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Clinical evaluation of performance, stability, and longevity of an accelerator system designed for boron neutron capture therapy utilising a beryllium target

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A R T I C L E I N F O

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A B S T R A C T

Boron neutron capture therapy for recurrent head and neck cancer has been approved as an insurance covered treatment in Japan since June 2020. The Kansai BNCT Medical Center has installed the NeuCure® BNCT system developed by Sumitomo Heavy Industries. This system utilises a beryllium target with a 30 MeV proton beam to generate neutrons. To date, the center has treated over 300 patients and the system is also used for quality control and fundamental research experiments. Information on the stability and longevity of the system is important for facilities and hospitals considering installation of a BNCT system in the future, particularly after an exchange of a major component, such as the target. The beam output (neutron and gamma ray) was measured before and after the exchange of the target. The thermal neutron, fast neutron and gamma ray distribution inside a water phantom was evaluated and the results showed no significant change in the beam quality after the exchange of the target. Furthermore, no significant change in the neutron flux as a function of increasing number of accumulated protons on the target was observed up to a value of just under 400 mAh. The NeuCure® BNCT system has been shown to be highly stable and the frequency of target replacement was much less than lithium target-based accelerators.

1. Introduction

The development of accelerators for producing neutrons for cancer therapy is rapidly increasing worldwide. One reason for this is the approval of boron neutron capture therapy (BNCT) as an insurance-covered treatment for recurrent head and neck cancer in Japan, with the preliminary clinical results showing high overall response rate [1]. Various types of accelerators are currently in development across the world (13 countries with over 25 facilities) [2]. The majority of these facilities have selected lithium as the target material (^{7}Li(p,n)^{7}Be reaction). At low proton energies (up to 8 MeV), the proton-lithium combination produces a higher neutron intensity when compared with the proton-beryllium combination. However, beryllium is much easier to handle and has a higher melting point than lithium (1287 °C–180.5 °C).

In Japan, the University of Tsukuba utilises a linear accelerator equipped with a beryllium target with a proton energy of 8 MeV [3]. In 2024, they announced the start of a clinical trial for glioblastoma with BNCT using this accelerator system. The National Cancer Center Hospital (NCCH) has employed a solid lithium target with a proton energy of

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2.5 MeV to generate neutrons [4]. This system is being developed by the Cancer Intelligence Care Systems (CICS) and is conducting a clinical trial of BNCT for malignant melanoma and angiosarcoma [5]. The Shonan Kamakura General Hospital (SKGH) has installed the accelerator system developed by Neutron Therapeutics (nuBeam®). This system employs a solid lithium target with a proton energy of 2.8 MeV and is currently in the commissioning phase [6].

Currently, the only commercially available accelerator system for clinical BNCT is the BNCT system NeuCure® (hereafter NeuCure), developed by Sumitomo Heavy Industries [7].The prototype, a cyclotron-based epithermal neutron source (CBENS), was developed by the Kyoto University BNCT research group at the Institute for Integrated Radiation and Nuclear Science [8,9]. In 2015, the same type of accelerator was installed at the Southern Tohoku General Hospital [10], and at the Osaka Medical and Pharmaceutical University, Kansai BNCT Medical Center in 2018 [11]. The system accelerates protons to an energy of 30 MeV, striking a beryllium target and generating fast neutrons (^{9}Be(p,n)^{9}B reaction). The fast neutrons traverse through a carefully designed beam shaping assembly, where the neutron energy is reduced to the therapeutic range (i.e. epithermal neutrons). This accelerator received medical device approval from the Japanese government in March 2020. The neutron energy spectrum of the above-mentioned neutron sources currently used for treating patients is shown in Fig. 1.

The NeuCure system accelerates a negative hydrogen ion, which is injected vertically into the high current cyclotron. The negative ion is converted to a position ion by a thin foil placed at the extraction orbit. The extracted proton beams are transported to the beryllium target with minimal loss using quadrupole, steering, and scanning magnets. The system is designed to generate 30 MeV proton beams with a current of 2 mA (currently it is clinically operated at 1 mA), which equals a beam power of 60 kW [13]. The generated fast neutrons traverse through the moderator/beam shaping assembly to reduce the neutron energy range down to approximately 4 eV–40 keV, which has been shown to be the most effective energy range for treatment of deep-seated tumours [14]. The target, a pure beryllium plate, is cooled by pure water to endure high heat load and the thickness is set to be less than the range of the 30 MeV proton in beryllium to avoid blistering of the target.

NeuCure was installed at the Kansai BNCT Medical Center (KBMC) in 2017, and acceptance and commissioning tests were performed in 2018. In 2019, an investigator led phase II clinical trial of accelerator-based BNCT for refractory and recurrent high-grade meningioma was conducted [15]. As of June 2020, KBMC offers BNCT covered by medical insurance for the treatment of unresectable, locally advanced, and recurrent carcinoma of the head and neck region. To date, KBMC has treated over 300 patients, with the number of patients being treated increasing each year. The accelerator is also being utilised for quality assurance (QA) tests and fundamental research experiments. Information about beam stability and long-term usage of the system is important, especially for hospitals that are considering the installation of an accelerator-based BNCT system. To date, there is no published report on the stability and information on the lifetime of a target that is routinely used for clinical BNCT treatment. This study aims to provide information on the NeuCure from a clinical perspective and compare the results with other accelerator BNCT systems used for treatment.

