The Leksell Gamma Knife Perfexion, introduced in 2006, is substantially different in its design from previous Gamma Knife models. The Perfexion Gamma Knife has been described elsewhere. Briefly, the Perfexion is characterized by a fully automated patient positioning system, as well as a novel collimator design. In previous Gamma Knife models, 4 collimators (helmets) were available, and the user was required to manually change helmets if > 1 collimator size was required for treatment. With the Perfexion, the collimator is located inside the Gamma Knife unit, and the ⁶⁰Co sources are situated in 8 independently moveable sectors that slide over the collimator and are set in 1 of 4 positions corresponding to a 4-, 8-, or 16-mm collimator or a blocked setting. Figure 1, reprinted with permission from notes provided at an Elekta training course, illustrates this design. Each sector contains 24 sources, making a total of 192 sources. As a result of the collimator and sector design of the Perfexion, it is possible to develop treatment plans containing hybrid shots, that is, shots that have different collimator values in different sectors, a feature that did not exist in previous Gamma Knife models.

Isodose distributions resulting from hybrid shots are not as intuitive as those resulting from single-value-collimator shots, as Fig. 2 illustrates. The lower half of this figure shows isodose distributions in the XY plane for two hybrid shots: one with 16-mm collimators in sectors 1 and 5 (the anterior–posterior sectors) and 8-mm collimators in all other sectors and one with 16-mm collimators in sectors 3 and 7 (the lateral sectors) and 8-mm collimators in...
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For comparison, isodose distributions for shots with either 8- or 16-mm collimators in all sectors are shown in the top half of Fig. 2. A striking feature of the isodose distributions for the two hybrid shots in Fig. 2 is that the low-value isodose line (20%) is elongated along the axis of the high-value collimators (16-mm). The high-value isodose lines (50 and 80%), on the other hand, are elongated in the orthogonal direction. The high-value isodose lines are elongated due to the larger width of the entering beams in the anterior-posterior direction in Fig. 2c and in the lateral direction in Fig. 2d.

The observation that the low-value isodose lines tend to be elongated along the axis of the high-value collimators suggests that care must be taken to avoid placing high-value sectors “adjacent to” critical structures when using hybrid shots and that there may be an advantage to aligning the low-value sectors with the edge of the critical structure. To date, perhaps because of the difficulty of predicting the dose fall-off characteristics of hybrid shots, most Perfexion users have advocated using hybrid shots only in treating single, eccentrically shaped lesions.1 The purpose of this paper is to explore the possibility of using hybrids when treating lesions close to critical structures by exploiting the unique dose fall-off characteristics of the hybrids. If we avoid using high-value collimators in sectors where their associated penumbra spills into critical regions and instead place low-value collimators in those sectors, we can minimize the number of blocked sectors required to safely treat the target. This strategy also allows a few high-value collimators to be used, whereas in a conventional treatment without hybrid shots, it might not be possible to use any high-value collimators. The overall advantage of using fewer blocked sectors and a few higher-value collimator sectors is that the beam-on time for the treatment is reduced, resulting in a more efficient treatment technique.

Methods

Twelve patients were considered in this study. All of the patients were treated at the Washington Hospital Gamma Knife Center (Taylor McAdam Bell Neuroscience Institute) between June 2007 and March 2008. The treatment indications were vestibular schwannoma (3 patients), pituitary adenoma (6 patients), meningioma (2 patients), and multiple brain metastases (1 patient). For the patient with multiple brain metastases, only one lesion, which was located adjacent to the brainstem, was considered. For all patients, the lesions considered in this study were located within 4 mm of at least one critical structure, namely the optic nerves or chiasm, brainstem, cochlea, or pituitary stalk. For each patient, 2 new plans were generated using the GammaPlan software (Leksell GammaPlan, release 8.0, Elekta Instruments). In one plan hybrid shots were used such that the steepest dose gradient was aligned with the junction between the target and the critical structure(s). In the second plan, hybrid shots were not used. Sector blocking was required for all treatment plans, regardless of whether hybrid shots were used, to achieve the required dose tolerance limits in the critical structures. The sector blocking was accomplished in the treatment planning software either by manually assigning blocked sectors or by using the “dynamic shaping” option available in the GammaPlan program.
Target doses prescribed by the physicians ranged from 12 Gy for the acoustic tumors to 30 Gy for some of the hormone-secreting pituitary tumors. Tolerance doses for critical structures were the same as those used clinically at our institution: no more than 8 Gy to the optic nerves, optic chiasm, and brainstem; no more than 4 Gy to the cochlea; and no more than 6–8 Gy to the pituitary stalk.

