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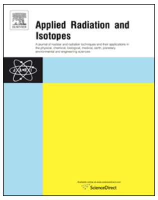

A prospective study to assess the performance of the improved Boron Neutron Capture Therapy Facility in Argentina

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HIGHLIGHTS

- Several planned modifications were implemented at the RA-6 reactor in Argentina.
- Modifications lead to significant benefits for future clinical BNCT treatments.
- New capabilities have been implemented in NCTPlan treatment planning system.
- Dosimetric reevaluation of clinical cases was performed in the new facility.
- Optimized plans that considered feasible patient set ups were assessed.

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ABSTRACT

From 2008 to 2011, several planned modifications were implemented at the RA-6 reactor in Argentina, leading to significant benefits for future BNCT treatments. New capabilities have been implemented in NCTPlan treatment planning system. To assess the performance of the new BNCT facility, a dosimetric reevaluation of previous clinical cases was performed, taking into account the modifications carried out in the new facility and compared the results of the original treatment plans with optimized plans that are considered as feasible patient setups.

1. Introduction

The first Boron Neutron Capture Therapy (BNCT) clinical facility in Argentina, named the "B1 beam", was developed in the RA-6 open-pool reactor located in the city of Bariloche (Rio Negro Province, Argentina) (Blaumann et al., 2004). The B1 beam exit port was circular, 15 cm in diameter opening on the wall, with a particular mixed spectrum of thermal and epithermal energies, referred to as a "hyperthermal" beam. In 2001, when the BNCT facility was built, the RA-6 reactor was working with 90% enriched U-235 fuel elements, at a 500 kW of nominal power. For 4 years (2003–2007), patients with melanoma in extremities were treated in this beam with BNCT (González et al., 2004, 2009; Menéndez et al., 2009).

During the years 2008–2011, and within the frame of the Reduced Enrichment for Research and Test Reactors (RERTR) international program, the Argentine RA-6 reactor's core reconversion process to operate with low-enrichment uranium was accomplished. Along this time, several planned modifications were implemented in the RA-6 BNCT facility, leading to significant benefits for future BNCT clinical treatments. The upgrades were meant not only to improve the spectral characteristics of the neutron beam and the treatment room capabilities (e.g., room dimensions, full degree of freedom positioning lasers, etc.), but also to integrate a protruding conical irradiation port to facilitate patient positioning during treatment. In order to continue with the clinical phase II trial started in 2003, an extensive quality assurance control has been performed comprising the physical and computational systems involved in the clinical treatment.

This work presents the improvements implemented in the clinically used treatment planning system, NCTPlan (González et al., 2002), and several computational dosimetry evaluations with the new beam (Longhino et al., 2012) (from now on, the "B2 beam") for two especially selected patients, treated between 2003 and 2007. Considering the results of these evaluations, a dosimetrical comparison

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with the former B1 beam is carried out, showing the present capabilities of the new BNCT facility.

2. Materials and methods

2.1. *NCTPlan treatment planning system upgrade*

In order to provide the necessary treatment plans for the continuation of the BNCT melanoma clinical trials in Argentina, new and superior capabilities have been implemented in NCTPlan treatment planning system, leading to its new version, NCTPlan v1.4. The most relevant features that were considered for this new version are the following:

- The integration of MPREP auxiliary code to the main architecture of NCTPlan.
- The possibility of dealing with neutron sources described in Track-by-Track (TBT) mode.
- The ability of managing volumetric representations of a wide variety of geometrical structures between the source and the patient (collimators, shields and additional filters).

