Optimization of couch angles and number of arcs in non-coplanar VMAT for pituitary adenomas

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Abstract. Non-coplanar VMAT spares critical organs with short delivery time while maintaining PTV coverage. Due to the growth patterns of pituitary adenoma, the beam angle selection step was simplified by finding the optimal couch angles and number of arcs. The 2 clinical cases with difference PTV sizes were selected to study the results of dose distribution between coplanar and non-coplanar techniques. Later, couch angles were varied from 30° to 90° and 270° to 330° with a 15° interval. The numbers of arcs were varied from 3 to 4 arcs. Then, the selected protocol was applied to 5 pituitary adenoma patients. It was found that 90° and 270° couch angle showed the highest scores. However, these beams passed directly through the body, so the second couch angles of 75° and 285° were selected instead. For number of arcs optimization, 3-arc plan and 4-arc plan demonstrated a similar score. However, the 3-arc plan illustrated an obviously shorter treatment time. After the selection was proven to the 5 patients, there were 4 patients who passed the criteria, while 1 patient did not pass the hippocampal planning criteria. In conclusion, the suggested couch angles were 75° and 285°. The optimal number of arcs for pituitary adenoma was 3 arcs.

1. Introduction
To treat a tumor in the brain, there are many organs at risk (OARs) for concern. Recently, non-coplanar beam arrangement was introduced to spare OARs superior to simple coplanar [1, 2]. In this research, pituitary adenomas were studied because of the incidence and tumor location. According to a United States statistical report (2009-2013) [3], pituitary tumors are the second most common tumor of non-malignant primary brain tumors. It is always found in the same location at the base of the skull due to its primary site. Thus, a limitation of a skull-based tumor is the critical organs that are close to the lesion or located in the same layer. This study proposed the optimization of couch angles and number of arcs in non-coplanar VMAT for pituitary adenoma. In addition, the dose distribution of coplanar and non-coplanar was compared.
2. Materials and methods
Two different tumor sizes were selected to study for dose distribution in different couch angles and number of arcs. There was case 1 with small PTV size and case 2 with medium PTV size, which were 7.4 cm$^3$ and 39.3 cm$^3$, respectively.

2.1 Treatment planning
The prescription dose was 50 Gy in 25 fractions for all plans. Following RTOG protocol, greater or equal to 95% PTV was covered 100% of the prescribed dose. The maximum dose did not receive more than 110% of the prescribed dose. Dose constraints for OARs were referred to RTOG 0225 and Silvia Scoccianti et al. [4] and Gondi et al. [5]. All of the criteria are shown in table 1.

| Organs                      | Dose constraints (References) |
|-----------------------------|-------------------------------|
| Optic chiasma and optic nerves | $D_{\text{max}} < 54 \text{ Gy}$       (Silvia Scoccianti et al. [4]) |
| Brainstem                   | $D_{\text{max}} < 54 \text{ Gy}$       (Silvia Scoccianti et al. [4]) |
| Lacrimal gland              | $D_{\text{max}} < 40 \text{ Gy}$       (Silvia Scoccianti et al. [4]) |
| Lens                        | $D_{\text{max}} < 6 \text{ Gy}$         (Silvia Scoccianti et al. [4]) |
| Hippocampus                 | $D_{40\%} < 7.3 \text{ Gy}$            (Gondi et al. [5]) |
| Eyes                        | $D_{\text{mean}} < 35 \text{ Gy}$       (RTOG 0225) |

2.1.1 Coplanar and non-coplanar VMAT Eclipse treatment planning was used to create the plan for Varian EDGE linear accelerator for 6 MV photon beams with a flattening filter. The maximum dose rate was set at 600 MU/min and collimator angles were 45° and 315°. First, a coplanar VMAT plan (coVMAT) was generated with 2 full arcs and eye sector avoidance at a couch angle of 0 degrees. Then, a non-coplanar VMAT plan (ncVMAT) was created with 2 coplanar arcs and sector avoidance at the eyes combined with 2 non-coplanar arcs using couch angles of 45 and 315 degrees. The beam directions are shown in figures 1 and 2.

