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Boron Neutron Capture Therapy for Glioblastoma: A Phase-I/II Clinical Trial at JRR-4

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Introduction

The first clinical trial of boron neutron capture therapy (BNCT) for brain tumours was performed in the 1950s using a research reactor in the United States [1–3]. Although glioblastoma (malignant glioma WHO grade 4; GBM) has been a candidate for BNCT for more than 60 years [4–12], BNCT for GBM has not become widely accepted for complex and diverse reasons. Over 900 patients have undergone BNCT worldwide and the radiobiological effects of BNCT on malignant tumours and normal surrounding tissue seemed to be established. However, all previous trials of BNCT for brain tumours had small patient series (Table 1) and used different treatment systems (ie, the neutron source and boron agents).

In addition, at present, the only neutron source suitable for BNCT is a nuclear research reactor. In Japan, to maintain safety standards at each nuclear reactor, the reactor must be shut down for several months each year and thus cannot be used for BNCT during that period. Research reactors require costly maintenance and adequate manpower, and the issue of nuclear fuel recycling is a worldwide problem. Moreover, the boron agents required for clinical trials are reagent products that require their own clinical trials to be certified as medical drugs.

We focused on clinical trials for glioblastoma and provide an overview of BNCT based on our BNCT experiences at the Japan Research Reactor No 4 (JRR-4) with a discussion of our new protocol and thoughts about the future of BNCT.

Principles of BNCT

BNCT ideally damages only boron-accumulating cells. Preloaded $^{10}$B, which is a non-radioactive isotope of boron, and low-energy thermal neutrons make the nuclear reaction notation $^{10}$B(n, $\alpha$) $^7$Li, which releases the high linear energy transfer of $\alpha$ particles and $^7$Li particles with a short path-length as cell diameter (Figure 1). Therefore, the cell-killing effect would be distributed only around the boron atoms. The effectiveness of BNCT depends on the boron distribution and the concentration ratio between normal tissue and tumour tissue, and on the neutron-beam permeability.

Materials and Methods

Neutron Source: Japan Research Reactor No 4 JRR-4 is a light-water-moderated and -cooled enriched-uranium swimming pool-style reactor that uses ETR-type fuel. Modification of JRR-4 for core conversion began in 1996, and a medical irradiation facility was installed for BNCT and the reactor was adopted to generate epithermal as well as thermal beams. The BNCT facilities are a neutron beam system, which can be used with thermal and epithermal neutrons and their mix-beam, a wide irradiation room, an irradiation monitoring system, and a fully equipped operation room for craniotomies and setting simulations. The neutron beam spectrum can be changed by $D_2O$ thickness in a heavy-water tank with a cadmium shutter [4].

We started clinical BNCT trials in 1998 at JRR-4 with the thermal neutron beam [5]. In this trial (protocol II), each patient receives general anaesthesia and intraoperative neutron irradiation is performed. At the later stage of intraoperative BNCT (since 1999), we used the epithermal beam mode. The epithermal neutron beam penetrates to deeper lesions compared to the thermal beam, and it thermalises in the tissue; the use of the epithermal beam thus improved neutron distribution at deep lesions.

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Abstract: Boron neutron capture therapy (BNCT) is a cell-selective radiation therapy for the treatment of glioblastoma. We reviewed the experience of our BNCT clinical trial and report the present state in 17 cases. Endpoints of our analysis were the efficacy and safety data of BNCT for newly diagnosed glioblastoma.
Using a pre-treatment simulation, we started a new protocol of non-craniotomy BNCT. However, in December 2007, a crack in a graphite reflector of the reactor core was found on a weld of the aluminium cladding. JRR-4 was stopped until February 2010 for replacement of the graphite reflector. After restarting BNCT in 2010, we treated 3 patients (with newly diagnosed GBM, recurrent GBM, and malignant meningioma, respectively) under the new protocol. Because of the March 2011 East Japan earthquake and tsunami, JRR-4 was stopped again with no prospect of restarting.

