Physica Medica 57 (2019) 145–152

Contents lists available at ScienceDirect

Physica Medica

journal homepage: www.elsevier.com/locate/ejmp

Original paper

A pre-absorber optimization technique for pencil beam scanning proton therapy treatments

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ARTICLE INFO

Keywords:
Range shifter
Pencil beam scanning
Proton therapy
Planning method

ABSTRACT

Purpose: To implement a new proton therapy planning method for the treatment of shallow lesions with PBS and to compare it to the standard method.

Methods and materials: In order to treat shallow lesions, a pre-absorber, usually called range-shifter (RS), is needed: it is used to degrade the beam energy and treat tumors shallower than the minimum range available. Its use is associated to dose calculation uncertainties and plan quality degradation which should be minimized. We studied five tumor localizations requiring RS and created three plans for each case: a) standard method with the RS close to the patient surface, b) with the RS used only for the shallow part of the tumor (when strictly needed) and completely retracted and c) as the b) approach but with the RS close to the patient. We called these two approaches 'Range Shifter Optimization' (RSO) techniques. We compared those plans in terms of dose distribution quality, delivery time and patient-specific-QA results.

Results: In most cases a good dose reduction to OARs with no significant loss in terms of target coverage was obtained when the RSO techniques were used. Patient-specific-QA gave very good results in terms of γ-Passing-Rate (PR) (3%, 3 mm) for both RSO techniques (mean 98.09%), while the standard had some very low PR (minimum 81.09%). The delivery time increased (5.0 min on average per treatment) but was still acceptable in terms of patient compliance.

Conclusion: We developed a new planning technique for shallow lesions and we demonstrated its superiority in terms of both plan quality and patient-specific-QA results with respect to the standard method. This technique is routinely used to treat patients in our center.

1. Introduction

In pencil beam scanning proton therapy treatments is possible to treat almost all tumors without using any passive object on the beamline. The only parameter that forces to use a passive beam modifier is the minimum energy. Usually the minimum energy is either 70 or 100 MeV [1], corresponding to 4.1 cm or 7.5 cm of water equivalent thickness, respectively [1]. This means that, for minimum energies available of 70 MeV, tumors located at a water equivalent depth shallower than 4 cm cannot be treated if a pre-absorber is not used. This pre-absorber, from here on named range shifter (RS), is made of plastic (e.g. acrylonitrile butadiene styrene, Lexan, Lucite, polyethylene, polystyrene, wax etc. [2]) and placed in front of the exit window of the nozzle. The RS is mounted on a moveable "snout" that allows to reduce the air gap between the RS and the patient surface [2–6].

Several studies have discussed and demonstrated that pencil beam dose calculation algorithms do not accurately estimate the dose when the RS is used [6–9] and the neutron produced in the RS and scattered in the beam direction are not accounted for in most commercially available treatment planning systems even if they have a Monte Carlo based dose calculation algorithm. Some of them include their fraction of absorbed dose in the energy balance [10]. Moreover, a large air gap implies a scatter source far from the patient, thus deteriorating the lateral penumbra and increasing the uncertainties in determining the dose in the patient [3,11,5,12,13,9]. Because of these uncertainties we introduce a technique to use the RS only when strictly needed (i.e. only for the shallower part of the tumor) in contrast with the standard technique that makes use of the RS to irradiate the entire volume. From

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https://doi.org/10.1016/j.ejmp.2018.12.014
Received 17 April 2018; Received in revised form 16 November 2018; Accepted 19 December 2018
Available online 09 January 2019

here on this approach will be called *Range Shifter Optimization* (RSO) method. In this work we present:

1- a complete description of the method,
2- a workflow to realize it in the planning phase of the treatment,
3- a planning comparison between the standard technique (RS always on the beamline during the delivery), the RSO method with the snout completely retracted and the RSO method with the snout extracted as close as possible to the patient surface for five different clinical cases,
4- a comparison of patient specific quality assurance (PSQA) results for each of these five cases,
5- an estimation of the increase of delivery time with the new technique.

To our knowledge this is the first study that shows in detail the impact of the use of RS on clinical examples of PBS proton therapy treatments.

2. Materials and methods

Our proton therapy center is a cyclotron-based facility (IBA ProteusPLUS) featuring pencil beam scanning as the unique beam delivery technique in two isocentric gantry rooms. The minimum energy available is 70 MeV and an extendable snout is mounted on each gantry (Fig. 1). Further technical details about our center can be found in Schwarz [1]. The physical thickness of the RS is 3.61 cm with a water equivalent thickness of 4.1 cm. It is made of lexan polycarbonate.

In this section the planning method of the Range Shifter Optimization is explained. The five patient cases included in this work will be introduced in order to show advantages and disadvantages of the planning method proposed. The TPS used is RayStation (RaySearch Laboratories, Stockholm, Sweden) version 6 [19].