![Figure 1. The beam direction of coplanar VMAT plan (coVMAT) in 3D view](image1)

![Figure 2. The beam direction of non-coplanar VMAT plan (ncVMAT) in 3D view](image2)

2.1.2 Vary couch angles In this step, the number of arcs was fixed to 3. There were 2 full coplanar arcs and 1 arc with various couch angles. A 15-degree interval couch angle was varied in 2 ranges; the first range was 30°-90° and the second was 270°-330°. The beam optimization parameters were fixed to the reference values (from ncVMAT plan). In each couch position, the PTV’s priorities were adjusted to approach the PTV goal. Moreover, the constant arc length was used in every couch angle. From this step, the proper beam directions were found by comparing RTOG CI, HI, GM, dose to PTV and dose to OARs of each couch angle. The values for each couch angle were noted and scored. For the scoring criteria of each range of couch angle, the maximum score was 5. The best values for CI, HI, GM, dose to PTV and dose to OARs got 5 points and the other values scored in descending order. For the same values of parameters, they received equal points.
2.1.3 Vary number of arcs The chosen couch angle from paragraph 2.1.2 was used to create a 3-arc plan (1 coplanar arc and 2 non-coplanar arcs). Later, the 3-arc plan was combined with vertex arc to create a 4-arc plan. To evaluate the appropriate number of arcs, all of the optimization parameters were fixed, but only PTV’s priorities were adjusted to fulfill PTV coverage. Not only dosimetric evaluation, but also the total treatment time of 3-arc plan and 4-arc plan were evaluated.

2.2 Plan evaluation
Homogeneity Index (HI) was used to quantify the homogeneity in the target volume. Ideally, HI equal to 0 represents the ideal uniform dose in the target volume. Equation 1 shows the HI formula. RTOG conformity index (RTOG CI) was used to investigate the target volume coverage. From equation 2, if CI is 1, 100% of a prescription dose is delivered to the PTV.

\[
HI = \frac{D_{2\%} - D_{98\%}}{D_{50\%}} \tag{1}
\]

where \(D_{2\%\}, D_{50\%\},\) and \(D_{98\%}\) are dose covering 2%, 50% and 98% of the target volume, respectively.

\[
CI_{RTOG} = \frac{V_{IR}}{TV} \tag{2}
\]

where \(V_{IR}\) is volume received for the prescribed dose and \(TV\) is the target volume.

Gradient measure (GM) was used to compare the dose gradients that steep outside of PTV. The smaller the value, the higher the dose gradient outside of PTV. It was a distance between sphere radii of the prescribed dose and 50% isodose line. Moreover, the near maximum dose (\(D_{2\%}\)) (following ICRU83) and mean dose (\(D_{\text{mean}}\)) of OARs (including optic nerves, optic chiasm, eyes, lens, brainstem, lacrimal gland and hippocampus) were assessed and compared. Besides, low dose volume of normal brain was evaluated by the brain volume that received 10 Gy (\(V_{10\text{Gy}}\)). The total treatment time was used to compare the plans with various numbers of arcs.

2.3 Apply selected protocol to patients
After the appropriate protocol was selected, the protocol was applied to 5 patients to verify its function. Later, the treatment plans for each patient were compared with the treatment criteria.

3. Results and discussion

3.1 Coplanar and non-coplanar VMAT
PTV coverage for both 2 cases was similar. However, the conformity indexes of both were better when using the non-coplanar technique. Also, the conformity indexes reduced from 1.10 to 1.02 for case 1 and from 1.07 to 1.03 for case 2. According to the homogeneity index (HI) parameter, case 1 and case 2 were rather similar. For case 1, it was 0.06 when using the coplanar technique and 0.08 when using the non-coplanar technique. HI values for case 2 were 0.07 for coplanar and 0.08 for non-coplanar. Furthermore, gradient measurements for the non-coplanar technique had a tendency to be lower than that for the coplanar technique. They decreased slightly from 0.86 cm to 0.75 cm for case 1 and from 1.31 cm to 1.08 cm for case 2. The \(D_{2\%}\) of brainstem, optic chiasm, left optic nerve and right optic nerves were similar across techniques in both 2 cases. However, case 1 and case 2 had a lower mean dose for the 4 organs when the non-coplanar technique was employed, except the optic chiasm of case 1. The mean doses of optic chiasm in case 1 were 2071.40 cGy and 2507.40 cGy for coplanar and non-coplanar, respectively. Because case 1 had a small part of the optic chiasis located in PTV and the majority located superior to PTV, non-coplanar beams irradiated this superior part of the optic chiasm. The non-coplanar technique substantially reduced \(D_{2\%}\) and mean dose for eyes, lacrimal glands, lens, \(V_{10\text{Gy}}\) of brain and \(D_{40\%}\) of hippocampus in both 2 cases. This result was similar to Valerie Panet-Raymond et al. [1], who reported that the dose to contralateral organs were reduced when using non-coplanar IMRT and non-coplanar VMAT. Besides, Megumi Uto et al. [2] reported that non-coplanar VMAT significantly decreased the dose to hippocampus, lower than the threshold in craniopharyngiomas, while mean dose to normal brain and CI were similar to previous techniques.
3.2 Optimal couch angle
The different couch angle affected the dose to surrounding organs. The plans that used a good couch angle had a low dose to OARs while maintaining PTV coverage. The results for each couch angle were recorded and scored. Table 2 shows the scores for each couch angle. It was found that the couch angle at 90 degrees for case 1 and 270 degrees for case 2 had the highest scores in their ranges. It indicated that 90 and 270 degrees of couch angle was the best couch angle to preserve OARs, but the beam of vertex arc clearly directed to the body that was a cause of higher dose to the body and thyroid gland. This will irradiate the body and thyroid, increasing the chance of stochastic effects. Also, Ruth A. Kleinerman [6] and Ron et al. [7] presented that the thyroid gland was very sensitive to radiation. In addition, children have a longer lifetime during which the radiation effect may occur. Thus, the second couch angles, i.e. 75 and 285 degrees, were chosen to use in the next step. However, the selected couch angles were closed to vertex arc. If the treatment plan consists of these couch angles, the short arc length is recommended for employment, which helps to decrease the dose exiting through the body.