### Design of Our Clinical Trial

The BNCT protocols were approved by the Medical Ethics Committee of the University of Tsukuba, and all participating patients were fully informed and provided their written informed consent. Table 2 summarises the changes in protocol. The later stages of this trial (protocols III and IV) were registered with the Japanese authority on clinical trial registration (ie, the University Hospital Medical Information Network Clinical Trial Registry: UMIN-CTR; trial IDs: C000000298, UMIN000003984, and UMIN000003692). The concept of our clinical trial was a phase-I/II study for newly diagnosed GBM. The primary endpoints were safety and dose distribution to the tumour evaluated in GBM patients who were treated with BNCT, secondary endpoint was the survival benefit. Yamamoto et al described the details of clinical trials IIs and III in 2009 [6]. After the restart of JRR-4 in 2010, we started up new protocols (protocols IV and IVr) and 3 patients were treated.
Table 2. BNCT protocols for malignant glioma by the University of Tsukuba.

<table>
<thead>
<tr>
<th>Protocol</th>
<th>Period</th>
<th>Tumour grade (WHO)</th>
<th>Beam</th>
<th>Operation</th>
<th>Dose estimation</th>
<th>Boron agents</th>
<th>Additional external radiotherapy</th>
<th>n (WHO IV/total)</th>
</tr>
</thead>
<tbody>
<tr>
<td>II</td>
<td>1999–2002</td>
<td>III, IV</td>
<td>Epithermal</td>
<td>+</td>
<td>JCDS</td>
<td>BSH 5 g/body</td>
<td>–</td>
<td>2/3</td>
</tr>
<tr>
<td>III</td>
<td>2003–2004</td>
<td>IV</td>
<td>Epithermal</td>
<td>–</td>
<td>JCDS</td>
<td>BSH 5 g/body + BPA 250 mg/kg</td>
<td>30 Gy/15 fr</td>
<td>8/8</td>
</tr>
<tr>
<td>IIIr</td>
<td>2005–2007</td>
<td>IV rec</td>
<td>Epithermal</td>
<td>–</td>
<td>JCDS</td>
<td>BSH 5 g/body</td>
<td>–</td>
<td>3/3</td>
</tr>
<tr>
<td>IV</td>
<td>2010</td>
<td>IV</td>
<td>Epithermal</td>
<td>–</td>
<td>JCDS</td>
<td>BPA 250 mg/kg</td>
<td>40 Gy/20 fr</td>
<td>1/1</td>
</tr>
<tr>
<td>IVr</td>
<td>2010</td>
<td>IV rec</td>
<td>Epithermal</td>
<td>–</td>
<td>JCDS</td>
<td>BPA 250 mg/kg</td>
<td>–</td>
<td>1/1</td>
</tr>
</tbody>
</table>

JCDS: JAERI-computed dosimetry system; IV rec: Patients of grade-IV recurrence or malignant transformation pathologically proven by surgical specimens; BPA: boronphenylalanine; BSH: sodium mercaptoundecahydro-closo-dodecaborate; fr: fraction

Inclusion criteria for newly diagnosed GBM were met by patients who had supratentorial unilateral tumours, located no deeper than 7 cm from the brain surface, with a Karnofsky Performance Status (KPS) ≥ 50, who had undergone neither previous chemotherapy or radiotherapy nor previous therapy for any other cancers, and who had no allergy to sodium borocaptate (BSH) or p-dihydroxyboryl-phenylalanine (BPA), and no previous malignancy. Patients with tumour dissemination were excluded. For recurrent cases, almost the same criteria were adopted, but a history of radiotherapy or chemotherapy was accepted. 17 GBM patients were enrolled in the clinical trial.

From the start of protocol III, newly diagnosed patients were treated with additional radiochemical radiotherapy. Radiotherapy was started within 2 weeks after BNCT and consisted of fractionated focal irradiation at a dose of 30 Gy delivered in 15 fractions of 2 Gy over a 3-week term. The most recently used protocol, IV, permits additional conventional radiotherapy at a dose of 40 Gy delivered in 20 fractions of 2 Gy and the concomitant use of temozolomide (TMZ) while not using BSH infusions. Protocols IIIr and IVr were treatments for recurrent or regrowing GBM patients. These are corresponding to protocols III and IV, respectively, except for previous radiochemotherapy in the inclusion criteria. Additional post-BNCT X-ray radiotherapy was abbreviated in protocols IIIr and IVr.

BORON COMPOUNDS

Two boron compounds are used clinically in BNCT. Their chemical structures are shown in Figure 1C. First, we use sodium mercaptoundecahydro-closo-dodecaborate Na₁₂B₁₂H₁₁SH (BSH). BSH distributes only through the fragile tumour vessels and cannot pass the normal blood-brain barrier. Twelve hours prior to neutron irradiation, 5 g of BSH is dissolved in 500 ml normal saline and given to the patient in a 1-h intravenous infusion. The tumour/blood boron concentration ratio was not high in our patient series (n = 15), but no adverse event related to BSH infusion was reported.