Each patient was planned with the Single Field Optimization method (SFO) [14] with a dose grid of 2 mm^3 of resolution. At the end of the section the patient specific QA method and its data analysis is described.

RayStation gives the possibility to use a pencil beam and a clinical version of a Monte Carlo dose calculation algorithm [10,12]. The choice of the algorithm used has an impact on the dose calculation accuracy. The pencil beam, at the time being, is still the most widespread even if recent publications highlighted its weaknesses on dose accuracy [9,6,12]. We used the pencil beam algorithm for the planning phase. For patient specific QA we recalculated each plan with Monte Carlo algorithm to show the impact that a more reliable code can have on patient specific QA results.

2.1. Range shifter optimization planning method

The precondition to use the Range Shifter Optimization method is to have a lesion where the volume deeper than 4 cm water equivalent thickness (WET) is at least as large as the volume shallower than 4 cm. If this condition is not verified, the method is not applied and a single beam with the RS always in the beamline is used. This condition ensures that the number of energy layers delivered without the range shifter (tumor part deeper than 4 cm) is greater than or equal to the number of energy layers delivered with the range shifter (tumor part shallower than 4 cm). If the number of layers delivered without the RS is smaller compared to the number of layers delivered with the RS it is more convenient in terms of delivery times to treat the patient with the standard technique.

If the above condition is verified the use of RS is optimized in order to reduce its use as much as possible. Once the beam arrangement is determined each beam is divided into two parts: the first part is limited to ranges between 0 cm and 4 cm WET and makes use of the RS. The second part is restricted to depths from 4 cm to the distal end of the target volume and does not make use of the RS. For the beam with the RS we set the maximum deliverable radiological depth of the pencil beams to be equal to 4 cm WET. With this method a distribution of spots as shown in Fig. 2 is obtained.

Once the spots are placed, the two beams are optimized together and treated as one by the optimization algorithm in order to have a homogeneous dose distribution.

2.2. Clinical cases

In order to evaluate the impact of the different techniques on different organs at risk, five different tumor lesions were selected, and one of them was studied in two different locations (medulloblastoma, treated with cranio-spinal irradiation, in the region of eyes and kidneys): a lumbar chordoma (spine tumor in the pelvic region), a paraganglioma (Head & Neck tumor), a medulloblastoma (a pediatric tumor which requires the whole brain and the entire spinal cord irradiation), a meningioma (brain tumor) and an osteosarcoma (base-skull tumor). For each case three plans were optimized:

- Standard plan: no RSO method was used and, when the RS was needed it was always on the beamline as close as possible to the patient surface.
- Max Air Gap plan: RSO was used but the RS was not extracted (i.e. the distance from the isocenter was the maximum available).
- Min Air Gap plan: RSO was used and the RS was extracted as close as possible to the patient surface.

We optimized each plan in order to reach the same coverage of the target for every technique.

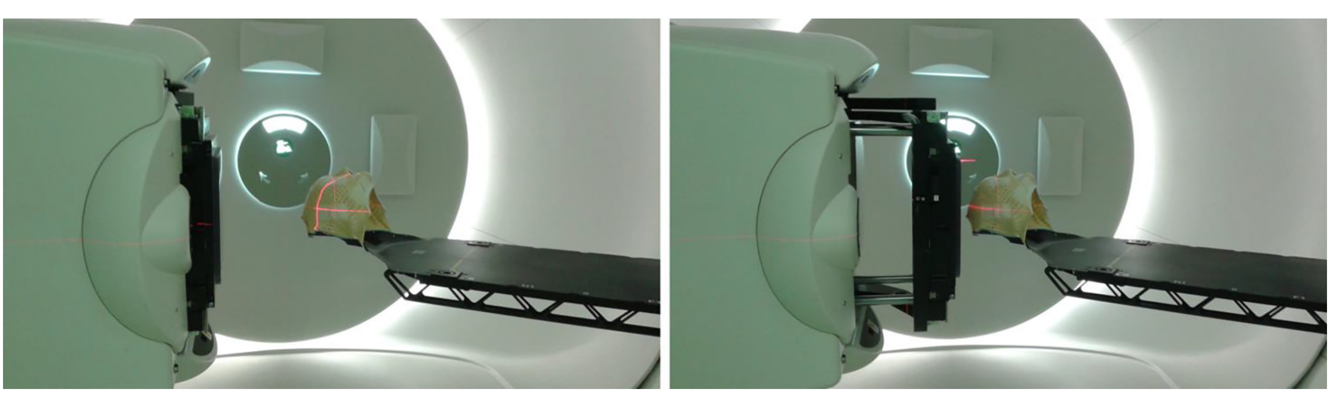

Fig. 1. Left: range shifter mounted in front of the gantry head. Right: range shifter extracted toward the patient in order to reduce the air–gap [3].

