Radiosurgery – LINAC or Gamma Knife: 20 Years of Controversy Revisited

Moshe Attia MD, Janna Menhel MSc, Dror Alezra PhD, Raphael Pffefer MD and Roberto Spiegelmann MD

Department of Neurosurgery and LINAC Radiosurgery Unit, Sheba Medical Center, Tel Hashomer, Israel

Key words: radiosurgery, LINAC radiosurgery, gamma knife, tumors, arteriovenous malformations

IMAJ 2005;7:583–589

For Editorial see page 597

Radiosurgery is defined as the acute high dose irradiation of a precisely defined intracranial lesion with an external source. High energy radiation beams penetrate the brain without the need for a physical opening. A high enough radiation dose deposited at the target results in its biological elimination. A steep radiation fall-off outside of the treated volume is mandatory to avoid radiation injury to normal tissue.

Several sources of ionizing radiation have been used for radiosurgery, including photon beams (gamma or X-rays) and particle beams (charged, such as protons, or uncharged such as neutrons). For practical reasons, most of the radiosurgery today is done with high energy photon beams [1].

Gamma knife radiosurgery

The first clinically useful device developed for photon beam radiosurgery was the gamma-knife, introduced by Lars Leksell et al. in 1968. In its current configuration, this machine has 201 Cobalt^{60} sources arranged in a heavy-metal hemispheric helmet. The high energy gamma rays (photons) emitted by these sources are all directed towards a single point at the center of the helmet. For treatment, the lesion in the patient's head is brought to coincide with that point. In order to modify the cross-section of the beams, a secondary helmet (collimator) is adapted to the treatment couch. There are four collimator helmets, each of them with 201 identical holes that enable almost circular cross-sectional beams of 4, 8, 14 or 18 mm [Figure 1]. For technical reasons, collimator helmets larger than 18 mm are not feasible [2]. At treatment, the patient's head is contained within a stereotactic frame and attached to the collimator helmet. The couch then moves towards the core of the gamma knife and parks when the holes of the collimator helmet match the cobalt sources, allowing the 201 radiation beams to pass to the patient's head. Given the fixed-beam geometry of the gamma knife (circular or elliptic), tailoring the irradiation shape to the targets requires irradiation with "multiple shots" (multiple isocenters). Since no movement of mechanical parts occurs during radiation treatment, the stability of the isocenter is guaranteed. Mechanical accuracy is in the order of 0.2 mm.

There are more than 150 gamma knives installed in medical centers around the world. With a record spanning more than 35 years, its mechanical stability and ease of use, [1,2] and a wealth of peer-reviewed publications describing its efficacy in multiple applications, the gamma knife is the gold standard in radiosurgery. Its main limitation is the limited range of beam diameters and the need for multiple isocenters to treat most targets. The decay in the radiation sources results in a progressive increase in the time required to deliver a given radiation dose as time goes by (it will double after 5 years), so it is necessary to replace the radiation source every 5 to 10 years..

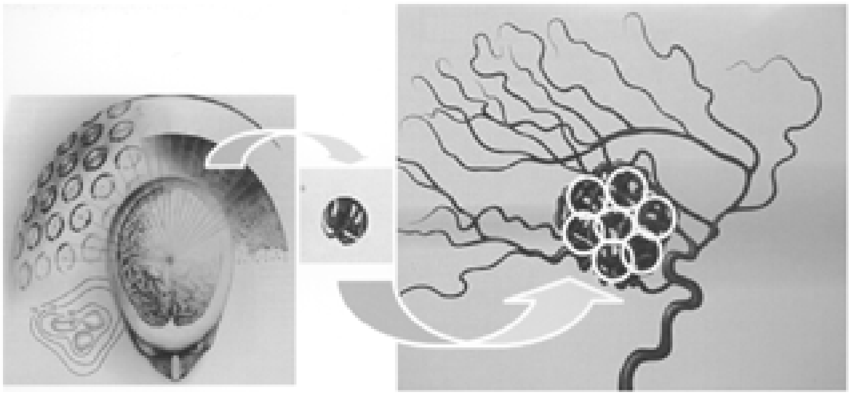

Figure 1. The gamma knife has only four different collimators. Each of them has 201 openings arranged in a hemispheric pattern. The openings have a fixed diameter of 4, 8, 14 and 18 mm. Since many targets have diameters in excess of the gamma knife collimators cross-section, tumors are irradiated with several "shots" (isocenters). This results in excellent conformality of the radiation shape to the target's margins. The trade-off is the production of "hot spots" within the target: areas wherein the overlap of radiation coming from two or more isocenters results in deposition of much higher radiation. In targets containing functional tissue this might be detrimental.