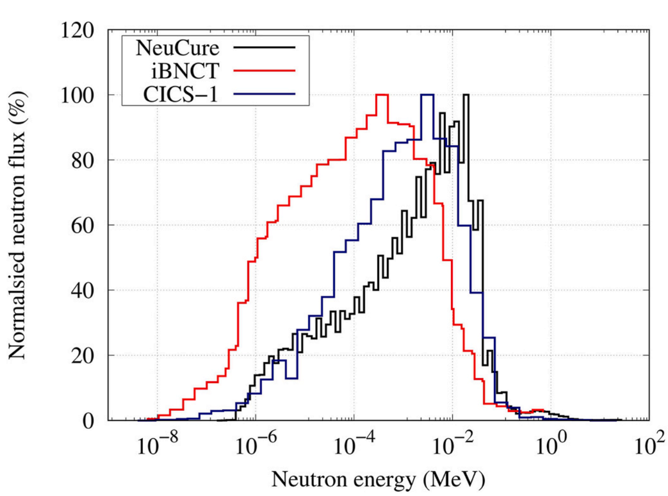

Fig. 1. Neutron spectrum of the NeuCure accelerator system along with the iBNCT system (Be target [3]) and CICS-1 (Li target [12]). The neutron intensity was normalised to the peak value of each spectrum.

2. Material and method

At KBMC, the beryllium target has been replaced twice, once in December 2021 (from target 1 to target 2) and in again in December 2023 (from target 2 to target 3). It is replaced every two years, according to the manufacturer's recommendation. The breakdown of the accelerator usage at KBMC is shown in the appendix.

2.1. Beryllium target replacement

A simplified image of the NeuCure and the target replacement process is shown in Fig. 2. The target duct was detached from the beam shaping assembly (BSA) and automatically transferred to the basement for temporary storage before disposal. The time it took from removal and storage of the target duct, installation of the new target duct, vacuum evacuation, and to beam on was monitored.

2.2. Neutron flux distribution before and after target replacement

The central axis and off-axis thermal neutron distribution inside a water phantom were measured using the gold foil activation method. A thin gold cylindrical wire (diameter 0.25 cm × 10 cm in length, with a 99.99% purity, The Nilaco Corporation, Tokyo, Japan) was placed inside a water phantom used for routine quality assurance. The wire was positioned along the central beam axis to measure the depth profile and perpendicular to the beam axis to measure the off-axis profile. Since gold reacts to both thermal and epithermal neutrons, a cadmium tube cover, manufactured by Shieldwerx™ (10 cm in length and approximately 1.3 mm and 2.3 mm for the inner and outer diameter, respectively), was used to calculate the cadmium ratio. A proton charge of 0.3C and 0.6C was delivered for the bare gold wire and gold wire covered with the cadmium tube, respectively. After irradiation, the gold wire was cut into small pieces (5 mm in length) and measured using a high purity germanium detector (HPGe, ORTEC ICS-P4). The reaction rate per unit

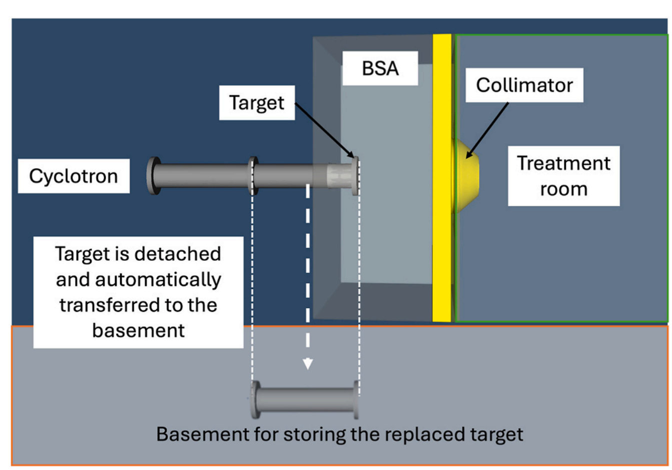

Fig. 2. Simplified image of the NeuCure showing the different components and the target replacement process.

charge of the gold wire was calculated using the expression below.

$$R = \frac{\lambda N}{\epsilon \gamma e^{-\lambda T_c}(1-e^{-\lambda T_m})\sum_{i=1}^{n}\left(\frac{Q_i}{\Delta t}(1-e^{-\lambda \Delta t})e^{-\lambda(n-i)\Delta t}\right)}$$

Where ϵ is the detection efficiency of the detector for the gamma rays emitted from ^{198}Au, γ is the gamma ray emission rate from ^{198}Au decay, λ is the decay constant of ^{198}Au, T_c is the time from irradiation to the start of the measurement, T_m is the measurement time, N is the peak count due to the detector-measured gamma rays emitted from ^{198}Au and Q_i is the electric charge irradiated on the target at each interval, Δt. For the measurement of fast neutrons, aluminium foil was used (20 mm with a thickness of 0.5 mm with a 99.99% purity, The Nilaco Corporation). ^{27}Al is excited by the (n,α) process, producing ^{24}Na, which returns to the ground state by emitting a 1369 keV gamma ray. The above reaction has a threshold and occurs when the neutron energy is above approximately 5 MeV. Therefore, for low energy accelerators (such as the Li target system) this measurement is not necessary.

The aluminium foil was placed on the surface of the phantom, at 1, 2, and 6 cm from the surface along the beam central axis. Each foil was covered by cadmium to reduce unnecessary activation with thermal neutrons. A total proton charge of 3.6C was delivered. After irradiation, the activation was measured using the same method as the gold wire measurement. All measurements were repeated three times.

2.3. Gamma ray distribution before and after target replacement

The central axis gamma ray distribution inside a water phantom was measured using thermoluminescence dosimeters (TLDs). Commercially available BeO powdered TLDs are usually encapsulated in borosilicate glass, which has a high sensitivity to thermal neutrons. Therefore, a custom made TLD enclosed in a quartz glass capsule was used to measure the gamma ray dose rate [16,17]. It consisted of Na-doped BeO grains encapsulated in a 2 mm diameter, 12 mm height quartz glass tube. The Panasonic UD-5120PGL TLD reader was used to measure the signal of the TLD. The TLDs were calibrated using the ^{60}Co gamma ray source at Kyoto University, and the thermal neutron sensitivity was evaluated using the Kyoto University Reactor. Measurements were performed at 0, 2, 4, 6, 8, and 10 cm depth inside the water phantom. All measurements were repeated three times.