Next we tried the combined use of 2 drugs in protocol III, BSH and BPA, to improve the boron concentration of the target lesion. 90 minutes prior to neutron irradiation, dissolved BPA-fructose complex was given. Active tumour cells accumulate the BPA for protein synthesis as an amino-acid analogue. The most recent protocol IV used BPA only because we add X-ray external irradiation after the BNCT, and this protocol may have an effect equal to that of the non-selective boron dose.

BSH was purchased from Katchem spol. (Prague, Czech Republic), and BPA was purchased from Interpharma Praha (Prague, Czech Republic) or Stella Pharma Corp (Osaka, Japan).

TREATMENT-PLANNING SYSTEM

We calculated the photon-equivalent BNCT dose by multiplying the weighting factors. We detected the thermal neutron dose by radio-activation methods with gold wire or foil placed into the operative field during craniotomy for neutron irradiation. The gold wire measured radioactivity and was pulled out during or after radiation. It reflected thermal neutron fluence at the lesion. Once epithelial neutrons were introduced, BNCT was performed without craniotomy. Therefore, we cannot directly measure the neutron dose at the tumour site by gold-wire activation. To evaluate the normal and target doses a treatment planning system for BNCT was required. Previously, several systems were used for BNCT treatment planning [7, 8]. Kumada et al released the JAERI computational dosimetry system (JCDS) for clinical epithelial beam BNCT [9, 10]. The most useful point of the JCDS system was that it was manufactured by the researchers and a new version can be created for treatment [11, 12].

The JCDS generates a 3-D volume of data for each patient; based on the CT scan, the tissue is automatically divided into soft tissue, bone, and air. The material data of each composition have been defined by the International Commission on Radiation Units (ICRU).

The medical team defines the region of interest (ROI) of the lesions and surrounding critical organs as well as the ideal incident direction of the neutron beam. After defining the boron-related parameters including the predictive average tumour and normal boron concentrations, the relative biological effectiveness, and the limiting dose of normal surrounding tissue, the JCDS calculates the dose with a particle transport simulation – for example, using the MCNP code with the Monte-Carlo method.

The output from the JCDS can display the dose-volume histogram, the isodose contour image, which contains the boron-
related dose, and the boron-unrelated dose. The boron-unrelated dose includes the “nitrogen dose” from the interaction with nitrogen in the tissue, the “gamma-ray dose” consisting of the primary gamma-ray dose transported from the reactor core, and the secondary gamma-ray dose induced by the reaction in the tissue. The fast neutrons induce the “fast-neutron dose” by the proton recoil reaction with hydrogen nuclei.

The BNCT dose was calculated by multiplying the weighted factors to account for the radiobiological effect of the high-LET dose. There are still unsolved problems regarding the estimation of the true radiation effect because the tumour tissue is heterogeneous, and different microdistributions of boron around and in the tumour cells influence the effectiveness. The prediction of tumour boron concentration from the blood boron concentration and PET images could not reflect this heterogeneity on boron microdistributions. Hence, the tumour dose calculated here may be overestimated since there is a part of the tumour with lower boron concentration.

Estimation of Boron Concentration and Patient Position During and After Neutron Irradiation

The JCDS can compensate for the patient’s position with 3-D geometry position data. In our protocols, blood sampling was conducted right before and after irradiation; boron concentration of the whole blood was analysed by inductively coupled plasma-atomic emission spectroscopy (ICP-AES) and confirmed by prompt gamma ray analysis (PGA). We confirmed the patient’s final maximum normal brain dose after confirmation of the blood boron concentration and geometrical data. Later protocols permitted the performance of $^{18}$F-labelled BPA positron emission tomography (PET) [40, 41] to determine the lesion-to-normal ratio of BPA-mediated $^{10}$B for estimating the BPA-mediated tumour dose.