LINAC radiosurgery

Since 1982, conventional linear accelerators (LINACs) have been increasingly used as a radiation source for photon beam radiosurgery [3]. Linear accelerators were introduced into clinical practice for conventional external beam radiotherapy in the late 1950s. The early machines lacked mechanical precision, and for this reason were deemed inadequate for radiosurgical use. Late-generation machines have largely resolved this problem. In LINACs, the photon beam is electronically generated by accelerating electrons to almost the speed of light through a system of magnets. The electrons are then directed to collide with a heavy-metal target. The result of this "collision" is the emission of high energy photons (called X-rays), which exit the head of the LINAC (gantry) as a highly focused beam directed to a single point (isocenter). For radiosurgery, the lesion in the patient's head is brought to coincide with the LINAC isocenter. To generate multiple beams, the radiation source rotates around the isocenter, delineating a radiation arc (composed of multiple individual beams). After an arc is completed, the patient's head is rotated around the isocenter several degrees, and a new gantry rotation is executed. In this manner, multiple non-coplanar arcs of radiation are administered, with hundreds of radiation beams focused on the same point [Figure 2].

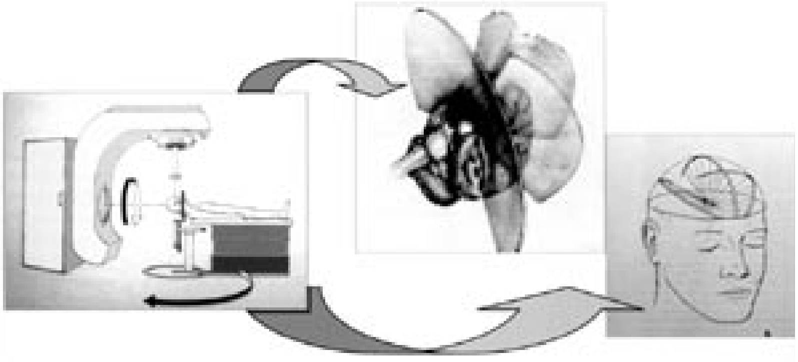

Figure 2. The linear accelerator produces high energy photons that exit the gantry as a well-focused beam directed to the isocenter. The isocenter is the point in space where the axis of the beam crosses the axis of rotation of the gantry and that of the couch where the patient rests. During treatment, the gantry rotates around the target in the patient's head, while a constant flow of radiation beams is being fired. This results in an "arc" of multiple beams focused on the target. The couch is then rotated to offer a different area of the patient's head to the beam. Multiple non-coplanar arcs of radiation are then produced. Hundreds of beams irradiate the target, while very little radiation crosses other areas of the brain.

The energy of the X-ray photons delivered by linear accelerators (averaging 2 million electron/volts in low energy machines), or the gamma-ray photons produced by the gamma knife (1.25 million electron/volts) is very similar. Thus, from a purely physical point of view, there is no practical difference in the irradiation effect achieved by either machine.

In classical LINAC radiosurgery, the cross-section of the beam is determined by attaching a cylindrical collimator with a small opening to the LINAC gantry. Only one collimator is necessary to generate the multiple beams. LINAC radiosurgery systems have a wide range of interchangeable collimators, with circular openings ranging from 5 mm through 50 mm in 2 or 2.5 mm increments so that there is no physical restriction to the cross-section of the beam. Elliptic or spherical targets can be irradiated with a single isocenter ("single shot"), regardless of their size. For irregular targets, classical LINAC radiosurgery is executed as with the gamma knife with "multiple shots." When multiple shots are used, the mechanical accuracy of the system is critical since the shape of the radiation distribution can vary sharply with small differences in the relative spacing of each isocenter.

Unlike the gamma knife, not all LINAC radiosurgery systems are born equal. The quality of a LINAC radiosurgery system depends on: a) the mechanical accuracy of the radiation source (the linear accelerator), and b) the features of the treatment-planning software. Most commercially available LINAC treatment-planning softwares are based on strong dosimetry principles. The mechanical accuracy of the linear accelerator is a feature that has to be measured for any particular machine, and may vary significantly in different machines constructed by the same provider. For conventional radiosurgery, the machine should have a mechanical accuracy within 0.7 mm, at any range of motion.