2.4. Neutron intensity, gamma ray dose, and proton current over time

The change in neutron flux as a function of total number of protons delivered to the target was investigated. At KBMC, neutron and gamma ray output measurements inside a water phantom (at the surface of the phantom, 2 cm, and 6 cm depths) are performed on a weekly basis. The peak thermal neutron flux (depth of 2 cm) and the corresponding cumulative number of protons delivered to the target between June 2020 and March 2024 were extracted and plotted. The results were compared with the accelerator system at the NCCH. The stability of the proton current at the target was measured over an irradiation time of 1 h, which is the typical maximum irradiation time for the current clinical protocol. The results were compared with the accelerator system at the SKGH.

3. Results

Table 1 shows the time spent on each process during the target replacement of the NeuCure. The exchange of the target duct took approximately 1 h. Including the vacuum evacuation procedure and verifying the beam output, the entire process took approximately 3 h.

The thermal neutron distribution along the central axis and off-axis at a depth of 2 cm is shown in Fig. 3. The percentage difference between the two different targets at each position was found to be less than 2%. The gamma ray and fast neutron distribution along the central axis is shown in Figs. 4 and 5, respectively. The percentage difference between the two different targets at each position was found to be less than less than 4% for the gamma ray dose and 3% for the fast neutron. The percentage difference between the datasets was lower than the experimental uncertainty (±5–7% for gold foil activation method [18,19], ±20% for TLD [17], and ±15–20% for Al foil activation method [20]).

Table 1
Chronological order of the target replacement process of the NeuCure.

Time (hh:mm)	Process
8:45	Detachment of the target duct from the accelerating tube
8:55	Opening of the BSA
9:05	Installation of the driver system to transfer the target duct to the basement
9:10	Lowering of the target duct to the basement
9:15	Relocating the used target duct within the basement
9:30	Installing the new target duct
9:40	Closing of the BSA
9:45	Attaching the target duct to the accelerating tube
12:00	Vacuum evacuation procedure and verification of beam on complete

The change in the neutron intensity over time for each of the targets is shown in Fig. 6. A total of 310 mAh (1116C) and 372 mAh (1339 C) were delivered to target No.1 and target No.2, respectively. No significant change in the neutron intensity was observed for the three different targets. Compared with the lithium target at NCCH, the results indicated the beryllium target used at KBMC (NeuCure) could be used for a longer period, without the need for a replacement.

Fig. 7 shows the thermal neutron flux and gamma ray dose measured at three different locations (surface, 2 cm, and 6 cm) over a four-year period with three different beryllium targets. The results indicated no significant change in the thermal neutron and gamma ray dose rate output between the different targets. These measurements were only a single measurement. The slight change in the output constancy between target No.1 and target No.2 was due to the re-calibration of the detector system (HPGe detector and TLD reader). Nevertheless, over the four-year period, the output results were all within the vendor specified tolerance range.

The stability of the proton current over a typical 1-h irradiation is shown in Fig. 8. The proton current reached the set value (1 mA) instantaneously and kept this value during the entire irradiation. A similar stability has been reported with the iBNCT system which also utilises a Be target [21]. A small build-up time at the beginning was observed, but the proton current was stable and constant until the end of irradiation (40-min irradiation). The proton current stability of the of the nuBeam (Li target) was observed to slightly decrease during irradiation [6].

4. Discussion

With the gradual increase in the number of patients treated with BNCT each year, the long-term stability of the NeuCure along with the reproducibility of the beam characteristic upon exchange of the beryllium target is important from a clinical standpoint. The target replacement process and the beam output verification took 1 h and 3 h, respectively. This is highly advantageous from a clinical perspective, as the machine downtime can be kept low, and more patients can be treated.

The routine output measurements indicated that both the neutron and gamma ray distribution inside a water phantom did not change significantly after the exchange of the beryllium target, indicating high quality of the material and high accuracy and precision of the target replacement process. This is extremely important from a clinical perspective, particularly to those staff members who will be performing the QA tests after target exchange, because a vigorous full beam data collection (i.e. beam commissioning and updating the data in the

