X-rays.

4.4 Temperature change of pyroelectric crystal

The temperature of the pyroelectric crystal irradiated by UV laser light of 40 mJ/pulse increased by 6 K from room temperature in about 9 min. This rise in temperature is based on the synthetic fused silica used in order to decrease the energy of the UV laser, because the temperature of only the pyroelectric crystal rose by about 1 K from room temperature. Moreover, the synthetic fused silica is not necessary when using the UV laser with pulse energy of μJ order. Thus, this X-ray source system will greatly reduce the burden of cooling the source portion.

5. Conclusion

The proposed X-ray source system using the UV laser and pyroelectric crystal could be used for medical treatment by improving the count and stability of the X-ray output. Furthermore, the system is useful in terms of safety of medical treatment, since the generation of X-rays does not require an external voltage and the rise in temperature of the pyroelectric crystal during UV laser irradiation is low.

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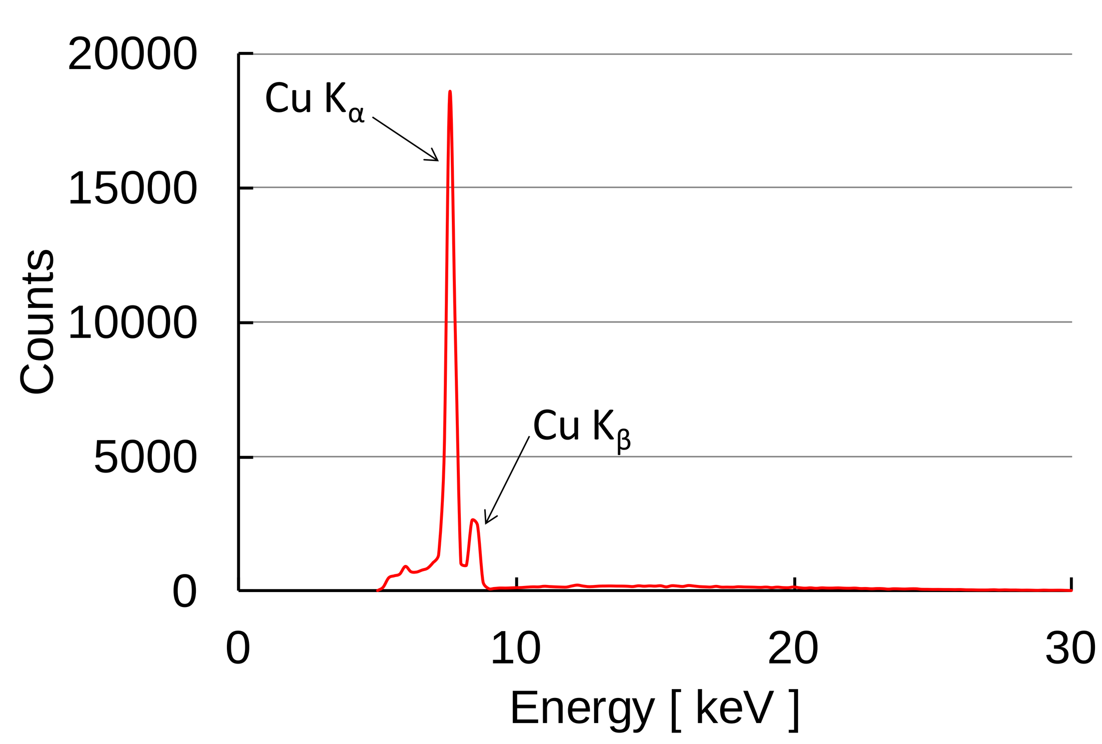

Figure 2: Energy spectrum of X-rays detected during UV laser irradiation of the pyroelectric crystal for 300 s.