Conformal beam radiosurgery

A revolutionary piece of hardware called the mini-multileaf collimator is at the core of a new stereotactic radiation technique

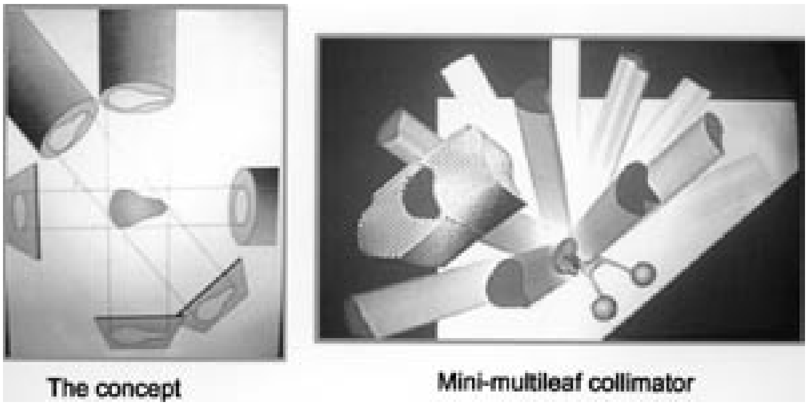

Figure 3. Current LINAC radiosurgery systems produce conformal radiation beams adapted to the target's shape from any point in space. Thus, regardless of the shape and size of the target, LINACs do not need more than one "shot" to produce excellent conformality. This results in a smooth radiation distribution across the tumor. At the core of this LINAC capability is the mini-multileaf collimator.

LINAC = linear accelerator

available in modern LINAC systems. The mMLC[2] is a collimator composed of several independent leaves of high density metal, each of them driven by an independent motor. Each metallic leaf has a width of 2–3 mm (at isocenter). Whatever the shape of the intracranial target, the mMLC can reproduce it, generating an individual radiation beam that closely mimics the target from any given profile. The ability to produce a beam adapted to the target shape from any point in space eliminates the need for multiple isocenter irradiation. We demonstrated in a pilot study [4] that for any target size, mMLC-generated radiation distributions are superior to multiple isocenter counterparts [Figure 3].

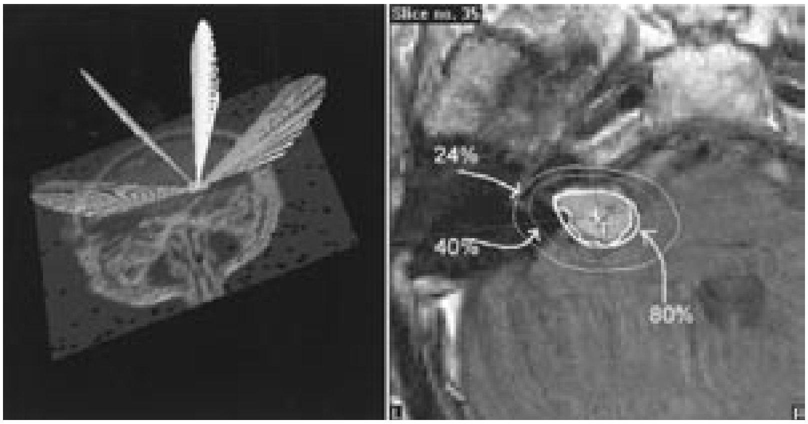

Figure 4. Magnetic resonance imaging reconstructed image of the radiosurgical plan for a small acoustic neurinoma. The arrows point to isodose lines. These lines enclose areas receiving a percentage of the maximum radiation delivered to the target. The 100% is usually a point in space. For this reason, the treatment dose is prescribed to a lesser isodose line, which encloses the tumor well. The tumor is treated with a single isocenter with beams produced by a mini-multileaf collimator and the dynamic conformal arcs technique. Conformality to the target is excellent.