Irradiation Set-Up (of Protocols III and IV)

JRR-4 is located approximately 60 km from the University of Tsukuba Hospital. At the hospital, the patient is administered intravenous BSH 24 h prior to the predicted irradiation start time. An ambulance with the medical team takes the patient to JRR-4. At JRR-4, to reduce exposure, the patient position setting is done at a radiation port model, and intravenous BPA administration is initiated 1.5 h before the start of neutron irradiation. A blood sample is taken, and an electrocardiogram monitor, blood oxygen saturation monitor, and drip infusion unit are implemented. After the patient enters the irradiation room, the 3-dimensional coordinates of the patient’s head are set and recorded. By monitoring the output of the reactor and the blood...
boron concentration just before irradiation, we decide on the radiation time so that the normal surrounding-brain dose is less than 12 Gy-Eq.

Clinical Follow-Up
All 17 patients were carefully followed up every 1–3 months by means of neurological examinations and MRI imaging. The time to progression and overall survival (OS) were determined. Adverse events were recorded with grading by the National Cancer Institute Common Toxicity Criteria Versions 2 and 3. The patients were treated with nimustine- (ACNU-) based chemotherapy as a general rule during the follow-up period. No patient had been treated with TMZ before tumour regrowth, except for one treated under protocol IV.

Results
The patients’ characteristics and average boron concentrations, calculated tumour and normal brain doses are shown in Table 3. The data of 15 patients with newly diagnosed GBM were retrospectively analysed [6].

Adverse Events
Only 2 of the newly diagnosed GBM patients suffered an acute adverse event beyond grade 2. One protocol-III patient suffered transient orbital swelling accompanied by double vision (grade 2); one of the protocol-I patients suffered post-epileptic brain swelling (grade 4) requiring surgical intervention. We had some grade-1 adverse events of redness, fever, and itching in protocols I and II.

Boron Concentration
Patients provided as many as 7–10 blood samples before and after irradiation. Both concentrations (boron from BSH and boron from BPA) were predicted from the time course of the boron concentration curve. Average blood boron concentration from the predicted BSH and BPA concentrations was 34.6 ± 9.6 µg/g for BSH and 17.4 ± 2.4 µg/g for BPA (protocol III, n = 8).

Dose Estimation
In protocol I, the neutron dose was analysed with a gold radio-activation method using fine gold wires. We placed the gold wire on the surface of the brain and in the surgical cavity during craniotomy, but the spatial resolution of the measurement point was > 5 mm. The peak dose of the treatment field is described in Table 3. The maximum normal brain dose of protocols I and II was 29.4 ± 6.0 Gy-Eq (n = 7, range 20.1–36.0).

In protocols II–IV, as described in the treatment planning system, the boron dose and the non-boron dose were summed and converted to the equivalent dose of 2-Gy-fraction conventional radiotherapy. The maximum normal brain and skin doses were 11.4 ± 1.5 Gy-Eq. The minimum tumour dose of the clinical target volume (CTV –2 cm) was 15.1 ± 5.4 Gy-Eq.

Protocol-IV Case
The 40-year old male patient had suffered from severe headaches due to increased intracranial pressure. Emergency left-temporal tumour removal was performed and the pathological specimen revealed a GBM. Two months after surgery, BNCT was performed. The average blood boron concentration was 12.6 µg/ml, the maximum skin dose was 9.8 Gy, and the normal brain dose was 11.7 Gy. The minimum target (GTV + 2 cm) dose was 11.2 Gy. After BNCT, he received 40 Gy of 20 fractionated external photon irradiations instead of a BSH-induced boron dose. The serial MRI scan is shown in Figure 2. The tumour was controlled for 1 year, but out-of-field tumour growth resulted in his death 19.9 months after BNCT. Normal brain tissue tolerated this protocol. The effect of the protocol on the patient’s scalp was unremarkable, but loss of hair remained for more than 1 year.

Protocol-IVr Case
The 53-year old male patient had a tumour in the left-temporal lobe removed with the pathological diagnosis being GBM. At a deep part of the surgical defect, there was a residual tumour growing during postoperative radiation and concomitant temozolomide treatment. He was referred to our hospital for additional BNCT, which was performed 4 months after initial surgery, using BPA only. Average blood boron concentration was 13.7 µg/ml, maximum skin dose was 8.4 Gy, and normal brain dose was 10.5 Gy. Minimum target (GTV + 2 cm) dose was 15.9 Gy. The serial MRI image is shown in Figure 2B. The patient underwent skin and muscle transplantation due to infection and necrosis, but more than 3 years after BNCT, the MRI image of the tumour and his performance status were stable.