Table 2. Score summary of various couch angles for 30-90 degrees and 270-330 degrees

|        | C30 | C45 | C60 | C75 | C90 | C270 | C285 | C300 | C315 | C330 |
|--------|-----|-----|-----|-----|-----|------|------|------|------|------|
| Case 1 | 53  | 72  | 61  | 90  | 109 | 94   | 82   | 80   | 80   | 54   |
| Case 2 | 77  | 65  | 76  | 83  | 85  | 113  | 92   | 67   | 68   | 51   |

3.3 Optimal number of arcs
After determining the optimal couch angle for pituitary adenoma, the selected couch angles were combined to create the 3-arc plan and 4-arc plan. CI HI and GM of the 3-arc plan and 4-arc plan were slightly different. The scores for the 3-arc plan and 4-arc plan were quite comparable. In case 1, there were 39 and 38 for the 3-arc plan and 4-arc plan, respectively. The scores for case 2 were 38 and 39 for 3-arc plan and 4 arcs, respectively. Thus, the dosimetric results were alike.

The 3-arc plan used less time than the 4-arc plan. The 3-arc plan used only 20 minutes for both cases 1 and 2, while the 4-arc plan used 24 minutes (case 1) and 25 minutes (case 2). The longer treatment time may cause more intrafraction error. Beltran C et al. [8] studied the impact of intrafraction motion in pediatric tumor patients. The report presented that there were similar doses to CTV, but increased dose to OARs. Hence, the selected protocol was the 3-arc plan, which not only reduces intrafraction error, but also decreases the workload of the treatment room while maintaining the equal plan quality.

3.4 Apply protocol to patients
To ensure that the protocol could be used with other patients, these couch angles and numbers of arcs were used with 5 pituitary adenomas, which have centrally-located lesions. There were 4 patients who passed all organ criteria. For the other, the only organ which did not pass the dose criteria was the hippocampus. The $D_{90\%}$ of bilateral hippocampus was 1561.01 cGy for patient 2, who had large PTV size. Thus, most of the volume for the hippocampus was located close to PTV in many layers. Besides, the patient with large PTV size may receive a higher dose for a superior brain. Because of PTV size, the field sizes were wildly varied. At couch angles of 75 and 285 degrees, 2 beams were close. Thus, the beams were overlapped to increase the dose in the upper area. The other parameters are shown in table 3 and table 4.
### Table 3. Dose to PTV (using 3-arc protocol)

|       | Patient 1 | Patient 2 | Patient 3 | Patient 4 | Patient 5 |
|-------|-----------|-----------|-----------|-----------|-----------|
| Size (cm³) | 14.2      | 124.2     | 5.9       | 25        | 23.4      |
| CI     | 1.06      | 1.00      | 1.07      | 1.02      | 1.05      |
| HI     | 0.10      | 0.09      | 0.08      | 0.09      | 0.10      |
| GM (cm) | 0.95      | 1.57      | 0.85      | 1.18      | 1.11      |