To make a fair comparison between the treatment plans with and without hybrid shots, each pair of plans was designed to be equally conformal and to achieve the same dose constraints in the critical structures, in as much as this was possible. That is, the quality of the treatment plans, as measured by the Paddick conformity index, was approximately the same for each pair of plans. The Paddick conformity index is defined as:

$$C.I. = \frac{V_{TP}}{V_T} \times \frac{V_{TP}}{V_P}$$

where $V_{TP}$ is the volume of target contained within the prescription isodose surface, $V_T$ is the target volume, and $V_P$ is the prescription isodose volume. Both terms in this product are necessarily $< 1$. The first term describes the fractional target coverage, and the second term describes how well the prescription-isodose volume matches the target coverage. The Paddick gradient index, which describes how quickly the dose distribution falls off outside of the target, was also calculated for each plan. The gradient index is defined as:

$$G.I. = \frac{V_{p/2}}{V_p}$$

where, $V_{p/2}$ represents the volume contained in one half of the prescribed isodose and $V_p$ is the prescription isodose volume.

Figures 3 and 4 show the conformity indices and gradient indices for each pair of plans. The average conformity index was 0.715 using hybrid shots and 0.698 without hybrid shots (Fig. 3). Performing a two-tailed Student t-test to determine whether these values are statistically different yields a p-value of 0.1, indicating that although the conformity index was slightly higher using hybrid shots, the conformity indices with and without hybrids were not significantly different. The average gradient index was 2.89 using hybrids and 2.76 without hybrids (Fig. 4). It is interesting to note that although these values are close to each other (as close as we could reasonably obtain), they are statistically different ($p = 0.003$). This point will be addressed in the Discussion section of this paper.

Results

Figure 5 shows an example of a plan that utilized hybrid shots for treatment of an acoustic schwannoma. In the highlighted shot, 4-mm collimators were used in sectors aligned with the brainstem and cochlea and 8-mm collimators were used in sectors where a steeper dose gradient was not needed. The 12-, 8-, and 4-Gy isodose lines are shown in Fig. 5. The brainstem and cochlea, outlined by the physician on appropriate imaging studies and displayed on the $T_1$ MR image in Fig. 5, received $\leq 4$ Gy in this plan.
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The average number of shots required for the plans using hybrids was not significantly different from the average number of shots for the plans in which hybrids were not used (16.7 vs 16.6 shots [p = 0.9]). However, the average number of blocked sectors required when hybrid shots were used was significantly smaller than when hybrid shots were not used (7.0 vs 14.8 blocked sectors [p = 0.01]). Figures 6 and 7 show these data for the individual patients in this study.

The data shown in Fig. 7 were analyzed in terms of “small” and “large” targets. Small targets were defined

Fig. 3. Bar graph showing Paddick conformity index (C.I.) for treatment plans with and without hybrid shots for 12 patients with lesions close to critical structures. Ave = average.

Fig. 4. Bar graph showing Paddick gradient index (G.I.) for treatment plans with and without hybrid shots for 12 patients with lesions close to critical structures.
as having a volume $\leq 1.0 \text{ cm}^3$ and large targets as having a volume $> 1.0 \text{ cm}^3$. For small targets, the number of blocked sectors increased by a factor of 1.4 on average if hybrid shots were not used in the treatment plan (9.2 blocked sectors when hybrids were used vs 12.8 blocked sectors when hybrids were not used). For large targets, the number of blocked sectors increased by a factor of 2.5 if hybrid shots were not used (6.6 blocked sectors when hybrids were used vs 16.7 blocked sectors when hybrids were not used). Thus, use of hybrids was associated with a greater reduction of blocked sectors for the larger targets ($> 1 \text{ cm}^3$) than for smaller ones.

