Fractionated stereotactic radiosurgery with adaptive dose delivery in Mannheim using Gamma Knife® Icon™

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1. Introduction
Meningiomas are tumors from the arachnoidal cells. Benign tumors (WHO Grade I) in particular show only slow progression and often no neurological symptoms. Standard treatment is surgical resection or primary radiotherapy, with local control rates over 90% after 5 years. In cases of incomplete resection, as well as recurrent, primary and non-resectable tumors, radiotherapy is the treatment of choice. To date, two regimes of radiotherapy are established: Full course fractionated stereotactic radiotherapy (FSRT) and stereotactic radiosurgery (SRS)\(^1\). While SRS with 12-15 Gray (Gy) is limited for small lesions distant to critical structures, FSRT with total doses of 50-57.6 Gy in single dose fractions of 1.8 Gy can be given even for larger lesions very close to organs-at-risk with very good results. However, the average treatment time of six weeks is challenging for many patients.

To date, there are only a few reports with small numbers of patients describing hypofractionated radiotherapy of benign meningioma\(^4\). Single doses of 3-7 Gy in three to 15 fractions have been reported. The purpose of these case studies was to shorten the overall treatment time and achieve similar results regarding toxicity and local control compared to FSRT, and/or to limit normal tissue complication probability compared to single dose SRS.

Leksell Gamma Knife™ Icon™ (Elekta AB, Sweden) (Figure 1) allows the treatment of patients in a precise stereotactic environment using cone-beam computer tomography (CBCT) for positioning, a thermoplastic mask system for stereotaxy and fixation and an infrared-based high definition motion management system (HDMM) for patient tracking during treatment. Using these novel options, Gamma Knife Icon enables the possibility to adaptive fractionated stereotactic radiosurgery (a-gkFSRS).

2. Materials and Methods
A 76-year-old female patient presented in our department with a meningioma WHO grade I located at the left petrosal bone. The meningioma was first diagnosed in 2011 and remained stable until May 2015. Subsequently, a progression of 5 mm in all directions was detected on MRI (Figure 2). To date, the patient had no neurological symptoms.

The MRI images showed the typical radiological characteristics of a benign meningioma with a small dural tail. The maximum diameter was 2.7 cm and the volume 5.88 cm\(^3\).

Figure 1: Leksell Gamma Knife Icon in Mannheim

Figure 2: Diagnostic MR images
Because of the lesion’s large volume, its location in the posterior fossa, and the dural tail close to critical structures (e.g., 7th cranial nerve), we decided that this patient would be the first to receive treatment with Icon.

The patient received her first fraction with Gamma Knife Icon in Mannheim on August 27, 2015. Seven days earlier she had an MR scan and was pre-planned with the treatment planning system (TPS) GammaPlan® 11.0.1 (Elekta AB, Sweden). On the day of treatment the patient received an external planning CT (Brillance Big Bore, Phillips, The Netherlands) with Icon specific thermoplastic mask (Figure 3) to verify the tumor’s status and position.

Both image data sets were co-registered to verify the tumor position and to re-evaluate the treatment plan on CT images including the mask. The treatment plan was designed for 5 X 5 Gy for a total marginal dose of 25 Gy prescribed to the 46 % isodose line encompassing the tumor. Before finishing the treatment planning process a standalone cone-beam CT (CBCT) of high quality (CDTI 6.3 mGy) on Gamma Knife Icon was acquired to define the stereotactic reference for the fractionated treatment. At this step the plan is ready for execution.

For every fraction a daily CBCT was performed to verify the actual skull position. An automatic co-registration was performed using the anatomy of the skull to verify the target position. The treatment planning system (TPS) automatically adapts the shot positions to the daily position of the target and recalculates the dose distribution (online adaptive planning). Slightly different daily dose distributions can be the result, this daily discrepancy between difference for the actual situation to the planned situation was analyzed and approved by physician and medical physicist as per local protocol. Coverage, selectivity and gradient for the delivered dose was identical after adaption to the initially planned values of Table 1.

3. Results
Plan quality:

Dose calculation was performed with TMR10 algorithm. The plan quality values for conformity, selectivity, gradient and dose values for target and brain stem are shown in Table 1. The relatively short beam-on time of 15.2 minutes was due to the low daily dose (5 Gy per fraction). Example dose distributions are shown in Figure 4a-c.
Table 1: Planned quality values

<table>
<thead>
<tr>
<th></th>
<th>Coverage</th>
<th>Selectivity</th>
<th>Paddick Conformity index</th>
<th>Dose gradient</th>
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<tbody>
<tr>
<td>Values</td>
<td>0.98</td>
<td>0.92</td>
<td>0.90</td>
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<td>Brain Stem</td>
<td>0.6</td>
<td>2.4</td>
<td>8.9</td>
<td></td>
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<tr>
<td>Target</td>
<td>18.0</td>
<td>33.9</td>
<td>54.3</td>
<td></td>
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</table>

Figure 4a: Dose distribution based on MR images

Figure 4b: Dose distribution based on planning CT images

Figure 4c: Dose distribution based on Leksell Gamma Knife Icon CBCT
The treatment for fractions 2-5 was approximately 20 minutes. Positioning the patient required 50 sec, CBCT positioning plus acquisition was 1.03 min plus 0.62 min, CT data processing and adaptive planning was 2.66 min and treatment was 16 minutes.