### Table 4. Dose to organs (using 3-arc protocol)

|       | Patient 1 | Patient 2 | Patient 3 | Patient 4 | Patient 5 |
|-------|-----------|-----------|-----------|-----------|-----------|
| V₁₀G₅(cm³) | 236.45    | 631.79    | 106.21    | 207.20    | 241.23    |
| Lt eye  | D₂%b (cGy) | 532.66    | 629.58    | 497.56    | 449.75    | 782.94    |
|         | Dₘₐₑₜ c (Gy) | 122.30    | 338.10    | 196.40    | 160.30    | 448.70    |
| Rt eye  | D₂% (cGy)  | 509.34    | 320.53    | 388.13    | 776.73    | 774.89    |
|         | Dₘₐₑₜ c (Gy) | 133.30    | 256.90    | 148.50    | 318.30    | 313.90    |
| Lt len  | Dₘₐₑₜ c (Gy) | 71.65     | 183.79    | 224.95    | 238.05    | 436.33    |
|         | D₂% (cGy)  | 52.50     | 148.90    | 112.40    | 125.90    | 347.60    |
| Rt len  | Dₘₐₑₜ c (Gy) | 67.95     | 4837.97   | 175.31    | 243.32    | 135.75    |
| Brainstem | D₂% (cGy)  | 3767.98   | 5191.30   | 3216.69   | 3777.40   | 4787.89   |
|         | Dₘₐₑₜ c (Gy) | 1820.00   | 5119.50   | 1262.60   | 1259.90   | 1835.10   |
| Lt optic | D₂% (cGy)  | 441.00    | 5176.84   | 4722.89   | 5131.81   | 5193.71   |
|         | Dₘₐₑₜ c (Gy) | 1070.70   | 3602.40   | 1891.80   | 3147.60   | 2609.80   |
| Rt optic | D₂% (cGy)  | 5062.82   | 5149.52   | 2995.87   | 5150.49   | 5178.23   |
|         | Dₘₐₑₜ c (Gy) | 1649.00   | 3328.70   | 975.60    | 3564.70   | 3310.60   |
| Lt lacrimal gland | D₂% (cGy)  | 210.99    | 586.94    | 227.25    | 602.18    | 270.33    |
|         | Dₘₐₑₜ c (Gy) | 100.10    | 320.80    | 79.90     | 358.40    | 101.20    |
| Rt lacrimal gland | D₂% (cGy)  | 176.78    | 543.79    | 331.79    | 468.89    | 579.12    |
|         | Dₘₐₑₜ c (Gy) | 87.30     | 402.30    | 104.70    | 304.50    | 245.90    |
| Optic chiasm | D₂% (cGy)  | -         | 5176.84   | 2887.53   | 4978.33   | 5182.98   |
|         | Dₘₐₑₜ c (Gy) | -         | 3602.40   | 1159.80   | 3746.70   | 3931.20   |
| D₄₀% Bi-hippo d (cGy) | 558.24    | 1561.01   | 403.67    | 561.21    | 658.18    |

a The brain volume received dose 10 Gy
b Dose near maximum
c Mean dose
d Dose that covers 40% volume of the bilateral hippocampus
The protocol reduced $D_{40\%}$ of hippocampus in 4 patients lower than 7.3 Gy. In this study, the dose per fraction was 2 Gy. Thus, the equivalent dose in 2-Gy fractions ($EQD_2$) to 40% of volume for the bilateral hippocampus was equal to the dose to 40% of the volume ($D_{40\%}$) for the bilateral hippocampus. According to Gondi et al. [5], “EQD$_2$ to 40% of the bilateral hippocampus ($D_{40\%}$) greater than 7.3 Gy could predict the impairment in list-learning delayed verbal recall”. Hence, the protocol reduced EQD$_2$ lower than the threshold predicting cognitive impairment.

3.5 Limitations of the study and future works
In this research, only centrally-located tumors were studied. For the samples, only 2 patients were employed to study the dose distribution of various couch angles and numbers of arcs. It might be a minimal number of samples, but it could show the effect of couch angle and number of arcs. Besides, the collected patients whose lesions were centrally located were done in only 5 patients. For scoring, it did not concern the different values. Thus, only a few differences of dose or CI or HI or GM got a lower score than the others, which had only a few differences. From the investigated couch angle method, couch angle was varied every 15 degrees. That might not be scrupulous. For finding the optimal number of arcs, only 3 arcs and 4 arcs were evaluated. Thus, the selected couch angles and number of arcs were not the best couch angle and number of arcs for pituitary adenoma, but they provided a satisfactory treatment plan.

These limitations might be minimized in future works. According to the small sample sizes, more patients might be added to improve the reliability of this study. The number of patients will be calculated from the sample size formula. Also, other tumor locations will be studied. Moreover, the scoring procedure will be adjusted to take into account the differences of values between the 2 plans. Future study could divide the couch angle into a smaller interval. Also, the multiple-arc VMAT plan could be varied with more than 4 arcs.

4. Conclusion
In conclusion, this study found that the optimal number of arcs for pituitary adenoma was 3 arcs. These 3 arcs consisted of 1 coplanar arc and 2 non-coplanar arcs. The 2 recommended couch angles were 75 and 285 degrees. The suggested protocol should be used with centrally-located tumors. Moreover, these couch angles should be used with short arc lengths to avoid dosage to the body and thyroid glands. This protocol is probably useful to guide the planning by beginners in using the non-coplanar technique. Further, using the protocol with a planner’s objective parameters may shorten the planning time. Besides, it reduces the workload in the treatment room.

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