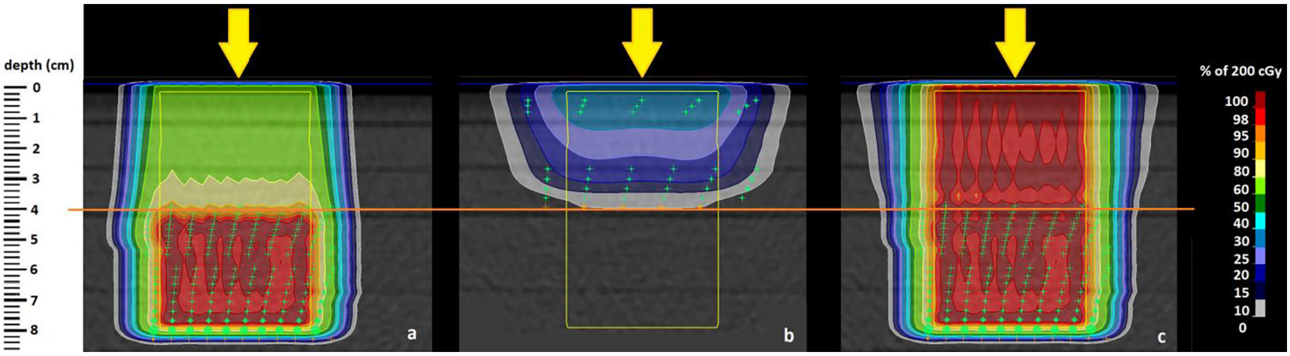

Fig. 2. Yellow arrows represent the beam incident direction. a: the beam without RS places spots from 4 cm to the distal end of the target volume. In the same figure its dose distribution is shown. b: the beam with the RS places spots from the surface (blue line) up to 4 cm in depth. c: the final dose distribution given by the sum of dose distributions of the two beams. In the figures the dose is normalized to 200 cGy. The yellow contour is the target delineated to optimize the SOBP. The horizontal orange line highlights the 4 cm depth of interest. On the left there is the scale to associate the depth in water. The green crosses represent the spots as they are placed by TPS in the treatment volume. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The effect on the plan quality and PSQA results due to the use of the RSO method and the reduction of RS distance from the isocenter were investigated. A detailed description of the prescription, plan parameters (beam arrangement, snout extensions etc.) and an estimation of the delivery time for each method were reported.

2.2.1. Case 1: Lumbar chordoma

For this case the clinician contoured two volumes: a low risk and an high risk target. The first was treated with 50 GyRBE (2 GyRBE per fraction), while the second was treated with up to 74 GyRBE with a sequential boost using the same fractionation scheme. Each PTV started from the patient surface and reached a maximum physical depth of 16.2 cm (Fig. 3a). The low risk PTV had a volume of 2110.25 cc, while the high risk volume was 626.52 cc. The OARs considered for the analysis were the cord, the duodenum and the kidneys.

The beam arrangement was the same for both volumes: two posterior beams with gantry angles of 175° and 195°. In the standard plan and in the *Min Air Gap* plan the snout to isocenter distance was 36 cm. For these plans the air gaps of the two fields were 13.5 and 24.0 cm, respectively. It was not possible to further reduce the air gap because of geometrical collisions.

2.2.2. Case 2: Paraganglioma

This is a case of head and neck tumor, as showed in Fig. 3b. The prescribed dose for the PTV (Fig. 3b) was 50 GyRBE (2 GyRBE per fraction). The PTV volume was 115.54 cc and the maximum physical depth was 7.75 cm. The OARs considered were the brainstem, the cord, the thyroid and the coclea.

Three beams were used: a posterior beam (no RS needed) and two oblique beams: one with gantry angle at 40° and couch angle at 0°and the second with gantry at 90° and couch angle at −15°. The snout to isocenter distance for standard and min *Air Gap* plans were 20.0 cm and 27.3 cm, for the two beams with the RS, respectively. The corresponding air gap was 4.0 cm for both of them.

2.2.3. Case 3: Medulloblastoma

This is a pediatric tumor treated with cranio-spinal-irradiation (CSI). In this study we focused on the region of the spine close to the kidneys and on the brain region close to the eyes and cribriform plate (see Fig. 3c). A detailed description of the beam arrangement used in this planning technique is given in [4,15]. For the first 11 fractions the vertebral bodies and the whole brain were treated with 1.8 GyRBE per fraction. For other 9 fractions, only the spinal canal and the whole brain were treated with the same fractionation scheme (1.8 GyRBE). At the end of the treatment the vertebral bodies received 19.8 GyRBE while

