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Abstract Title: Enhancement on Beam Spot Quality and Dosimetric Benefits of using In-house Designed Mobile Range Shifter in Non-Extendable Nozzle Proton Pencil Beam Scanning System for Nasopharyngeal Carcinoma

Author Names: Wai Wang Lam[1], Chun Kei Law[2], Hui Geng[1], Yeung Sum Wong[1], Ka Keung Tang[1], Ting Chuan Li[1], Chin Chak Ho[1], Wing Ki Claudia Chan[1], Shu Ting Hung[1], Bin Yang[1], Kin Y.Yin Cheung[1], Siu Ki Yu[1]

[1] Medical Physics Department, Hong Kong Sanatorium & Hospital, Hong Kong

[2]Department of Clinical Oncology, Hong Kong Sanatorium & Hospital, Hong Kong

Background / Aims:

To illustrate the enhancement of pencil beam spot quality using in-house designed mobile range shifter system (MRS) compared to machine-mounted range shifter system (FRS) in non-extendable nozzle of a proton pencil beam scanning system and evaluate dosimetric benefits on target coverage and parotid sparing in multi-field optimized(MFO) proton therapy for nasopharyngeal carcinoma(NPC).

Subjects and Methods:

The study evaluated spot characteristics in terms of lateral spot size (σ) and penumbra ($P_{80\text{-}20\%}$) for monoenergetic proton beams (95.8, 142.2, and 221.2MeV) comparing two range shifter configurations: MRS (WET=4.0cm) with 5-10cm air gaps (range shifter to water surface) and FRS (WET=4.5cm) with 30-35cm air gaps. Simulations were performed in RayStation 2024A at in-air (1cm above water surface) and at 1cm water depth for all energies, with additional depth-specific simulations (2cm for 95.8MeV; 7cm for 142.2/221.2MeV).

Picture 1 showed the application of MRS for NPC treatment. For clinical validation, five NPC cases were replanned with identical posterior and bilateral oblique beams using Monte Carlo-based MFO, with robust optimization. MRS (5-10cm air gap) or FRS (30-35cm air gap) were used. Plan quality was assessed via target coverage metrics [$D_{98\%}$, conformity number(CN), heterogeneity index(HI)] and parotid sparing parameter (D_{mean}, $V_{20\%}$, $V_{5\%}$). Statistical comparisons between MRS and FRS were performed using paired t-tests with Shapiro-Wilk test, p<0.05. Correlations between parotid metrics were analyzed using Pearson correlation.

Picture 1. Simulation for the application of MRS and FRS systems for a head and neck patient during treatment.

Results:

Figure 1 demonstrated MRS significantly outperformed FRS, reducing both σ and penumbra across all tested beam energies at the same depth. The improvements were pronounced at lower energies, where scattering effects were more substantial. The data revealed a parallel 62% reduction in both in-air σ (from 2.59cm to 0.99cm) and penumbra (from 1.10cm to 0.42cm) while a 57% improvement in both σ (from 2.79cm to 1.19cm) and penumbra (from 1.18cm to 0.51cm) at 2cm water depth for 95.8MeV beam. From Table 1a, MRS showed statistically significant reductions in parotids D_{mean} by 1.12Gy(*p=0.002**) compared to FRS while maintaining equivalent target coverage across all CTVs. Substantial benefit was seen in intermediate-dose [$V_{20Gy(RBE)}$] and low-dose volumes [$V_{5Gy(RBE)}$] with reduction of 5.59*%(p=0.0003*)* and 8.98*%(p<0.0001*)*, respectively. Table 1b showed strong linear relationships between parotid dosimetric metrics in, indicating unified sparing effects.

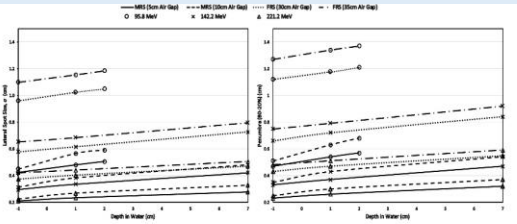

Figure 1. Plots of Lateral Spot Size (Left) and Penumbra (Right) of various proton beam spot energies as a function of in-air and penetration depth in water at different air gap distance from MRS/FRS to water surface.

Targets/ OARs	Metrics	MRS (Mean ± SD)	FRS (Mean ± SD)	Mean Difference (95% CI)	*p*-value
CTV70Gy(RBE)	D98 [Gy(RBE)]	71.32 ± 0.38	71.36 ± 0.32	-0.04 (-0.22, 0.14)	0.82
	CN	0.29 ± 0.06	0.28 ± 0.05	0.01 (-0.04, 0.06)	0.75
	HI	4.67 ± 1.24	5.17 ± 1.32	0.50 (-1.21, 0.21)	0.14
CTV63Gy(RBE)	D98 [Gy(RBE)]	65.86 ± 1.42	65.60 ± 1.72	0.26 (-0.41, 0.93)	0.56
	CN	0.25 ± 0.09	0.24 ± 0.09	0.01 (-0.05, 0.07)	0.62
	HI	12.56 ± 2.92	13.79 ± 2.43	-1.23 (-3.16, 0.70)	0.17
CTV54Gy(RBE)	D98 [Gy(RBE)]	54.66 ± 0.38	54.59 ± 0.33	0.07 (-0.14, 0.28)	0.72
	CN	0.50 ± 0.05	0.50 ± 0.06	0.00 (-0.05, 0.05)	0.91
	HI	25.52 ± 9.93	26.36 ± 10.06	-0.84 (-2.98, 1.30)	0.38
Parotid Glands	Dmean [Gy(RBE)]	19.99 ± 5.12 Gy	21.11 ± 5.31 Gy	-1.12 Gy (-1.76, -0.48)	*0.002**
	V20 (%)	38.58 ± 9.64%	44.17 ± 9.47%	-5.59% (-8.06, -3.12)	*0.0003**
	V5 (%)	75.32 ± 7.14%	84.30 ± 6.56%	-8.98% (-11.85, -6.12)	*<0.0001**

Notes:
- *p*-values were calculated using a paired t-test (two-sided).
- Normality of differences was confirmed using the Shapiro-Wilk test (all $^*p^* > 0.05$).
- Significant differences ($p < 0.05$) are marked with an asterisk (*).

Table 1a. Summary of dosimetric results of target coverage and parotid glands.

Comparison	Pearson's *r*	*p*-value
Dmean vs. V20	0.94	*<0.001**
Dmean vs. V5	0.89	*0.001**
V5 vs. V20	0.82	*0.004**

Notes:
- Correlations were computed using Pearson's product-moment correlation test.
- The *p* values test the null hypothesis that the true correlation coefficient (ρ) is zero.
- *p*-values were derived from the t-distribution with $^*n^* - 2$ degrees of freedom, where $^*n^* = ^*n_1^* + ^*n_2^* = 20 (= 10 + 10)$.
- All correlations were statistically significant ($p < 0.05$) and are marked with an asterisk (*).

Table 1b. Summary of correlations between parotid gland dosimetric metrics.

Conclusions

MRS improved beam spot quality, achieving smaller σ and sharper penumbra for non-extendable nozzle proton machine. This reduced low-dose halo to parotids and may lower xerostomia risk while maintaining tumour control in NPC cases, warranting further investigation in larger cohorts.

E-mail: tomie.ww.lam@hksh.com