The rotational and translational shifts of the five daily CBCTs in low quality mode (CDTI 2.3 mGy) compared to the reference standalone CBCT are shown in Table 2. The mean values and standard deviations for rotation were $-0.59^\circ \pm 0.49^\circ / 0.18^\circ \pm 0.20^\circ / 0.05^\circ \pm 0.36^\circ$ and for translation were $0.94 \text{ mm} \pm 0.52 \text{ mm} / -0.08 \text{ mm} \pm 0.08 \text{ mm} / -1.13 \text{ mm} \pm 0.89 \text{ mm}$.

<table>
<thead>
<tr>
<th></th>
<th>Rotation [degrees]</th>
<th>Translation [mm]</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>X</td>
<td>Y</td>
</tr>
<tr>
<td>Day 1</td>
<td>0.06</td>
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</tr>
<tr>
<td>Day 2</td>
<td>-0.26</td>
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<tr>
<td>Day 3</td>
<td>-0.27</td>
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<tr>
<td>Day 4</td>
<td>-0.99</td>
<td>-0.02</td>
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<td>Day 5</td>
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<td>Day 5-2</td>
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<td>0.39</td>
</tr>
</tbody>
</table>

Table 2: Daily shifts in rotation [degrees] and translation [mm]

The largest rotation along all axes was seen along the vertical axis with $1.08^\circ$. The largest translational deviation of 2.58 mm was seen in the longitudinal direction.

The HDMM system monitors the movement of the nose tip and thus the patient movement. The movement is displayed as a continuous vector length over time on the system console. The default threshold is 1.5 mm but can be changed between 0.5 mm - 3.0 mm. (Figure 5).

On day five, a second CBCT was acquired after treatment to verify the intrafractional patient movement, by comparing changes to the target position seen on CBCT to the changes seen on the IFMM system. The absolute difference between both CBCTs on day five was $0.06^\circ / 0.27^\circ / 0.32^\circ$ in rotation and $0.15 \text{ mm} / 0.06 \text{ mm} / 0.20 \text{ mm}$ in translation.

![Figure 5: HDMM recorded movements in millimeters over time. On day 2 and 3 no patient motion was recorded. Measurements are taken with a frequency of 20 Hz.](image-url)
Adaptive Dose Delivery

The treatment planning system, Leksell Gamma Plan, records the daily dose differences and allows the analysis and display of the actual delivered total dose distribution. The daily Adaptive Dose Delivery was very accurate and yielded quality measures, e.g., coverage, selectivity and gradient for the delivered dose were identical with respect to the initial values seen in Table 1.

Outcome

The patient tolerated the treatment very well. After the first treatment session the patient complained of a slight headache and received Dexamethasone 4 mg for three days and then 2 mg for the following three days with complete resolution of symptoms within a day. No other problems occurred. At a follow up visit six weeks after treatment, the patient presented in good clinical condition. No neurological symptoms has been reported from the patient except for occasional slight headache.

Leksell Gamma Knife Icon provides the combination of the accuracy of the stereotactic Gamma Knife system with the flexibility of fractionated treatment using a linear accelerator with mask system and CBCT. Further, Icon introduces a new patient tracking system to the clinical routine.

4. Conclusion

The interfractional accuracy of patient positioning was controlled with a thermoplastic mask and CBCT. The deviation in daily positioning was within 2.58 mm and 1.08 degrees, respectively, and compensated for by Adaptive Dose Delivery. Adaptive Dose Delivery was performed in just 1.25 minutes and allowed significant control of plan quality. Identical dose was delivered each day thanks to Adaptive Dose Delivery.

Intrafractional movement was monitored and controlled by the HDMM system and showed similar results to those seen with repeated CBCT after treatment. This aspect is shown by the HDMM system (Figure 4) and by the difference between the two CBCTs on day five (Table 2; < 0.32° and 0.20 mm). The HDMM system provides online tracking during treatment as expected.
REFERENCES


ABOUT ELEKTA
Elekta’s purpose is to invent and develop effective solutions for the treatment of cancer and brain disorders. Our goal is to help our customers deliver the best care for every patient. Our oncology and neurosurgery tools and treatment planning systems are used in more than 6,000 hospitals worldwide. They help treat over 100,000 patients every day. The company was founded in 1974 by Professor Lars Leksell, a physician. Today, with its headquarters in Stockholm, Sweden, Elekta employs around 4,000 people in more than 30 offices across 24 countries.