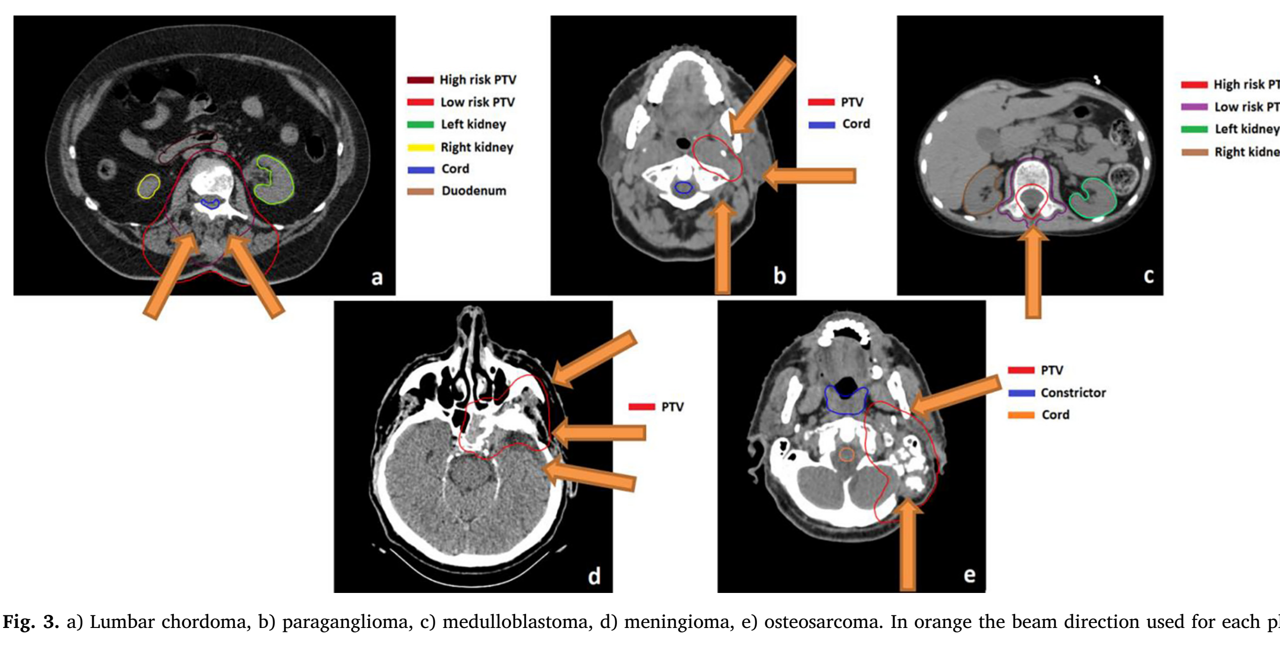

Fig. 3. a) Lumbar chordoma, b) paraganglioma, c) medulloblastoma, d) meningioma, e) osteosarcoma. In orange the beam direction used for each plan.

the brain and the spinal cord received 36 GyRBE (medulloblastoma high risk prescription). The OAR considered for this study were the kidneys and the lenses. In the planning phase the primary aim was the coverage of the target including the cribriform plate in the brain while reducing as much as possible the dose to the lenses.

The minimum snout to isocenter distance when the RS was extracted towards the patient was 33.0 cm and 36.0 cm for the posterior and the lateral oblique beams used for the irradiation of the brain, respectively. The air gap were 11.0 and 1.0 cm respectively. For the posterior beam it was not possible to bring it closer to the patient due to geometrical collision. The maximum depth in the lower part of the spine for the posterior beam was 15.37 cm while the maximum depth in the brain was 26.24 cm.

2.2.4. Case 4: Meningioma

This is a case of brain tumor, as showed in Fig. 3d. The prescribed dose for the PTV (Fig. 3d) was 54 GyRBE (1.8 GyRBE per fraction). The PTV volume was 183.52 cc and the maximum physical depth was 9.13 cm. The OARs considered for this study were the brainstem, the parotid, the ear canal and the optical nerve.

Three beams were used: one with gantry angle at 70° and couch angle at −40°, the second with gantry at 95° and couch angle at 0° the last with gantry at 90° and couch at −80°. The snout to isocenter distance for standard and min *Air Gap* plans were 20.0 cm, 28.0 cm and 20.0 cm, respectively. The corresponding air gap were 8.2 cm, 10.0 cm and 5.0 cm.

2.2.5. Case 5: Osteosarcoma

This is a case of skull-base tumor, as showed in Fig. 3e. The prescribed dose was 70 GyRBE (2.0 GyRBE per fraction). The PTV volume was 219.76 cc and the maximum physical depth was 12.1 cm. The OARs considered for this study were the brainstem, the spinal cord and the constrictor.

The plan was prepared by using two beam directions: one posterior beam with the couch at 0° and one lateral-oblique beam with gantry angle at 80° and couch angle at 0°. The snout to isocenter distance for standard and min *Air Gap* plans were 33.0 cm and 30.0 cm, respectively. The airgap were 8.8 cm and 1.5 cm, respectively.