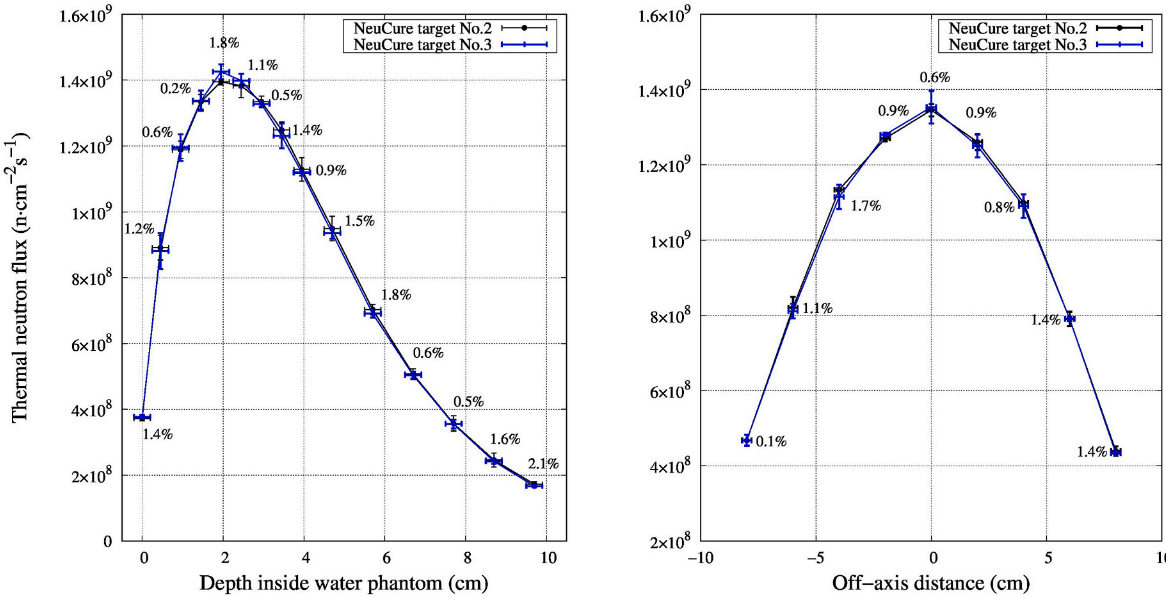

Fig. 3. Left) Central axis thermal neutron distribution inside a water phantom for a 12 cm diameter collimator for the two different Be targets. Right) Off-axis thermal neutron distribution inside a water phantom at a depth of 2 cm for a 12 cm diameter collimator for the two different Be targets.

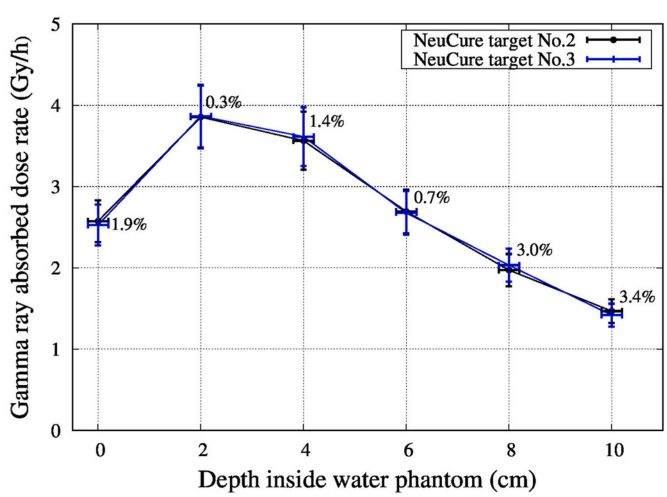

Fig. 4. Central axis gamma ray dose distribution inside a water phantom for a 12 cm diameter collimator for the two different Be targets.

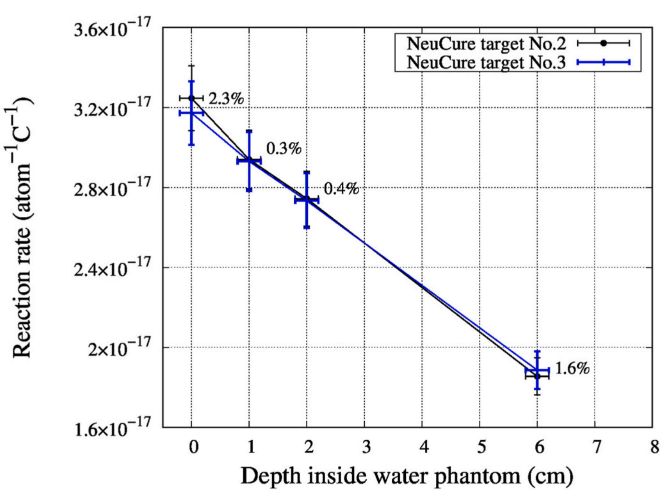

Fig. 5. Central axis fast neutron distribution inside a water phantom for a 12 cm diameter collimator for the two different Be targets.

treatment planning system) may not be required and a subset of the full commissioning tests may be suffice. A summary of the tests performed during commissioning of the NeuCure at KBMC is shown in Table 2. A total of approximately 50 mAh of protons were delivered to the target to perform a comprehensive check. Although the entire test may not be necessary upon target exchange, a large portion of the tests will need to be performed to check the beam characteristics and safety of the system before releasing it for clinical use.

Currently, there is no national nor international standard on what tests should be performed after target replacement. To perform the whole commissioning tests listed in Table 2, considering just the irradiation time (i.e. beam on time), it would take approximately 6 days (assuming an 8-h working day). The neutron beam intensity of the NeuCure was shown to be stable up to at least approximately 350 mAh, so delivering 50 mAh for beam testing is not an issue. On the other hand, the beam intensity of the CICS accelerator system (lithium target) would drop by approximately 5%, so a correction factor of some sort will need to be applied before clinical use. Since the only clinically accepted method for neutron detection is the metal foil activation method, the time it takes to perform routine weekly QA is long (several hours including both irradiation time and data analysis time). A more quick and simplistic method to measure the neutron and gamma ray distribution is highly sought out. Yamamoto et al., developed a method to use an optical imaging device to measure the 2D distribution of thermal neutrons inside a water phantom in real-time [22]. Such a method would not only reduce the time it takes to perform QA but also reduce the load on the target, which would be favourable for facilities utilising a lithium target.

Although the results show the target system of the NeuCure is highly reliable, there were 7 cases where treatment had to be postponed due to malfunction of the NeuCure, all unrelated to the target system. This equates to 2.1% of the total number of treatments so far, which is 340.