OS of Newly Diagnosed GBM
Median overall survival (mOS) of GBM patients has already been reported [34]. In our series, mOS was 22.3 months for grade-4 patients (protocols I, II, III, and IV; n = 16). The Kaplan-Meyer curve is given in Figure 3. The longest mOS was that obtained in protocol III (n = 8) alone, which was 27.1 months.
Discussion

In our case series, we selected patients with shallow glioblastoma and KPS > 50 %. During the protocol-III period, about ¼ of the GBM patients underwent BNCT, and another ¼ underwent proton radiotherapy. The remaining half were treated by conventional radiotherapy. We have reported that the positive effect of BNCT and proton treatment is unlikely to reflect patient selection alone in our serial case series [6], and overall survival of a particle therapy group was 24.4 months (95-% CI: 18.2–30.5 months) compared with 14.2 months (95-% CI: 10.0–18.3 months) for those treated with conventional radiotherapy. This survival difference between the conventional treatment group and the high-dose particle radiation group suggests that our case selection was appropriate.

Among the 15 selected GBM cases, we observed one long-term survivor who did not develop a recurrence over a period of > 5 years. She has shown no symptoms and takes no medication. Even if a statistically significant difference is not revealed in the entire series, curing GBM is possible by choosing the cases appropriately.

GBM is the most common and invasive form of malignant glioma. The Japanese tumour registry indicates that the 1-year survival rate for GBM is 55.1 %, and the 5-year survival rate is 6.9 %. This data was collected before the approval of temozolomide, and recent data would be pre-analytical. Randomised clinical trials for GBM patients have been initiated; for example, a search of clinicaltrials.gov revealed 829 trials for glioblastoma but only 45 trials with results. This illustrates that the difficulty in completing a clinical trial for GBM patients is due to the onset frequency and the limited number of patients.

Randomised controlled trials for GBM indicate that at least several hundred cases would be necessary to statistical-ly prove the effectiveness of new chemoradiotherapy. Because reactor-based BNCT can be conducted only at a few sites around the world, it is challenging to enroll the necessary hundreds of GBM cases in order to perform randomised controlled trials and test the effectiveness of BCNT for this disease. Moreover, primary brain tumours are an “orphan disease” as the Japanese brain tumour registry revealed an annual incidence of primary brain tumours of approximately 12–15 cases per 100,000 persons and a 9.1 % rate of prilm brain tumours for GBM [42].

Other BNCT Trials for Glioblastoma

Previous BNCT clinical trials for glioma are summarised in Table 1. Kyoto University and Osaka Medical School carried out clinical trials with modern BNCT techniques. They used 100 mg/kg BSH and 700 mg/kg BPA with a 6-h infusion, and the patients also received an X-ray boost. MOS was 23.5 months following diagnosis [29, 43, 44].

Kankaaranta et al at the Helsinki University Central Hospital and the VTT Technical Research Center of Finland performed BNCT for GBM and recurrent GBM, using 290 mg/kg BPA or 450 mg/kg; the reported survival was 13.4 months and 21.9 months, respectively [27]. The European Organization for Research and Treatment of Cancer carried out a phase-I study of BSH-based BNCT (protocol #11961). They reported the toxicity of BSH-based BNCT, cerebral atrophy, and white-matter abnormalities [25, 45, 46]. A group in Sweden used 900 mg/kg BPA for a 6-h infusion. MOS for their 29 patients was 14.2 months [36, 37]. All of these clinical trials were carried out with very small numbers of patients and the patients were selected cases. It is thus difficult to compare these results with historical or standard therapy data.

Developing Accelerator-Based BNCT

If there are many target patients, treatment throughput is very inefficient with reactor-based BNCT because of difficulties in enrolling the treatment. It is difficult to market medical equipment using a nuclear reactor in Japan, but the development of the accelerator neutron source is of greater concern. Although the accelerator neutron source presents the issues of the heat-treatment of the target and radio-activation of the facilities, a clinical treatment facility was built by Kyoto University, and a phase-I clinical trial is ongoing at the facility.
Conclusions

Our clinical trial of BNCT for glioblastoma patients showed promising survival benefits. BNCT presents a difficulty as a high-throughput treatment, and thus the studies of BNCT clinical treatment have all used small case series. To overcome these difficulties we look forward to the development of accelerator-based BNCT.

Conflict of Interest

The authors have no conflicts of interest to report.