This new radiosurgical technique has been termed Conformal Beam Radiosurgery, and can be executed in two forms:

- **Static conformal beams**, wherein the radiation source (gantry) remains stationary while the patient is irradiated. Eight or more radiation beams coming from different gantry positions are used to irradiate the target. This technique is still valuable when irradiating tumors are closely apposed to the optic nerve, since it is relatively easy to select beam positions which exclude the nerve, resulting in very steep radiation fall-offs in its direction.
- **Dynamic conformal arcs.** Increased computer power makes possible the use of mMLCs with the classical multiple, intersecting, non-coplanar arcs technique. The radiation source (LINAC gantry) rotates around the patient's head, while the mMLC dynamically changes its shape, adapting it to the changing shape of the intracranial target. Dynamic conformal beam radiosurgery is today the best option for smooth and precise acute irradiation of most intracranial targets [Figure 4].

Linac radiosurgery vs. gamma knife: Outcome

Regardless of physical and theoretical considerations, any treatment modality has to be judged by its clinical results. Radiosurgery is currently applied to a host of intracranial pathologies, including benign tumors (meningiomas, acoustic neuromas, pituitary adenomas, etc.), malignant tumors (mostly metastases) and arteriovenous malformations. "Functional" applications are yet experimental and include the production of radio-lesions in different brain structures as an alternative to open surgery. The available data will be discussed in relation to the different pathologies.

Arteriovenous malformations

The treatment of AVMs with radiosurgery has become mainstream in the last 15 years. Radiosurgery damages the wall of the small vessels comprising the AVM nidus, triggering the development of intimal hyperplasia, proliferation of smooth muscle cells, and elaboration of extracellular collagen. All of these eventually result in vessel occlusion. This process is gradual, taking 1–3 years until completion. The end result is the total obliteration of the AVM, with regression of the hypertrophic changes in the arteries and veins subserving the nidus.

Microsurgical removal remains the treatment of choice for AVMs since it is the only therapy that can achieve acute and complete removal of the nidus, immediately eliminating the risk of bleeding. Endovascular treatment also has the potential of acute obliteration of the nidus by embolization. Nonetheless, *complete* obliteration is achieved in fewer than 20% of AVMs, rendering embolization as an adjuvant treatment to reduce the flow and the size of AVMs before surgery or radiosurgery. Radiosurgery is indicated for any AVM with a maximal diameter of 30–35 mm (depending on its location), whenever surgery is deemed either not possible or excessively risky, and when angiography shows an angio-architecture not amenable to complete obliteration by embolization techniques. Until the AVM is completely obliterated, the risk of bleeding remains as in untreated lesions (3–4% annually) [5]. Radiosurgery does not increase the risk of bleeding. The obliteration rate of radiosurgery is high, albeit dependent on the size of the nidus. For small AVMs (up to 4 mm) the success rate is approximately 85% at 3 years [5–7], and for larger niduses 55–65% [8–10]. Radiation-related side effects are dependent on radiation dose, nidus volume, and nidus location [5,10]. Overall, the rate of permanent neurologic deficit following radiosurgery for AVMs is about 3% [5,8–11]. The outcome in gamma knife and LINAC radiosurgery series is similar [5,8–11].

Retreatment for a residual nidus is possible, with similar obliteration rates [7,12,13]. The risk for permanent neurologic deficit is thought to be cumulative, although a recent publica-

---

mMLC = mini-multileaf collimator
AVM = arteriovenous malformation

tion demonstrated no change [7]. For large AVMs exceeding the size considered suitable for radiosurgery (more than 35 mm in more than one dimension), the use of embolization techniques to reduce the nidus size as a step previous to radiosurgery has been standard for many years. Recent data suggest that partial embolization results in poorer obliteration rates for radiosurgery. For this reason, the application of new techniques is being explored in the last few years. One of these is "staged radiosurgery," where the nidus is subdivided into two to three smaller portions that are separately irradiated in two to three sessions. Another is "hypofractionated stereotactic radiation," where the total radiation dose is divided into smaller fractions administrated over four to seven sessions to the whole nidus. Preliminary reports lend some support to these approaches [14,15].

At Sheba Medical Center 135 AVMs have been treated with radiosurgery to date. In 80 cases, follow-up of at least 36 months was available at the time of writing. Sixty-one patients were cured (76%). Eleven patients had a second treatment for an incompletely closed nidus (usually more than 3 years after the first treatment). Of 104 patients followed for at least 1 year, 4 suffered a bleeding episode and 2 of them died (at 20 and 24 months post-treatment). Six patients had transient neurologic deterioration due to radiation injury. Mild permanent deficits remained in three.