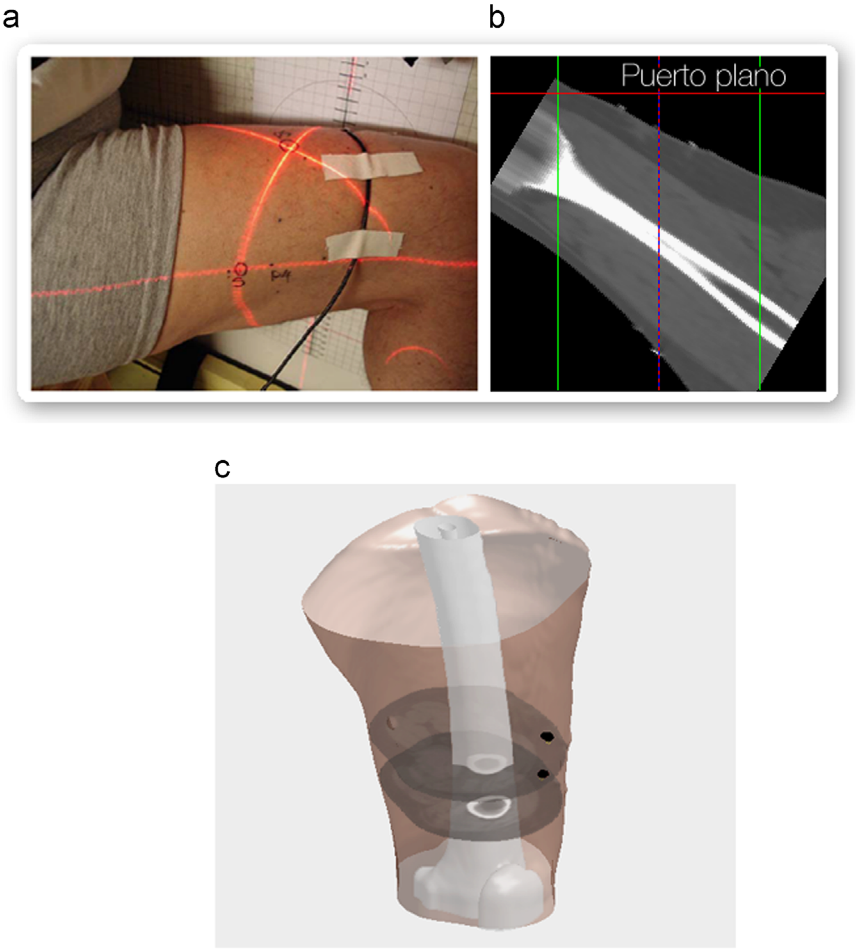

Fig. 1. Patient position during treatment verification (a) and NCTPlan v1.3 central axis view with the B1 beam port plane localization (b). Patient's computational reconstruction showing the position of both nodules (c).

Fig. 2. NCTPlan v1.3 coronal view (left) and sagital view (right) centered in the B1 beam entry coordinates. Patient position during treatment; Note that the foot limits the distance to the beam port (center).

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- In addition, a new module for accelerator-based treatment planning has also been included.

2.2. *RA-6 beam characterization*

To study the quality and performance of the new RA-6 clinical beam B2, simulations of a water cubic phantom irradiation were performed and a dosimetric analysis was carried out. The results were compared with the former B1 clinical beam. The comparison was performed in terms of the standard dose components usually adopted in any BNCT treatment calculation, i.e., boron, thermal neutron, fast neutron and gamma dose components.

2.3. *Clinical cases analyzed based on the B2 beam*

To assess the performance of the new BNCT facility, a dosimetric reevaluation of previous clinical cases was performed. The evaluation took into account the modifications carried out in the new facility and compared the results of the original plans with those improved plans that considered feasible patient's set ups in the new facility.

In this work, two representative cases of cutaneous melanoma were studied; these cases were chosen in order to quantify the improvement in dose delivery when positioning constraints are not present. The first patient analyzed was a woman with two nonsuperficial lesions located on the inner face of the right leg. The location of the nodules made difficult to achieve the best patient positioning for the treatment, since no protruding cone existed in the former B1 beam. This leads to an unequal distance between the irradiation port and the lesions. Fig. 1 shows the original positioning and the treatment plan visualization in the main axis.

The second patient selected for the comparison was a woman with several lesions disseminated over the anterior part of the right leg. Lesions location in combination with the B1 beam treatment room dimensional limitations and treatment duration (around 70 min) did not allow to minimize the distance between the region to treat and the neutron beam port (Fig. 2).

To overcome these restrictions, and to improve treatment outcomes in future patients considering the aforementioned modifications in the treatment facility, different treatment plans were assessed using NCTPlan v1.4 with a MCNP5 (X-5 Monte Carlo Team, 2008) TBT detailed B2 beam description.

3. Results and discussions

3.1. *Global characteristics of the RA-6 B1 and B2 beams*

Although B2 beam characteristics were profusely assessed and experimentally validated by the reactors and medical physics departments before embarking on treatment plans, we simulate the different dose components in a cubic water phantom, and compared them with the B1 beam dose components in order to fully understand the potential of the new beam. For simplicity, the overall characteristics of both beams are presented in terms of the boron dose component: depth–dose profiles along the beam central axis and transversal profiles at the depth of maximum dose for each beam.