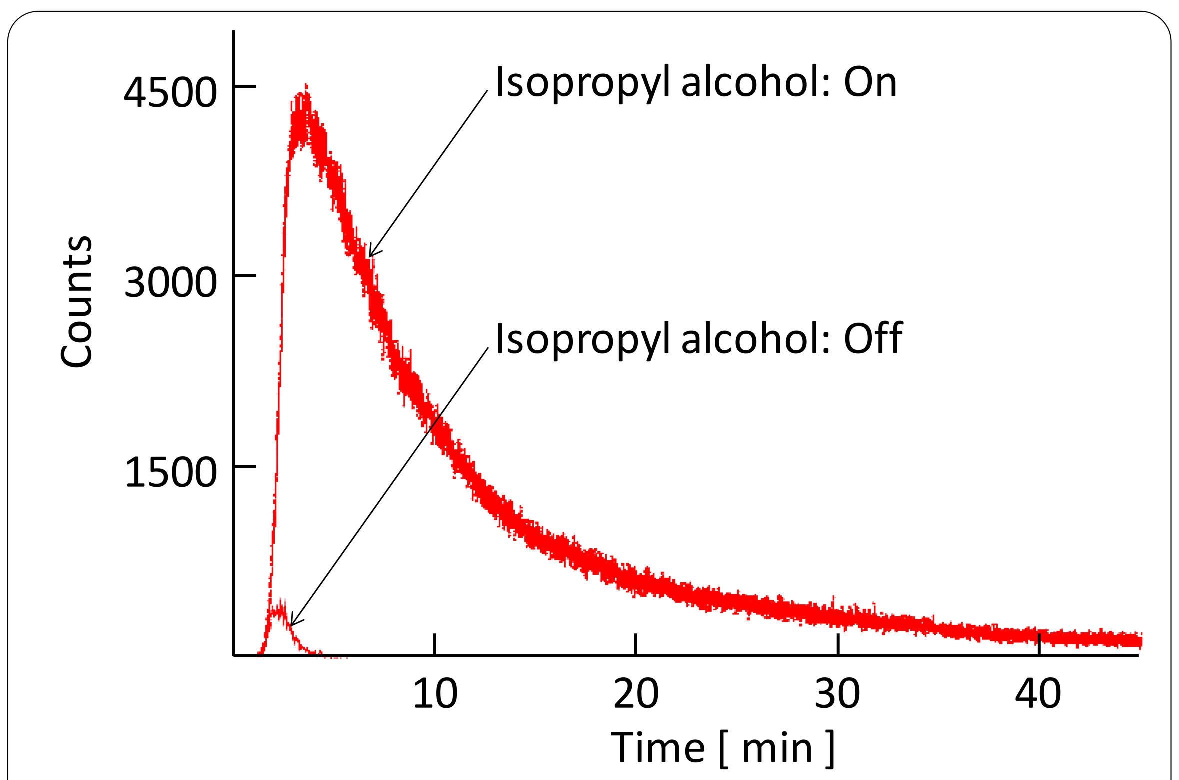

Figure 3: Temporal response of X-ray count detected during UV laser irradiation of the pyroelectric crystal. (Isopropyl alcohol introduced: On; Isopropyl alcohol not introduced: Off)

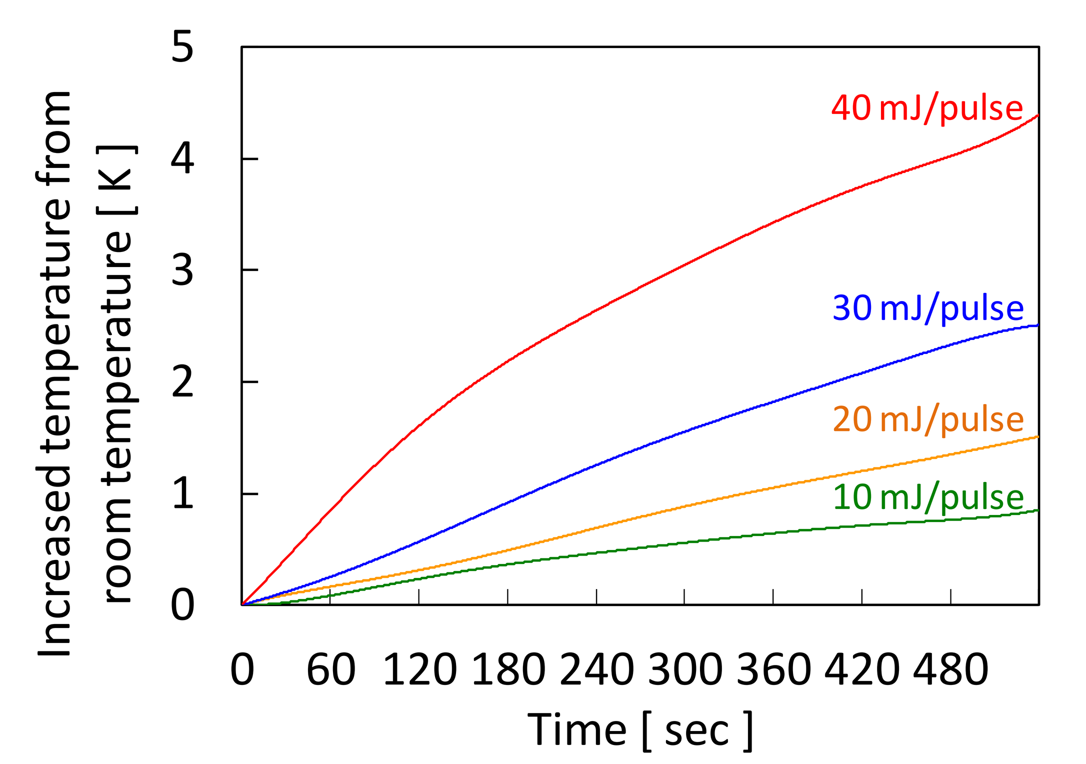

Figure 4: Temperature change of the pyroelectric crystal during UV laser irradiation.