As mentioned earlier, there is no information available on the performance and long-term use of the target for the other clinical BNCT systems (both Be and Li target). The results from this study aim to shed some light on this matter and provide real-world data from a clinical institution and act as a baseline for other facilities that are developing an

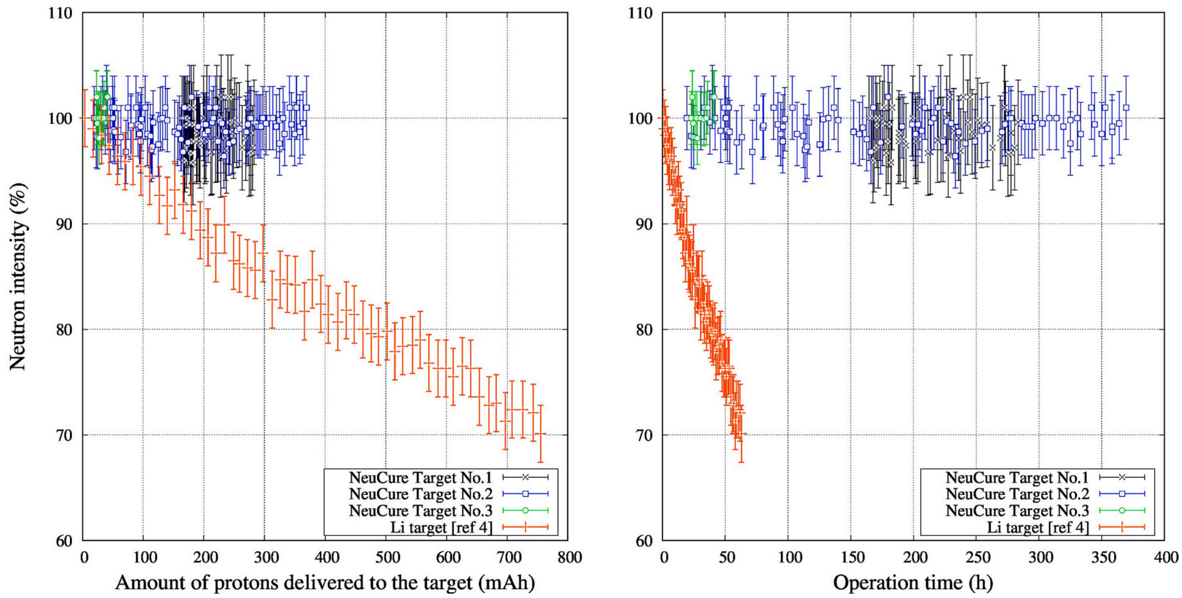

Fig. 6. Left) Neutron peak intensity as a function of the total number of protons delivered to the target. Right) Neutron peak intensity as a function of accelerator operation time. The accelerator at KBMC is operated at a proton current of 1 mA and the lithium target accelerator at NCCH is assumed to be operated at 12 mA.

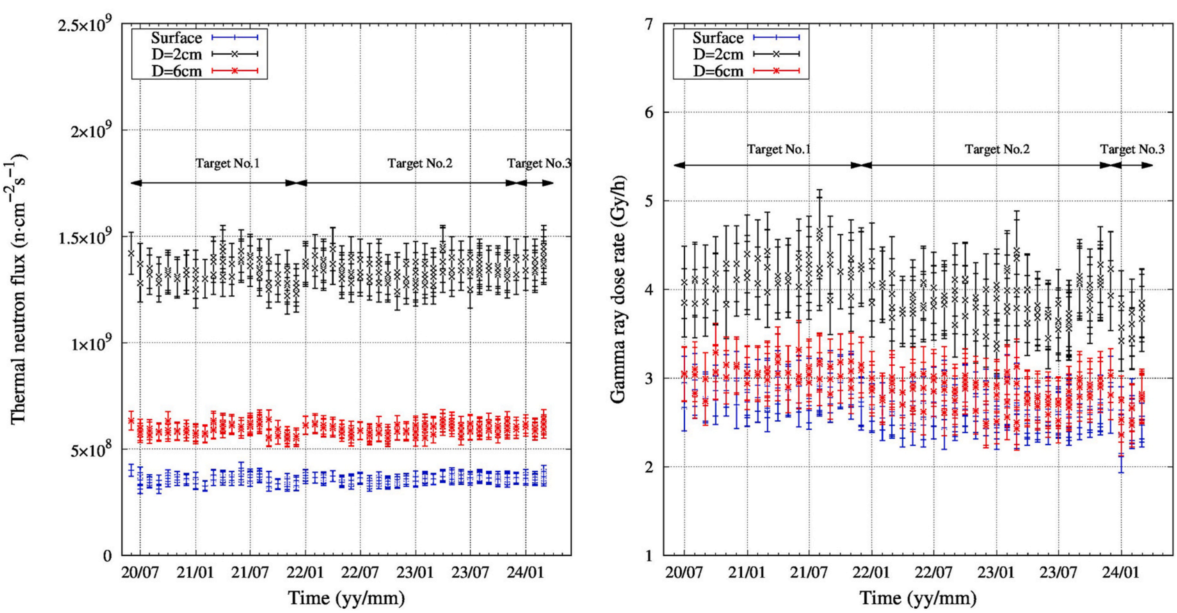

Fig. 7. Thermal neutron flux (left) and gamma ray dose rate (right) at three different depths for the three different targets over the period from the start of clinical BNCT (June 2020).

accelerator system for the purpose of performing clinical BNCT.

5. Conclusion

The long-term stability and performance of the NeuCure system after target replacement was evaluated and comparison was made with other accelerator systems. Due to the limited data available on lithium target accelerators for BNCT used in the clinic, a comprehensive comparison was difficult to perform. But when compared with the available data, both the neutron intensity and proton beam current was found to be more stable with the NeuCure system. No significant difference in the beam output was observed after the exchange of the target. It was evident that the NeuCure (beryllium target) has a better longevity than the lithium target accelerator, which would mean the target replacement would be less frequent, resulting in less machine downtime, and potentially be more favourable for a busy hospital environment.

CRediT authorship contribution statement

Naonori Hu: Writing – original draft, Validation, Methodology, Investigation, Data curation, Conceptualization. **Ryo Kakino:** Formal analysis, Data curation. **Akinori Sasaki:** Formal analysis, Data curation. **Syuushi Yoshikawa:** Resources. **Kazuhiko Akita:** Resources. **Satoshi Takeno:** Resources. **Yuki Yoshino:** Resources. **Teruhito Aihara:** Resources. **Keiji Nihei:** Resources. **Mai Nojiri:** Formal analysis, Data curation. **Nishiki Matsubayashi:** Formal analysis, Data curation. **Takushi Takata:** Resources, Data curation. **Hiroki Tanaka:** Supervision. **Minoru Suzuki:** Supervision. **Koji Ono:** Supervision.