As can be seen in Fig. 3(a), B2 in-phantom maximum thermal neutron flux is located 3 mm deeper than that of the B1 beam. This implies, in addition to the slight improvement in over 90% dose region width, an increase in total neutron fluence and uniformity, allowing to treat volumes seated up to 25 mm depth.

Fig. 3(b) shows the comparison between the transversal profiles at the depth of maximum dose for both beams. It can be seen that the dose distribution is flatter in the new configuration compared to the former, providing a larger irradiation area and in consequence better capabilities for treating multiple scattered

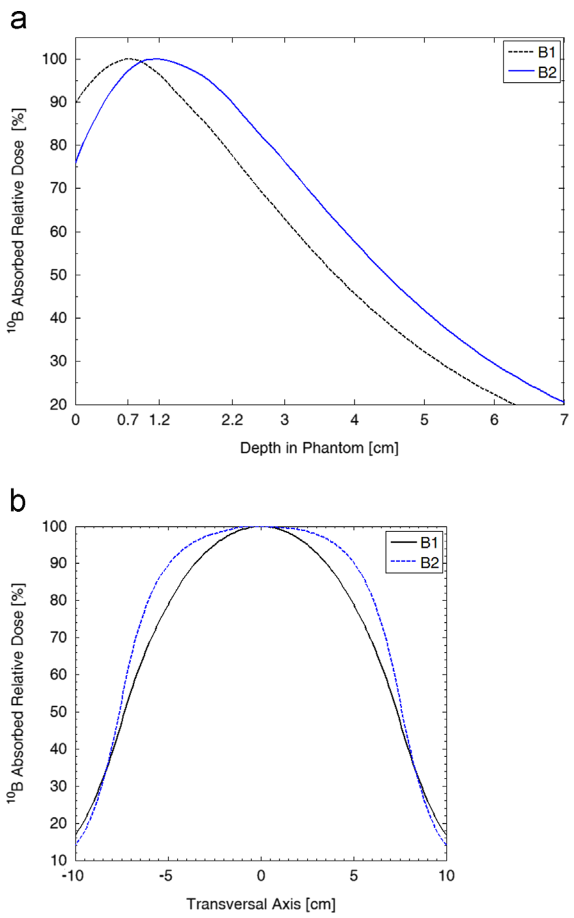

Fig. 3. Boron dose comparison between B1 and B2 beams in a cubic water phantom. Depth–dose profiles (a) and transversal profiles at maximum dose depth (b) are presented.

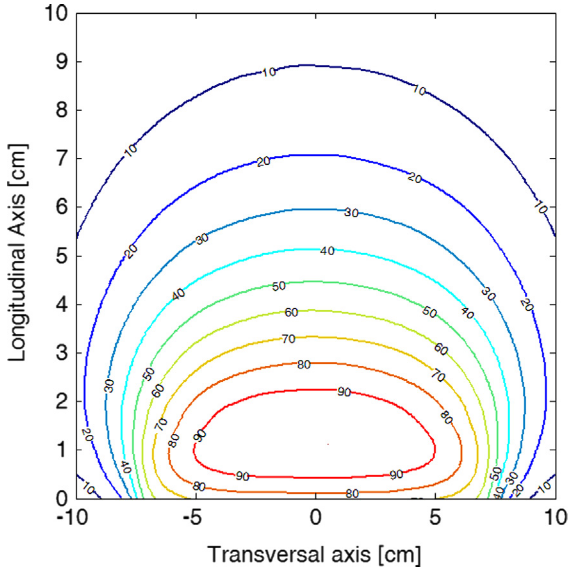

Fig. 4. Boron dose component isodose curves in depth. 2 cm depth and 10 cm transversal region encompassing the 90% isodose are shown.