Acoustic neurinomas

These benign tumors are relatively frequent, representing 10% of all primary intracranial tumors and 80% of cerebellopontine angle tumors. They are traditionally managed by microsurgical resection. Preservation of the VII and VIII cranial nerves (facial and acoustic nerves) intimately apposed to the tumor represents a technical challenge even for the seasoned surgeon. Results of acoustic neuroma surgery are highly dependent on tumor volume and the surgeon's experience [16–22]. The acute rate of VII neuropathy is approximately 40%, with some 10% of permanent facial paresis in the best hands [16]. Hearing preservation is only possible in small tumors (usually <20 mm), and again is in the order of 30–40% in experienced hands. Tumor recurrence after complete removal is reportedly 1–10%.

Radiosurgery for acoustic neuromas was first indicated for recurrent or residual tumors. During the last decade, and owing to its excellent control rates, it is also being offered to patients with newly diagnosed tumors. Long-term tumor control rates are better than 90% in all published series [17,23,24].

The incidence of facial neuropathy, which was always low, has been reduced further by lowering the therapeutic radiation dose delivered to the tumor. With current techniques, facial neuropathy (mostly transient) is seen in less than 2% of patients. Hearing preservation rates at 3 years range between 50 and 77% [17]. Most tumors (>70%) shrink gradually over time. Most of the reported experience comes from groups using the gamma knife.

More than 200 patients with acoustic neurinomas have undergone radiosurgery at our facility. Our early results [25] reflected the evolution in this treatment modality. Permanent facial nerve deficit was seen in 8%, which included patients treated with relatively high radiation doses. This has been the experience in other centers as well, regardless of the radiosurgical technique (gamma knife or LINAC).

With the current low therapeutic doses, only one case of transient facial neuropathy occurred (1.4%) in our last 77 evaluable patients. Radiosurgery is currently offered in our center as first-choice treatment for tumors up to 30 mm in diameter in patients 55 years of age or older. In younger patients, microsurgery remains the first line of treatment. The reason is because there are not as yet actual epidemiologic data on the risk of developing secondary tumors 20 years or more after radiosurgery. For tumors larger than 30 mm, we offer partial removal with subsequent radiosurgery or fractionated stereotactic radiation, depending on the patient's clinical presentation. We believe that subtotal removal of large acoustic neuromas provides a better chance of preserving facial nerve function than complete removal. This contention is controversial.

Meningiomas

Radiosurgery is indicated for meningiomas of suitable size in surgically difficult locations such as the cavernous sinus and petroclival area. Radiosurgery also plays a significant role in the management of residual or recurrent tumors in areas where complete surgical resection is rarely achieved. This is the case of parasagittal, torcular and latero-tentorial meningiomas, which usually invade sinusal walls and therefore cannot be completely resected. A high incidence of recurrence is associated with residual tumor within the sinus [17]. Since radiosurgery does not obliterate major arteries or veins, it can be applied safely to tumors encasing important vessels. According to most current published data and our own, radiosurgery controls more than 90% of treated meningiomas. Tumor shrinkage occurs gradually in some 50–60% of the tumors. The incidence of complications is low and dependent on tumor location [17,26,27].

For meningiomas involving the cavernous sinus, radiosurgery is in our opinion the treatment of choice. Surgical series of parasellar meningiomas have reported a high incidence of major complications (6–42% cranial neuropathies, 10–15% ischemic brain damage due to lesioning of the internal carotid artery, 10% mortality). Gross complete tumor removals are achieved in up to 70% of cases. Recurrence rates after gross total resection are reportedly 10% [28–33]. Incompletely resected tumors usually regrow. The mean follow-up in most surgical series are substantially shorter than in radiosurgical series [30,31].

In our own series of 69 tumors followed for 1–7 years, cranial nerve neuropathy occurred in 3% (mostly transient) and optic neuropathy in 1.5%. No patient developed pituitary insufficiency. Several patients with previous cranial neuropathies experienced improvement or resolution. Mean follow-up for this series was 38 months (currently 60 months). One tumor grew 36 months after treatment and later stabilized. All the other patients had either stable or reduced (60%) tumor volumes at last follow-up [28].

The results in our center compare favorably with those reported by other groups (either gamma knife or LINAC series) [34,35]. Of note, the rare occurrence of symptomatic delayed intracavernous sinus carotid artery occlusion/stenosis several years following gamma knife radiosurgery of cavernous sinus meningiomas was recently brought to attention. This could theoretically be related to "hot spots" of radiation induced by multiple isocenter treatment. Hot spots are not an issue in conformal beam radiosurgery as performed with state-of-the-art LINAC systems [36].