2.3. Patient specific QA measurements and analysis

Once the plan was approved by the clinician it was dosimetrically verified by performing the PSQA procedure. Part of this procedure consisted in to delivering each beam with gantry and couch angles collapsed at 0°, on an homogeneous water equivalent phantom and to measuring the planar dose distribution at, at least, three depths per field, in the high dose region of each field, with an array of ionization chambers [16–18]. In particular for Chordoma case measurements were performed at 2, 8 and 14 cm, for Paraganglioma case at 2, 4 and 6 cm, for Medulloblastoma at 2, 4 and 8 cm, for Meningioma at 2, 4, 6 and 10 cm while for Osteosarcoma at 2, 4, 6 and 10 cm. Those measurements were compared with TPS calculation via a γ analysis with 3%, 3 mm agreement criteria (global approach). The acceptance threshold for the γ passing rate was set to 90%. Given the results obtained in Shirey et al. [5], Saini et al. [12] and Langner et al. [13] we recalculated all the PSQA with the Monte Carlo dose calculation algorithm available in our TPS [10,12,19]. The dose grid size and resolution used was the same as for the pencil beam algorithm, the statistical uncertainty was set at 0.5%. The statistical uncertainty in RayStation 6 is defined as the average statistical uncertainty for all voxels with dose larger than 50% of the maximum dose [10].

3. Results

In Table 1 dosimetric indexes describing the results obtained by each planning approach for the five studied cases are summarized.

Table 1

Main DVH indexes of three different plans optimized for each case. Dosimetric values selected for OARs useful for the evaluation of the planning technique are shown. Dose indexes are expressed in GyRBE unless otherwise specified.

a) Case 1: Chordoma

Chordoma	DVH index	Plan Type		
		Standard Plan	RSO Max Air Gap	RSO Min Air Gap
PTV LowRisk	V_{95}	99.90%	99.91%	99.92%
	D_{95}	51.52	50.81	50.57
	D_1	75.60	75.43	75.39
PTV HighRisk	V_{95}	93.00%	94.34%	93.33%
	D_{95}	69.51	69.86	69.82
	D_1	76.65	76.51	76.48
Cord	D_1	49.67	49.74	49.72
Duodenum	D_1	35.20	30.37	30.42
Right Kidney	Mean Dose	1.33	0.42	0.41
Left Kidney	Mean Dose	5.86	2.88	2.85

b) Case 2: Paraganglioma

Paraganglioma	DVH index	Plan Type		
		Standard Plan	RSO Max Air Gap	RSO Min Air Gap
PTV	V_{95}	98.19%	97.52%	98.38%
	D_{95}	49.47	48.63	49.33
	D_1	52.89	52.83	53.13
Brainstem	D_1	46.75	45.82	46.46
Cord	D_1	11.04	9.94	10.05
Thyroid	D_1	21.08	27.93	19.87
Left Coclea	Mean Dose	34.57	34.40	34.39

c) Case 3: Medulloblastoma

Medulloblastoma	DVH index	Plan Type		
		Standard Plan	RSO Max Air Gap	RSO Min Air Gap
PTV	V_{95}	98.46%	98.77%	98.79%
	D_{95}	35.14	35.47	35.19
	D_1	37.33	37.55	37.38
Left Kidney	Mean Dose	4.70	3.53	2.80
Right Kidney	Mean Dose	2.96	2.10	1.48
Left Lens	D_1	12.26	9.57	9.50
Right Lens	D_1	11.69	9.85	9.95
Cribriform Plate	D_{95}	34.38	34.19	34.14

d) Case 4: Meningioma

Meningioma	DVH index	Plan Type		
		Standard Plan	RSO Max Air Gap	RSO Min Air Gap
PTV	V_{95}	99.82%	99.00%	99.70%
	D_{95}	54.41	53.53	54.11
	D_1	57.86	57.62	57.62
Brainstem	D_1	45.93	42.50	42.77
Ear canal	Mean Dose	15.02	16.56	12.52
Optical Nerve	D_1	53.89	53.64	53.67
Parotid	Mean Dose	3.49	5.75	3.56

e) Case 5: Osteosarcoma

Osteosarcoma	DVH index	Plan Type		
		Standard Plan	RSO Max Air Gap	RSO Min Air Gap
PTV	V_{95}	97.52%	96.62%	97.96%
	D_{95}	67.64	67.28	67.99
	D_1	73.56	73.87	73.85
Brainstem	D_1	62.04	63.14	62.76

(*continued on next page*)

Table 1 (*continued*)

e) Case 5: Osteosarcoma				
Osteosarcoma	DVH index	Plan Type		
		Standard Plan	RSO Max Air Gap	RSO Min Air Gap
Spinal Cord	D_1	40.44	33.52	33.01
Constrictor	Mean Dose	13.13	9.71	9.52

For the chordoma case the main dose difference are for duodenum and kidneys (Table 1a). The former receives 5 GyRBE less in terms of D_1 with RSO techniques, the latter about 50% less of mean dose with the RSO technique with respect to the standard one. In the first row of Fig. 4 there are the dose differences between the two RSO plans and the standard plan. The reduction of lateral penumbra around the target up to 10 GyRBE is evident for both plans.