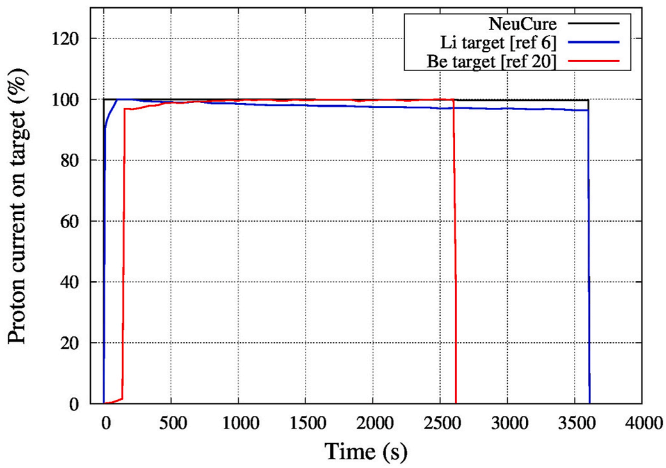

Fig. 8. Average proton current at the target during irradiation.

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Declaration of competing interest

The authors declare that there are no conflicts of interest regarding the publication of this paper. The research was conducted independently, and no financial or personal relationships exist that could have appeared to influence the work reported in this paper.

Appendix

Accelerator usage at Kansai BNCT Medical Center

The building works began in September 2016, the installation of the accelerator system began in September 2017, the acceptance testing began in March 2018, and commissioning of the system was finalised in August 2018. The initial target was used for the irradiation of 18 brain tumour patients and 53 head and neck patients. A total of 1116 C (310 mAh) of protons were delivered and most irradiations performed were for QA/maintenance of the accelerator. The second target was used for the irradiation of 5 brain tumour patients and 207 head and neck patients. A total of 1339 C (372 mAh) of protons were delivered. As shown in Fig. 9, over 50% of the total accelerator usage is due to QA/maintenance. The tests performed during commissioning of the NeuCure at KBMC is summarised in Table 2.

Table 2
Summary of the tests performed during commissioning of the NeuCure BNCT system at KBMC.

Component	Profile	Medium	Collimator type	Diameter (cm)	Charge (C)
Thermal	CAX	Water	Standard	10	0.9 × 3 measurements = 2.7
Thermal	CAX	Water	Standard	12	0.9 × 3 measurements = 2.7
Thermal	CAX	Water	Standard	15	0.9 × 3 measurements = 2.7
Thermal	CAX	Water	Extended 5 cm	12	0.9 × 3 measurements = 2.7
Thermal	CAX	Water	Extended 10 cm	12	0.9 × 3 measurements = 2.7
Thermal	OCR	Water	Standard	10	0.9 × 3 measurements = 2.7
Thermal	OCR	Water	Standard	12	0.9 × 3 measurements = 2.7
Thermal	OCR	Water	Standard	15	0.9 × 3 measurements = 2.7
Thermal	OCR	Water	Extended 5 cm	12	0.9 × 3 measurements = 2.7
Thermal	OCR	Water	Extended 10 cm	12	0.9 × 3 measurements = 2.7
Gamma	CAX	Water	Standard	10	0.3 × 3 measurements = 0.9
Gamma	CAX	Water	Standard	12	0.3 × 3 measurements = 0.9
Gamma	CAX	Water	Standard	15	0.3 × 3 measurements = 0.9
Gamma	CAX	Water	Extended 5 cm	12	0.3 × 3 measurements = 0.9
Gamma	CAX	Water	Extended 10 cm	12	0.3 × 3 measurements = 0.9
Gamma	OCR	Water	Standard	10	0.3 × 3 measurements = 0.9
Gamma	OCR	Water	Standard	12	0.3 × 3 measurements = 0.9
Gamma	OCR	Water	Standard	15	0.3 × 3 measurements = 0.9
Gamma	OCR	Water	Extended 5 cm	12	0.3 × 3 measurements = 0.9
Gamma	OCR	Water	Extended 10 cm	12	0.3 × 3 measurements = 0.9
Fast	CAX	Water	Standard	10	1.8 × 3 measurements = 5.4
Fast	CAX	Water	Standard	12	1.8 × 3 measurements = 5.4
Fast	CAX	Water	Standard	15	1.8 × 3 measurements = 5.4
Fast	CAX	Water	Extended 5 cm	12	1.8 × 3 measurements = 5.4
Fast	CAX	Water	Extended 10 cm	12	1.8 × 3 measurements = 5.4
Fast	OCR	Water	Standard	10	1.8 × 3 measurements = 5.4
Fast	OCR	Water	Standard	12	1.8 × 3 measurements = 5.4
Fast	OCR	Water	Standard	15	1.8 × 3 measurements = 5.4
Fast	OCR	Water	Extended 5 cm	12	1.8 × 3 measurements = 5.4
Fast	OCR	Water	Extended 10 cm	12	1.8 × 3 measurements = 5.4
Thermal	WBD	Water	Standard	15	3.6 × 2 measurements = 7.2
Gamma	WBD	Water	Standard	15	3.6 × 2 measurements = 7.2
Fast	WBD	Water	Standard	15	7.2 × 2 measurements = 14.4
Thermal	Linearity	Water	Standard	12	0.3 × 3 measurements = 0.9
Thermal	Linearity	Water	Standard	12	0.6 × 3 measurements = 1.8
Thermal	Linearity	Water	Standard	12	1.2 × 3 measurements = 3.6
Thermal	Linearity	Water	Standard	12	2.4 × 3 measurements = 7.2
Thermal	Linearity	Water	Standard	12	3.6 × 3 measurements = 10.8
Thermal	Linearity	Water	Standard	12	4.2 × 3 measurements = 12.6
Thermal	OCR	Free air	–	–	0.9 × 3 measurements = 2.7
Gamma	OCR	Free air	–	–	0.3 × 3 measurements = 0.9
Fast	OCR	Free air	–	–	3.6 × 3 measurements = 10.8
					Total = 170.1C (47.3 mAh)

CAX: Central axis, OCR: Off center ratio, WBD: Whole body dose.