Metastases

The best management for brain metastases of solid tumors is still controversial, particularly for single brain metastasis. Surgery, whole brain radiation, and radiosurgery are currently standard. A decade ago, WBR was standard treatment for most patients [17]. Treatment by WBR carries a high risk of inducing delayed leukoencephalopathy, particularly in the elderly. The clinical result is progressive cognitive impairment with significant deterioration in quality of life [37]. In addition, WBR is only marginally effective for certain frequent "radio-resistant" metastatic tumors such as melanoma, colorectal and renal cell carcinoma.

Local treatment can be given by either open surgery or radiosurgery. The available data suggest that both modalities yield similar results (local control rates above 80%; local recurrence in less than 25%) [17,37,38]. Metastatic tumors in most cases are within the resolution of radiosurgery since, due to the significant brain edema that they cause, they are detectable while still small. Radiosurgery is effective even in classically radio-resistant tumors. The minimally invasive nature of radiosurgery is particularly advantageous in these patients: that it is a painless procedure, carries no risk of bleeding or infection, and requires only a short hospital stay are important assets for this frequently debilitated and/or immunosuppressed population. In addition, a patient with multiple metastases can have his or her treatment completed in a single session. LINAC radiosurgery has certain advantages over the gamma knife in the management of brain metastases. Due to space restrictions in the relatively small gamma knife hemispheric collimator, some patients with multiple metastases in peripheral locations of both hemispheres cannot be treated in a single session due to the need for frame reapplication. This limitation does not exist in LINAC systems. Conformal LINAC radiosurgery enables treatment of each metastasis with a "single shot," resulting in faster management of patients with multiple lesions than is possible with a gamma knife. Otherwise, results from radiosurgery for metastatic lesions are similar in gamma knife and LINAC series [38,39]. At Sheba Medical Center more than 400 patients with brain metastases have been treated in the last decade, which represents a third of our patient load and the most frequent pathology treated in our unit.

Functional radiosurgery

Radiosurgery was first devised by Lars Leksell as an alternative to open surgery for the creation of discrete lesions in the brain in the treatment of functional disorders. This application was subsequently abandoned due to inferior results. In the last few years, and mostly owing to refinements in brain imaging, functional radiosurgery is experiencing a revival [40]. A list of the procedures currently being performed at different centers follows. Of note, with the exception of radiosurgery for trigeminal neuralgia, most of them are still investigational.

- radiopallidotomy and radiothalamotomy for movement disorders
- mesio-temporal irradiation for temporal epilepsy and irradiation of hypothalamic hamartomas for the management of pediatric gelastic seizures
- irradiation of the trigeminal nerve root for trigeminal neuralgia
- anterior radio-capsulotomy or radio-cingulotomy for obsessive-compulsive disorder.

A detailed discussion of these applications is beyond the scope of this paper. Aside from irradiation for focal epilepsy which is low dose, the production of discrete lesions in normal structures requires very high radiation doses (75 Gy and higher). The gamma knife is specially adapted to this goal since higher doses require longer exposures but no movement of the patient or radiation source.

Conclusions

Radiosurgery has become a major tool in the management of intracranial tumors and vascular malformations. It is also establishing itself as a treatment option in functional brain disorders. For certain indications, such as metastases, parasellar and clival meningiomas, acoustic neurinomas in the mature population, and deep-seated AVMs, we hold that radiosurgery is today the treatment of choice for lesions of suitable size. For practical reasons, most of the radiosurgery is performed today with photon beam sources – either the gamma knife or linear accelerators.

For more than 15 years the gamma knife was the only practical radiosurgical tool. The advent of LINAC systems in the 1980s prompted a protracted and heated argument regarding which is the best radiosurgical tool. We have attempted here to show that from the physical standpoint both tools are similar, although each has advantages and limitations. The gamma knife holds the mechanical accuracy standard. LINACs have the potential for excellent mechanical accuracy, although this requires a dedicated mantainance and quality assurance team. On the other hand, the LINAC has a beam-shaping versatility that is unattainable with a gamma knife.

Beyond physical or theoretical considerations, the quality of any treatment modality has to be judged by its clinical results. For any currently accepted application for which relevant data are available, the results of radiosurgery are similar with either technique.