In Table 1b, for paraganglioma case, no evident difference can be highlighted. The only OAR with a significant dose difference was the thyroid that showed an increase in D_1 of about 8 GyRBE in the RSO plan with the maximum airgap. In the second row of Fig. 4 a comparison between the standard approach and the two RSO plans in terms of dose difference on the axial plane is shown. The maximum dose difference reaches about 6 GyRBE. It Is evident also that the region at the bottom of the neck receives more dose with the RSO plan with maximum airgap compared to the other two plans: up to 6 GyRBE.

For medulloblastoma case a significant dose reduction of D_1 to the lens and mean dose to the kidneys (2 GyRBE) is evident in Table 1c. In the third row of Fig. 4 there is a dose reduction up to 6 GyRBE around the target in the region of the lateral penumbra. The RSO plan with maximum airgap shows again an increased superficial dose (1.5–3 GyRBE) compared to the other two plans.

The meningioma case shows a significant decrease of maximum dose to the brainstem in the two RSO plans (more than 3 GyRBE, Table 1d) because it is deep and lateral to the target. The ear canal and the parotid, which are close to the surface, show an increase in mean dose in the RSO plan with maximum airgap. The optical nerve does not show any significative difference in the three plans. The fourth row in Fig. 4 shows the important dose reduction in the region of the brainstem when both RSO plans are used and an increase of the dose on the surface for the RSO plan with maximum airgap.

The osteosarcoma case shows no clinically relevant difference of the maximum dose to the brainstem between the three plans. There is a relevant reduction of maximum dose to the spinal cord (almost 7 GyRBE) because it is deep and lateral to the target and a reduction of more than 3 GyRBE to the constrictor mean dose. In the last row of Fig. 4 the dose reduction in the region of the spinal cord is highlighted.

In Table 2 the PSQA results in terms of gamma passing rate are reported for each plan technique, for each case and for each algorithm used.

For chordoma, medulloblastoma and osteosarcoma case the standard plan performed with pencil beam algorithm gave γ passing rate results with a very low minimum (86.43%, 81.09% and 85.02%, respectively) and standard deviations were high when compared to the other techniques (3.87%, 6.31% and 4.95%, respectively). The Monte Carlo results showed very good results for every scenario (average passing rate never lower than 98% and standard deviation never higher than 1.3%).

The delivery time of each plan (i.e. sum of mean beam-on time for each treatment field) is summarized in Table 3.

4. Discussion

We have presented a new planning technique for PBS proton irradiations that can be used when shallow lesions need to be treated. The Range Shifter Optimization technique aims to reduce as much as possible the use of the energy degrader during the delivery, in order to minimize the deterioration of the lateral penumbra associated with this device [20,21]. We planned all the cases by using the Pencil Beam algorithm because is the most widespread dose engine and the results can be more general and more usable by anyone approaching this method. For two cases (Chordoma and Paraganglioma) we used also the Monte Carlo algorithm to show that the nominal plan quality is not affected by the dose engine. These results are reported in the supplementary of this work. Since the use of RS led to some dose calculation problems a technique that reduce the use of it makes the dose distribution of the approved plans more reliable and realistic. With the RSO method the use of RS is reduced as much as possible and all the issues related to dose calculation accuracy are reduced; this was discussed and demonstrated also in Widesott et al. [9].

The dosimetric results of this work showed that the advantages of this technique have not a great impact on the dose to the OARs. In particular for the organs for which we analyzed the D_1 (as a surrogate of D_{max}), we found clinically non-significant difference in each case except for the brainstem in the meningioma case and the spinal cord in osteosarcoma case. These two organs showed a dose reduction in the RSO plans because they were located deep lateral to the target. The organs for which the mean dose was analyzed (i.e. kidneys for medulloblastoma and lumbar chordoma case, ear canal and parotid for meningioma case and constrictor for osteosarcoma case) seems to be more influenced by the use of the RSO technique. The reason of this is clear from Fig. 4. The physical effect of the use of RS in the standard plan led to an increment of the dose outside the target due to the large lateral penumbra. The RSO method proposed here let to reduce the dose outside the tumor with no impact on the target coverage. The dosimetric effect on specific OAR is strongly dependent by the anatomy of the patient: if no OAR are located deep lateral to the target no clinically relevant difference can be highlighted by using the RSO method: the meningioma and the osteosarcoma case highlighted a reduced D_1 to the brainstem and to the spinal cord, respectively, because of their deep lateral location respect to the target. In the case of paraganglioma and osteosarcoma the D_1 to the brainstem was not influenced by the RSO method because it wasn't deep lateral to the target. In the cases studied in this work the lumbar chordoma and the medulloblastoma showed a reduced mean dose to the kidneys and to the lenses while the osteosarcoma showed a reduced mean dose to the constrictor (almost 3 GyRBE less for each of them).