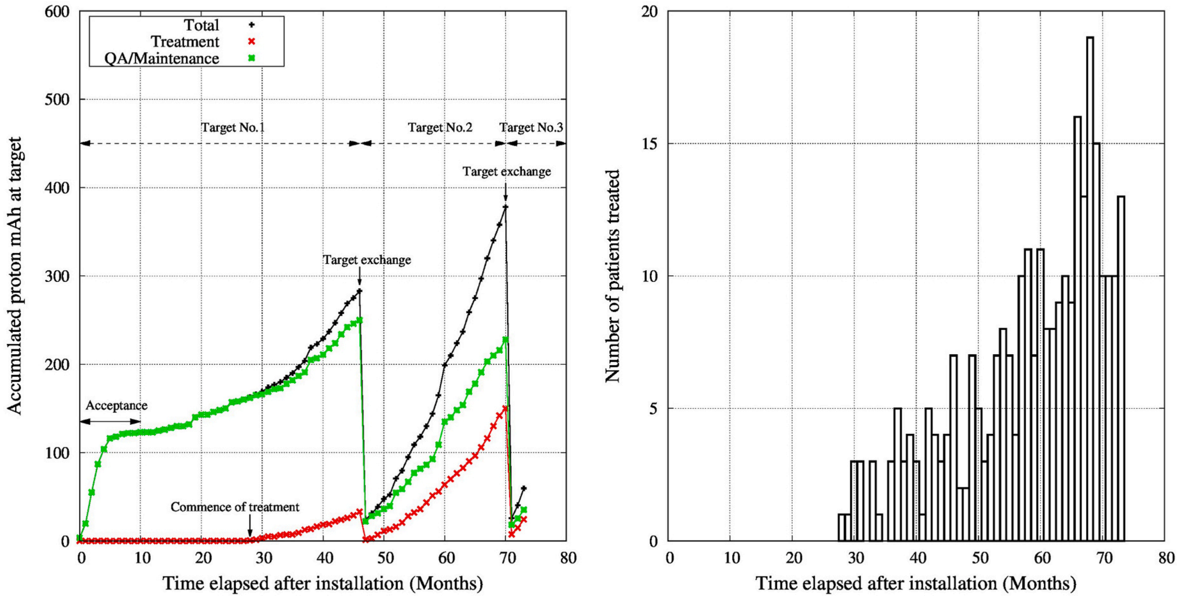

Fig. 9. Left) Breakdown of the accelerator usage at KBMC. Right) Number of head and neck patients treated at KBMC.

Data availability

Data will be made available on request.

References

[1] S. Takeno, Y. Yoshino, T. Aihara, M. Higashino, Y. Kanai, N. Hu, R. Kakino, R. Kawata, K. Nihei, K. Ono, Preliminary outcomes of boron neutron capture therapy for head and neck cancers as a treatment covered by public health insurance system in Japan: real-world experiences over a 2-year period, Cancer Med. 13 (2024), https://doi.org/10.1002/cam4.7250.

[2] W.A.G. Sauerwein, Bio-algorithms and med-systems principles , recent developments and perspectives in boron neutron capture therapy (BNCT) AVAILABLE MODALITIES IN. https://doi.org/10.5604/01.3001.0054.1824, 2023.

[3] H. Kumada, F. Naito, K. Hasegawa, H. Kobayashi, T. Kurihara, K. Takada, T. Onishi, H. Sakurai, A. Matsumura, T. Sakae, Development of LINAC-based neutron source for boron neutron capture therapy in university of Tsukuba, Plasma Fusion Res. 13 (2018) 1–6, https://doi.org/10.1585/pfr.13.2406006.

[4] S. Nakamura, H. Igaki, M. Ito, S. Imamichi, T. Kashihara, H. Okamoto, S. Nishioka, K. Iijima, T. Chiba, H. Nakayama, M. Takemori, Y. Abe, T. Kaneda, K. Takahashi, K. Inaba, K. Okuma, N. Murakami, Y. Nakayama, M. Masutani, T. Nishio, J. Itami, Neutron flux evaluation model provided in the accelerator-based boron neutron capture therapy system employing a solid-state lithium target, Sci. Rep. 11 (2021) 1–13, https://doi.org/10.1038/s41598-021-87627-8.

[5] H. Igaki, S. Nakamura, N. Yamazaki, T. Kaneda, M. Takemori, T. Kashihara, N. Murakami, K. Namikawa, T. Nakaichi, H. Okamoto, K. Iijima, T. Chiba, H. Nakayama, A. Nagao, M. Sakuramachi, K. Takahashi, K. Inaba, K. Okuma, Y. Nakayama, K. Shimada, H. Nakagama, J. Itami, Acral cutaneous malignant melanoma treated with linear accelerator-based boron neutron capture therapy system: a case report of first patient, Front. Oncol. 13 (2023), https://doi.org/10.3389/fonc.2023.1272507.

[6] S. Suzuki, K. Nitta, T. Yagihashi, P. Eide, H. Koivunoro, N. Sato, S. Gotoh, S. Shiba, M. Omura, H. Nagata, H. Tanaka, Initial evaluation of accelerator-based neutron source system at the Shonan Kamakura General Hospital, Appl. Radiat. Isot. 199 (2023) 110898, https://doi.org/10.1016/j.apradiso.2023.110898.