WBR = whole brain radiation

References

1. Chang SD, Adler JR, Steinberg GK. General and historical considerations of radiotherapy and radiosurgery. In: Winn HR ed. Youmans Neurological Surgery. Vol. 4, 5th edn. Philadelphia: WB Saunders, 2004:3991–8.
2. Witham TF, Kondziolka D. Gamma knife radiosurgery. In: Winn HR ed. Youmans Neurological Surgery. Vol. 4, 5th edn. Philadelphia: WB Saunders, 2004:4117–21.
3. Alexander E. Linac radiosurgery. In: Winn HR ed. Youmans Neurological Surgery. Vol. 4, 5th edn. Philadelphia: WB Saunders, 2004:4111–16.
4. Menhel J, Spiegelmann R. mMLC or multiple isocenters? When and Where [Abstract]. VIth Meeting of the International Society for Stereotactic Radiosurgery, Kyoto, Japan, June 2003.
5. Friedman WA, Foote KD. Radiosurgery for arteriovenous malformations. In: Winn HR ed. Youmans Neurological Surgery. Vol. 4, 5th edn. Philadelphia: WB Saunders, 2004:4073–86.
6. Friedman WA, Bova FJ, Mendenhall WM. Linear accelerator radiosurgery for arteriovenous malformations: the relationship of size to outcome. *J Neurosurg* 1995;83(2):381–2.
7. Foote KD, Friedman WA, Ellis TL, Bova FJ, Buatti JM, Meeks SL Salvage retreatment after failure of radiosurgery in patients with arteriovenous malformations. *J Neurosurg* 2003;98(2):337–41.
8. Yamamoto M, Jimbo M, Hara M, et al. Gamma knife radiosurgery for arteriovenous malformations: long term follow-up results focusing on complications occurring more than 5 years after irradiation. *Neurosurgery* 1996;38:906–14.
9. Pollock BE, Flickinger JC, Lunsford LD, et al. Factors associated with successful arteriovenous malformation radiosurgery. *Neurosurgery* 1998;42:1239–47.
10. Karlsson B, Lax I, Soderman M. Factors influencing the risk for complications following gamma knife radiosurgery of cerebral arteriovenous malformations. *Radiother Oncol* 1997;43:275–80.
11. Colombo F, Benedetii A, Pozza F, et al. Linear accelerator radiosurgery of cerebral arteriovenous malformations. *Neurosurgery* 1989;24:833–40.
12. Francel PC, Steiner L, Steiner M, et al. Repeat radiosurgical treatment in arteriovenous malformations following unsatisfactory results of initial single high-dose radiation. *J Neurosurg* 1991;74:352A.
13. Karlsson B, Kihlstrom L, Lindquist C, Steiner L. Gamma knife surgery for previously irradiated arteriovenous malformations. *Neurosurgery* 1998;42:1–6.
14. Lunsford LD, Niranjan A. Staged radiosurgery for large arteriovenous malformations. *Technique Neurosurg* 2003;9(3):116–18.
15. Lindvall P, Bergström P, Löfroth PO, et al. Hypofractionated conformal stereotactic radiotherapy for arteriovenous malformations. *Neurosurgery* 2003;53:1036–43.
16. Pollock BE, Lunsford LD, Kondziolka D, et al. Outcome analysis of acoustic neuroma management. A comparison of microsurgery and stereotactic radiosurgery. *Neurosurgery* 1995;36:215–29.
17. Niranjan A, Lunsford LD. Radiosurgery of tumors. In: Winn HR ed. Youmans Neurological Surgery. Vol. 4, 5th edn. Philadelphia: WB Saunders, 2004:4053–72.
18. Nadol JB Jr, Chiong CM, Ojemann RG, et al. Preservation of hearing and facial nerve function in resection of acoustic neuroma. *Laryngoscope* 1992;102:1153–8.
19. Samii M, Matthies C. Management of 1000 vestibular schwannomas (acoustic neuromas): hearing function in 1000 tumor resections. *Neurosurgery* 1997;40:248–62.
20. Gormley WB, Sekhar LN, Wright DC, et al. Acoustic neuromas: results of current surgical management. *Neurosurgery* 1997;41:50–60.
21. Fahlbusch R, Neu M, Strauss C. Preservation of hearing in large acoustic neurinomas following removal via suboccipito-lateral approach. *Acta Neurochir* 1998;140:771–7.