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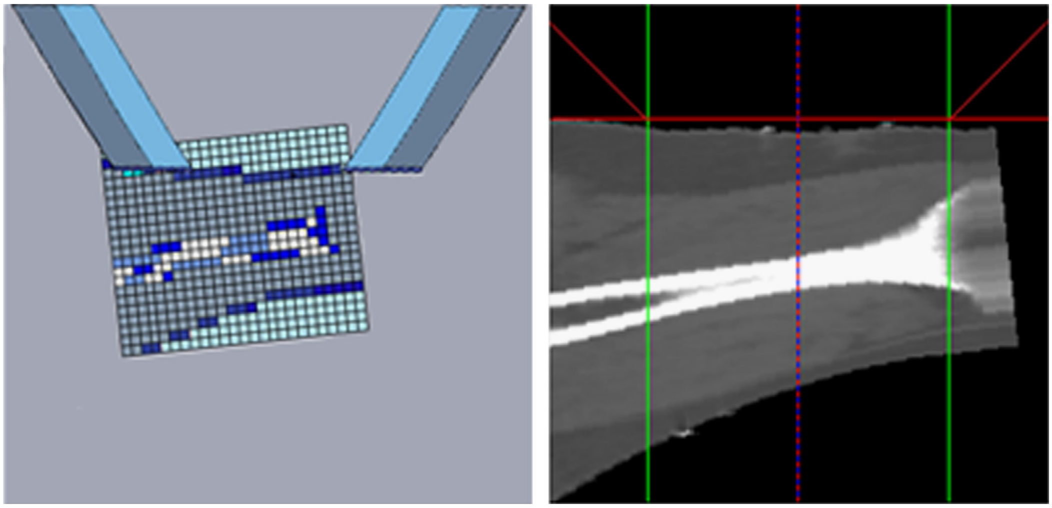

Fig. 5. NCTPlan v1.4 voxelized model in the new treatment plan position (left). Central axis CT slice location with respect to the cone plane shows that a better irradiation can be achieved (right).

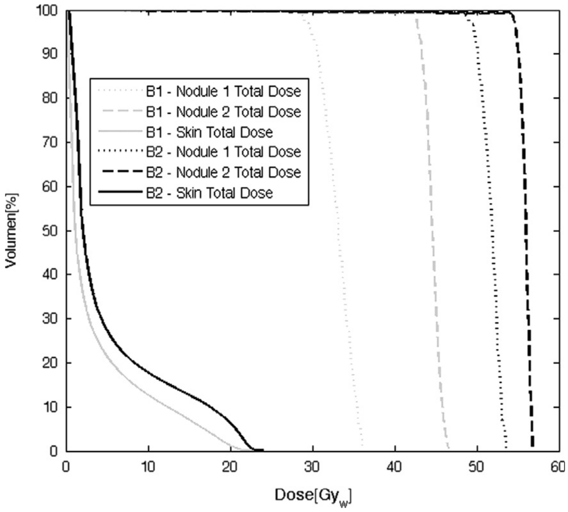

Fig. 6. DVH for skin (dose limiting organ) and nodules, for both beams. The dose delivered to the tumors exhibits an increased homogeneity considering the proposed treatment plan.

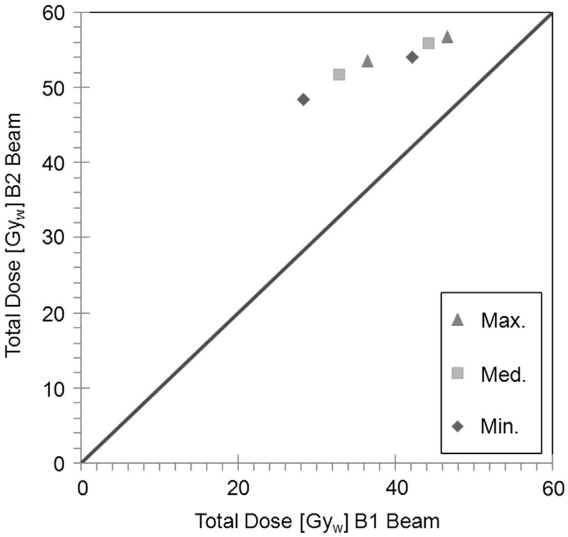

Fig. 7. Minimum, mean and maximum dose delivered to the nodules. Comparison between B1 and B2 beam dosimetry.

lesions. This is also appreciated when isodose curves are plotted in depth at the beam central axis (Fig. 4).

3.2. *Optimized cases*

In order to evaluate the impact of the new facility, a new treatment plan for the first patient was carried out, repositioning the anatomical volume in order to minimize the distance from the nodules to the beam port, a position totally feasible with the new protruding cone (Fig. 5) in a reproducible and safe way.

Treatment plan dosimetry was performed with NCTPlan v1.4 and MCNP5. Weighted dose and thus irradiation time were calculated using the same weighting factors and boron concentrations in order to reach the prescription dose adopted in the real treatment and reported in Comunicación Interna, Reporte Final: Paciente 7, Irradiación 9, (2007).

Fig. 6 shows a comparison between DVHs obtained with previous and optimized plans.