From Table 1 and Fig. 4 the dosimetric difference between RSO method with maximum and minimum airgap can be highlighted. If there are shallow OARs (i.e. thyroid in the paraganglioma case and ear canal and parotid in the meningioma case) the RSO plan with maximum airgap can be worse than the standard plan because the lateral penumbra in the shallow part of the lesion is larger due to the large airgap. This is confirmed in Fig. 4 were the local dose differences show an higher dose to surface in almost all plans. The lumbar chordoma and the medulloblastoma did not evidence this difference because, using posterior beams passing through the couch, was not possible to extend the snout closer to the patient due to geometrical limits. This made the two version of the RSO plan very similar. The RSO plan with maximum airgap becomes a valid alternative when there is the necessity to obtain a plan with the advantages of the RSO method in terms of lateral penumbra and fast enough to preserve the patient compliance. On the other hand, when it is possible these results confirmed the need to lower as much as possible the air gap when the RS is used and when a pencil beam algorithm is employed for dose calculation [3,11,5,12].

We investigated also the effect of this technique on PSQA results for each treatment plan. The only QA where a γ PR lower than 90% was scored belonged to the standard plan. In RayStation, as in many other commercial TPS, the RS is considered as an extension of the patient [10], i.e. no dedicated beam model with the RS is used. For this reason the pencil beam tracing starts at the entrance of the range shifter. This

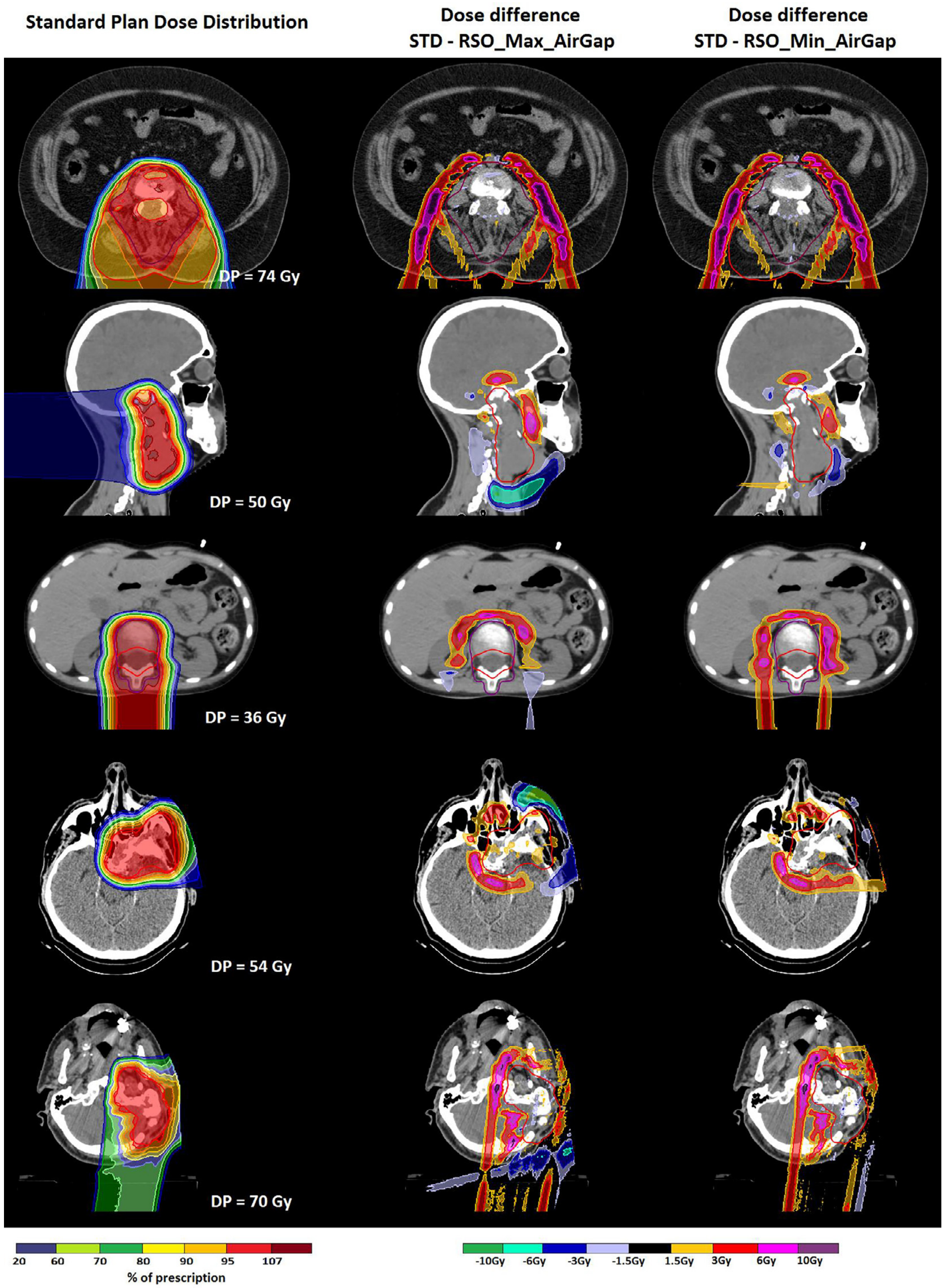

Fig. 4. First column: dose distribution of the standard plan for each case studied. Second and third column: dose difference between standard plan and RSO with maximum airgap (second column) and RSO with minimum airgap (third column). DP is the Dose Prescription which is also the value used to normalize each dose distributions.