[7] Sumitomo Heavy Industries, Sumitomo Heavy Industries, Ltd. Obtains Medical Device Approval for Manufacturing and Sales of Accelerator Based BNCT System and the Dose Calculation Program in Japan. - World's First BNCT Systems as Medical Device, 2020.

[8] H. Tanaka, Y. Sakurai, M. Suzuki, S. Masunaga, T. Mitsumoto, K. Fujita, G. Kashino, Y. Kinashi, Y. Liu, M. Takada, K. Ono, A. Maruhashi, Experimental verification of beam characteristics for cyclotron-based epithermal neutron source (C-BENS), Appl. Radiat. Isot. 69 (2011) 1642–1645, https://doi.org/10.1016/j.apradiso.2011.03.020.

[9] H. Tanaka, Y. Sakurai, M. Suzuki, S. Masunaga, Y. Kinashi, G. Kashino, Y. Liu, T. Mitsumoto, S. Yajima, H. Tsutsui, A. Maruhashi, K. Ono, Characteristics comparison between a cyclotron-based neutron source and KUR-HWNIF for boron neutron capture therapy, Nucl. Instrum. Methods Phys. Res. B 267 (2009) 1970–1977, https://doi.org/10.1016/j.nimb.2009.03.095.

[10] T. Kato, K. Hirose, H. Tanaka, T. Mitsumoto, T. Motoyanagi, K. Arai, T. Harada, A. Takeuchi, R. Kato, S. Yajima, Y. Takai, Design and construction of an accelerator-based boron neutron capture therapy (AB-BNCT) facility with multiple treatment rooms at the Southern Tohoku BNCT Research Center, Appl. Radiat. Isot. 156 (2020) 108961, https://doi.org/10.1016/j.apradiso.2019.108961.

[11] N. Hu, H. Tanaka, K. Akita, R. Kakino, T. Aihara, K. Nihei, K. Ono, Accelerator based epithermal neutron source for clinical boron neutron capture therapy, J. Neutron Res. 24 (2022) 359–366, https://doi.org/10.3233/jnr-220037.

[12] K. Kaneta, M. Nakamura, Chapter Eighteen - proton linear accelerator and lithium target system, in: T. Shirai, T. Nishio, K. Sato (Eds.), Advances in Accelerators and Medical Physics, Academic Press, 2023, pp. 199–209, https://doi.org/10.1016/B978-0-323-99191-9.00022-0.

[13] T. Mitsumoto, S. Yajima, H. Tsutsui, T. Ogasawara, K. Fujita, H. Tanaka, Y. Sakurai, A. Maruhashi, Cyclotron-based neutron source for BNCT, AIP Conf. Proc. 1525 (2013) 319–322, https://doi.org/10.1063/1.4802341.

[14] J.C. Yanch, X.L. Zhou, G.L. Brownell, A Monte Carlo investigation of the dosimetric properties of monoenergetic neutron beams for neutron capture therapy, Radiat. Res. 126 (1991) 1–20, https://doi.org/10.2307/3578165.

[15] S.-I. Miyatake, M. Wanibuchi, S. Kawabata, N. Ko, K. Ono, CTNI-56. A phase II clinical trial using accelerator-based BNCT system for refractory recurrent high-grade meningioma, Neuro Oncol. 22 (2020), https://doi.org/10.1093/neuonc/noaa215.222 ii55–ii55.

[16] K. Yamamoto, H. Kumada, Y. Torii, T. Kishi, T. Yamamoto, A. Matsumura, Simple estimation method of gamma-ray dose using low neutron-sensitive TLD (UD-170LS) for Intra-Operative Boron Neutron Capture Therapy (IOBNCT), in: B. Monduzzi, W. Sauerwein, R. Moss, A. Wittig (Eds.), Research and Development in Neutron Capture Therapy, 2002, pp. 499–503.

[17] Y. Sakurai, T. Kobayashi, Characteristics of the KUR Heavy Water Neutron Irradiation Facility as a neutron irradiation field with variable energy spectra, Nucl. Instrum. Methods Phys. Res. 453 (2000) 569–596, https://doi.org/10.1016/S0168-9002(00)00465-4.

[18] H. Kumada, K. Takada, S. Tanaka, Y. Matsumoto, F. Naito, T. Kurihara, T. Sugimura, M. Sato, A. Matsumura, H. Sakurai, T. Sakae, Evaluation of the characteristics of the neutron beam of a linac-based neutron source for boron neutron capture therapy, Appl. Radiat. Isot. 165 (2020) 109246, https://doi.org/10.1016/j.apradiso.2020.109246.

[19] N. Hu, H. Tanaka, R. Kakino, S. Yoshikawa, M. Miyao, K. Akita, K. Isohashi, T. Aihara, K. Nihei, K. Ono, Evaluation of a treatment planning system developed for clinical boron neutron capture therapy and validation against an independent Monte Carlo dose calculation system, Radiat. Oncol. 16 (2021) 1–13, https://doi.org/10.1186/s13014-021-01968-2.

[20] D. Rorer, G. Wambersie, Current Status of neutron capture therapy, IAEA 20o1 (8) (2001) 75–77. https://www.iaea.org/publications/6168/current-status-of-neutron-capture-therapy.

[21] T. Sugimura, Chapter Nineteen - proton linear accelerator and beryllium target system, in: T. Shirai, T. Nishio, K. Sato (Eds.), Advances in Accelerators and Medical Physics, Academic Press, 2023, pp. 211–223, https://doi.org/10.1016/B978-0-323-99191-9.00012-8.

[22] S. Yamamoto, T. Yabe, N. Hu, Y. Kanai, H. Tanaka, K. Ono, Technical note: optical imaging of lithium-containing zinc sulfate plate in water during irradiation of neutrons from boron neutron capture therapy (BNCT) system, Med. Phys. 49 (2022) 1822–1830, https://doi.org/10.1002/mp.15424.