In order to reach the prescription dose in skin (maximum 22 Gy$_W$) the required irradiation time decreases by 11% (61 min) while the delivered dose to the first and second lesion increases by 32% and 18%, respectively. Fig. 7 shows the comparison between B1 and B2 beams in terms of minimum, mean and maximum dose delivered to the nodules. The dose improvement in tumor with the new proposed treatment can be appreciated.

The second patient presented ten lesions scattered around a 70 mm radius area, as can be seen in Fig. 8. Treatment plan dosimetry was performed with NCTPlan v1.4 in order to maximize the number of lesions encompassed in the 90% or higher neutron flux region. Weighted dose and thus irradiation time were calculated using the same weighting factors and boron concentrations employed in the real treatment, in order to reach the prescription dose and reported in Comunicación Interna, Reporte Final: Paciente 3, Irradiación 3, (2004). The new proposed treatment reduces the irradiation time in 15% (70 min) compared with the original one, and a reduction of the relative different between maximum and minimum doses of each nodule in comparison with B1 implies a more homogenous dose distribution.

Fig. 9(a) shows the dose distribution in the proposed treatment. The results are consistent with the location of the nodules in the patient's leg (Fig. 8). In comparison with the B1 beam (Fig. 9 b), the proposed treatment shows an increment in the minimum dose

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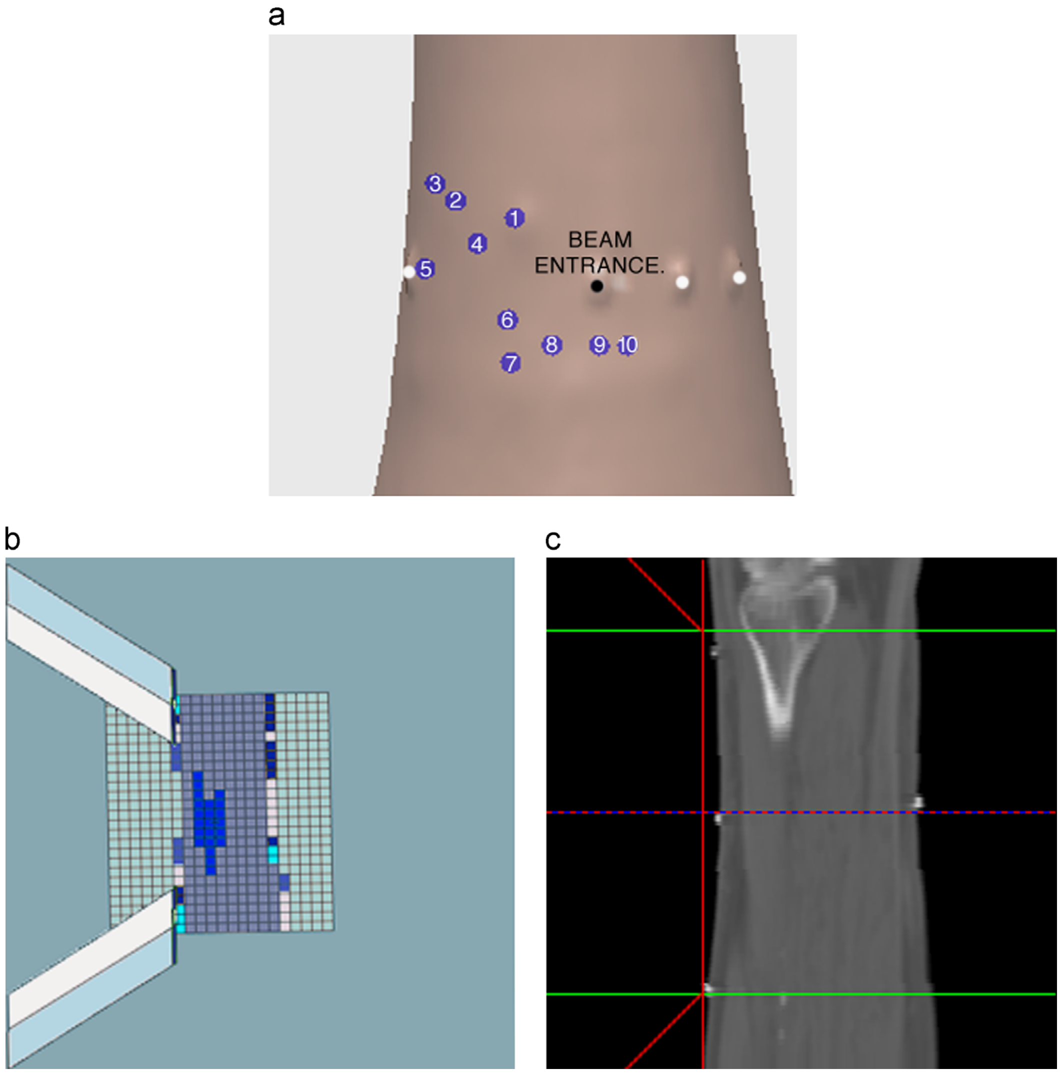