22. Colletti V, Fiorino FG. Retrosigmoid-transmeatal en bloc removal of small to medium sized acoustic neuromas. *Otolaryngol Head Neck Surg* 1999;120:122–8.
23. Lunsford LD, Niranjan A, Flickinger JC, Maitz A, Kondziolka D. Radiosurgery of vestibular schwannomas: summary of experience in 829 cases. *J Neurosurg* 2005;102(Suppl):195–9.
24. Meijer OW, Vandertop WP, Baayen JC, Slotman BJ. Single-fraction vs. fractionated linac-based stereotactic radiosurgery for vestibular schwannoma: a single-institution study. *Int J Radiat Oncol Biol Phys* 2003;56(5):1390–6.
25. Spiegelmann R, Lidar Z, Gofman J, Alezra D, Hadani M, Pfeffer R. LINAC radiosurgery of acoustic neurinomas. *J Neurosurg* 2001;94: 7–13.
26. Kondziolka D, Levy EI, Niranjan A, et al. Long term outcomes after meningioma radiosurgery: physician and patient perspectives. *J Neurosurg* 1999;91:44–50.
27. Hakim R, Alexander E 3rd, Loeffler JS, et al. Results of linear accelerator-based radiosurgery for intracranial meningiomas. *Neurosurgery* 1998;42:446–53.
28. Spiegelmann R, Nisim O, Menhel J, Alezra D, Pfeffer MR. LINAC radiosurgery for meningiomas in and around the cavernous sinus. *Neurosurgery* 2002;51(6):1373–80.
29. Cusimano MD, Sekhar LN, Sen CN, et al. The results of surgery for benign tumors of the cavernous sinus. *Neurosurgery* 1995;37: 1–10.
30. De Jesus O, Sekhar LN, Parikh HK, Wright DC, Wagner DP. Long term follow up of patients with meningiomas involving the cavernous sinus: recurrence, progression and quality of life. *Neurosurgery* 1996;39:915–20.
31. DeMonte F, Smith HK, Al Mefti O. Outcome of aggressive removal of cavernous sinus meningiomas. *Neurosurgery* 1994;81:245–51.
32. Kallio M, Sankila R, Hakulinen T, Jääskeläinen J. Factors affecting operative and excess long-term mortality in 935 patients with intracranial meningiomas. *Neurosurgery* 1992;31:2–12.
33. Dufour H, Muracciole X, Mètellus P, Règis J, Chinot O, Grisoli F. Long term tumor control and functional outcome in patients with cavernous sinus meningiomas treated by radiotherapy with or without previous surgery: is there an alternative to aggressive tumor removal? *Neurosurgery* 2001;48:285–96.
34. Roche PH, Règis J, Dufour H, et al. Gamma knife radiosurgery in the management of cavernous sinus meningiomas. *J Neurosurg* 2000;93(Suppl):68–73.
35. Chang SD, Adler JR Jr. Treatment of cranial based meningiomas with linear accelerator radiosurgery. *Neurosurgery* 1997;41:1019–27.
36. Stafford SL, Pollock BE, Foote RL, et al. Meningioma radiosurgery: tumor control, outcomes, and complications among 190 consecutive patients. *Neurosurgery* 2001;49:1029–38.
37. Mehta MP. Fractionated radiation therapy for malignant brain tumors. In: Winn HR ed. Youmans Neurological Surgery. Vol. 4, 5th edn. Philadelphia: WB Saunders, 2004:4015–26.
38. Alexander E 3rd, Moriarty TM, Davis RB, et al. Stereotactic radiosurgery for the definitive, noninvasive treatment of brain metastases. *J Natl Cancer Inst* 1995;87:34–40.
39. Gerosa M, Nicolato A, Severi F, et al. Gamma knife radiosurgery for intracranial metastases:from local tumor control to increased survival. *Stereotact Funct Neurosurg* 1996;66(Suppl 1):184–92.
40. Duma CM, Shea M, Jacques DB, Kopyov O. Functional radiosurgery. In: Winn HR ed. Youmans Neurological Surgery. Vol. 4, 5th edn. Philadelphia: WB Saunders, 2004:4087–94.

Correspondence: Dr. R. Spiegelmann, Director, Stereotactic Radiosurgery Unit, Dept. of Neurosurgery, Sheba Medical Center, Tel Hashomer 52621, Israel.
Phone: (972-3) 530-2486
Fax: (972-3) 535-4413
email: spiegel@sheba.health.gov.il