means that the broadening of the beam can be significant when it reaches the patient surface and the dose error caused by the infinite slab approximation can be large in presence of lateral inhomogeneity. This problem is minimized with the Monte Carlo dose calculation algorithm as demonstrated with the PSQA recalculated with this dose engine and as suggested in previous papers [3,5,12,13,9,6,8]. Even if the Monte Carlo can solve the dose calculation issues this method is still valid and useful to improve the plan quality of pencil beam scanning proton therapy treatments when RS is used.

We investigated also the effect of the range shifter optimization technique on the delivery time. Loading two beams instead of one, inserting and removing the RS and moving the snout to reduce the air gap will inevitably increase the delivery time. We estimated that this increase, in the worst case scenario, is almost 2 times the standard plan delivery time (about 5 min of difference). We consider this an acceptable delay for plan quality improvement that, nonetheless, has to be considered for patients not compliant with long treatments.

Table 2
Statistical results of patient specific QA expressed in terms of γ passing rate (%). The parameters of the γ were dose difference: 3%, distance to agreement: 3 mm. *Min* is the *Minimum* value reported in PSQA analysis.

	Chordoma			*Paraganglioma*			*Medulloblastoma*		
Pencil Beam	*Mean*	*St. dev*	*Min*	*Mean*	*St. dev*	*Min*	*Mean*	*St. dev*	*Min*
Standard Plan	97.30	3.87	86.43	99.76	0.49	99.02	96.12	6.31	81.09
RSO Max Air Gap	98.59	0.98	97.10	98.75	0.95	97.92	98.34	1.66	94.77
RSO Min Air Gap	98.52	1.02	97.20	98.45	0.52	97.98	96.85	2.33	93.75
Monte Carlo	***Mean***	***St. dev***	***Min***	***Mean***	***St. dev***	***Min***	***Mean***	***St. dev***	***Min***
Standard Plan	99.82	0.30	98.97	99.88	0.25	99.50	99.26	1.33	96.09
RSO Max Air Gap	98.72	1.03	97.43	99.66	0.43	99.10	99.19	0.89	97.41
RSO Min Air Gap	98.22	0.79	97.04	99.20	0.68	98.40	98.96	0.86	97.04
	Meningioma			***Osteosarcoma***					
Pencil Beam	***Mean***	***St. dev***	***Min***	***Mean***	***St. dev***	***Min***			
Standard Plan	97.59	3.13	91.09	94.03	4.95	85.02			
RSO Max Air Gap	99.12	1.00	97.33	99.89	0.28	99.31			
RSO Min Air Gap	99.69	0.50	98.59	99.89	0.28	99.31			
Monte Carlo	***Mean***	***St. dev***	***Min***	***Mean***	***St. dev***	***Min***			
Standard Plan	99.68	0.53	98.52	99.52	0.42	99.02			
RSO Max Air Gap	99.59	0.47	98.63	99.72	0.69	98.31			
RSO Min Air Gap	99.52	0.72	97.84	99.86	0.35	99.14			

Table 3
Mean delivery time for every technique.

	Standard Plan	RSO Max Air Gap		RSO Min Air Gap	
	Average time (s)	Average time (s)	Variation w.r.t. the standard plan	Average time (s)	Variation w.r.t. the standard plan
Case 1 (LowRisk)	244	330	35%	373	53%
Case 1 (HighRisk)	161	231	43%	240	49%
Case 2	166	203	22%	252	52%
Case 3	543	697	28%	827	52%
Case 4	234	425	81%	509	117%
Case 5	144	236	63%	297	106%

5. Conclusions

We presented a novel planning method to reduce as much as possible the use of range shifter in proton therapy with pencil beam scanning delivery technique. With our method the use of the pre-absorber is limited only for the tumor region where it is strictly needed. We demonstrated that this planning method improves the quality of the plan and the patient-specific QA results. The only disadvantage is the increase in delivery time that remain still acceptable in terms of patient compliance. This technique is now routinely used to treat patients in our center.

Acknowledgments

The authors thank the medical doctors involved in this study for the valuable support and the sharing of patient data: Dante Amelio, Marco Cianchetti, Francesco Dionisi and Sabina Vennarini.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ejmp.2018.12.014.

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