Fig. 8. Region treated computationally reconstructed (a). Nodules' position and ID numbers are depicted. Beam entrance point is indicated in black. NCTPlan v1.4 voxelized model in the new treatment plan position (b). Central axis CT slice location with respect to the cone plane shows that a better irradiation can be achieved (c).

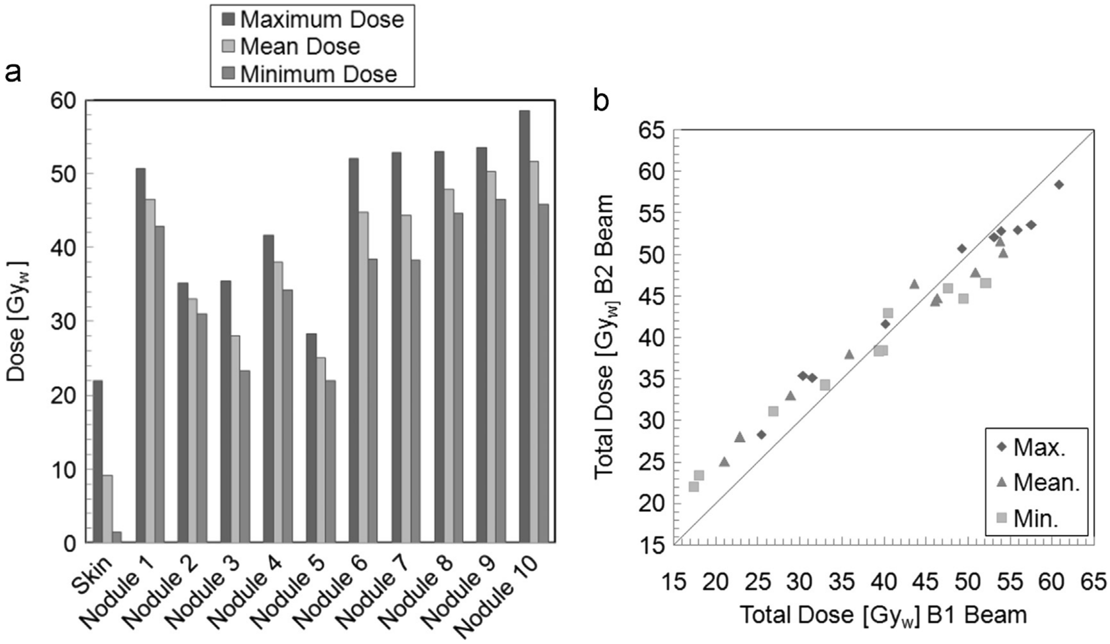

Fig. 9. Minimum, mean and maximum doses in each lesion using the proposed treatment plan with the B2 beam (a). Comparison between B1 and B2 beam treatments in terms of minimum, mean and maximum dose delivered to the nodules (b).

received by the farthest lesions in comparison with the original treatment. Central nodules present a small dose decrease, although the minimum dose delivered in these cases is always over 30 $\mathrm{Gy_W}$. Despite the reduction, all the optimized treatment doses are within the clinically accepted values.

4. Conclusions

NCTPlan, due to its robustness and versatility could be adapted to new requirements by introducing a new geometrical description module and a TBT source description support. Reevaluation of previous clinical cases with the new RA-6 BNCT facility has demonstrated the dependence of the treatment design with the beam characteristics. New positioning capabilities show improved treatment possibilities, resulting in very reasonable therapeutic dose values with an increased homogeneity.

The deeper and wider 90% isodose curve obtained with the new beam allows treating efficiently deeper nodules, and some additional strategies involving the use of bolus, filters and wedges, will be employed to treat the superficial ones. The new protruding conical irradiation ports and the new treatment couch and room dimensions will allow a more efficient treatment planning, resulting in a dosimetrical improvement and a safer and comfortable positioning for patients.

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