The number of high-value collimators used in each plan was also evaluated. For small targets ($\leq 1 \text{ cm}^3$), we defined 8 mm as a high-value collimator. For large targets ($> 1 \text{ cm}^3$), 16 mm constituted a high-value collimator. For small targets, the plans employing hybrids used an average of 2.3 times as many 8-mm sectors as did the plans without hybrids (7.4 vs 3.2 sectors). For large targets, hybrid plans used an average of 1.4 times as many 16-mm sectors as did their nonhybrid counterparts (10.7 vs 7.7 sectors). Thus, hybrid shots allowed use of more high-value collimator sectors, and this pattern appeared to be more pronounced for smaller than for larger targets.

The net result of using fewer blocked sectors and more high-value collimator sectors was that the beam-on time was reduced. The beam-on time for each pair of plans is shown in Fig. 8. The average beam-on time was 67.4 minutes for the plans that used hybrids and 78.4 minutes for plans that did not ($p = 0.0003$). The average ratio of the beam-on time without and with hybrids was 1.17.

![Fig. 5. Treatment plan for an acoustic tumor utilizing hybrid shots. The steepest dose gradient is aligned with the edge of the brainstem and cochlea.](image)

![Fig. 6. Bar graph showing the number of isocenters (shots) used in treatment plans with and without hybrid shots for 12 patients with lesions close to critical structures.](image)
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**Discussion**

Table 1 quantifies some the dose distribution characteristics for the shots shown in Fig. 2 if these shots were delivered to the (100, 100, 100) point in the Leksell coordinate space in the Leksell spherical dosimetry phantom. The data in Table 1 were calculated using Leksell GammaPlan, release 8.0. Consider the width of the 50% isodose line in the X and Y directions. The width corre-

![Bar graph showing the number of blocked sectors in treatment plans with and without hybrid shots for 12 patients with lesions close to critical structures.](image1)

**Fig. 7.** Bar graph showing the number of blocked sectors in treatment plans with and without hybrid shots for 12 patients with lesions close to critical structures.

![Bar graph showing the beam-on time for treatment plans with and without hybrid shots for 12 patients with lesions close to critical structures.](image2)

**Fig. 8.** Bar graph showing the beam-on time for treatment plans with and without hybrid shots for 12 patients with lesions close to critical structures.
sponds to the treatment volume for this shot. As one might expect, the 50% isodose width in the X and Y directions for a hybrid shot composed of 8- and 16-mm sectors (the third row in Table 1) lies between the corresponding 50% widths for shots composed entirely of either 8- or 16-mm sectors. The behavior of the penumbra, however, is not as intuitive. Consider the distance of the dose fall-off from the 50% level to the 20% level, which is a useful definition of penumbra for Gamma Knife, because doses are most often prescribed to the 50% isodose. In the X direction, the 50–20% distance for the hybrid shot in row 3 of Table 1 is sharper than that of the 8-mm collimator by about 0.5 mm. Furthermore, the 50–20% width in the Y direction for the hybrid exceeds that of the 16-mm collimator by almost 4 mm. Both of these observations are nonintuitive, since one would expect the penumbra for a hybrid shot composed of 8- and 16-mm collimators to lie somewhere between that for shots composed entirely of 8-mm collimators or entirely of 16-mm collimators. This finding further highlights the need for additional care when using hybrid shots to treat lesions close to critical structures and the advisability of using low-value as opposed to high-value collimator sectors.

A possible consequence of using hybrid shots, which appear to exhibit larger penumbras in at least one direction, is that the gradient index for the resulting plan is larger than that for a comparable plan without hybrids. The data in Fig. 4 support this assertion. For all but 1 patient (patient number 7) considered in this study, the gradient index was higher in the plans that used hybrid shots.

Although the average gradient indices for the plans with and without hybrids did not differ greatly (2.89 vs 2.76), the difference was statistically significant (p = 0.003). However, although higher, the gradient indices for the plans developed in this study are clinically reasonable.

Conclusions

In Gamma Knife radiosurgery with the Perfexion, the judicious use of hybrid shots for targets close to critical structures is an efficient way to achieve conformal treatments while minimizing the beam-on time. On average, we observed a savings of beam-on time of 17% by using hybrid shots. The reduction in beam-on time with hybrid shots is attributed to a reduction in the number of blocked sectors and an increase in the number of high-value collimator sectors.

Disclaimer

The authors report no conflict of interest concerning the materials or methods used in this study or the findings specified in this paper.

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