History of Cyberknife ™ Radiosurgery: How 2 Decades of Image-guided Precision have shaped radiosurgery

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Technological advancement is generally incremental. However, there are some innovations that prove to be so transformative that it not only improves upon existing technology, but also CREATES new opportunities and new treatments that did not previously exist. The introduction of Cyberknife ™ radiosurgery was a "disruptive technology" that helped to alter the trajectory of radiation medicine by demonstrating the feasibility and accuracy of image-guided radiation. Coupling its exquisite precision and accuracy with image-guidance in a comfortable, non-invasive, and flexible platform, the Cyberknife ™ has opened vast opportunities for new applications of radiosurgery.

The impetus for the development of the Cyberknife ™ was not only to address key limitations to frame- based radiosurgery, but also deeply rooted in a commitment to patient-centered care. While completing a stereotactic radiosurgery fellowship in Stockholm, Sweden under Lars Leksell in the mid 1980's, Dr. John Adler of Stanford University was intrigued by the precision of the Gammaknife, though also distressed by the discomfort of the stereotactic frame placement especially for pediatric patients. Furthermore, because of its requirement for rigid skeletal fixation, frame-based radiosurgery was limited only to treatment of the head and upper neck. Dr. Adler's vision was to develop a precise technology to treat brain tumors as well as other body areas without a stereotactic frame in a system that would permit the flexibility of fractionated radiation treatments.

Through collaboration with experts in computer science, medical informatics, imaging physics, and robotics, the Cyberknife ™ system was designed, comprised of a robotic retargeting of the therapeutic x-ray source based upon the location of the target as assessed by the images. By the early 1990's, early ideas of pre and intra-radiation image registration were beginning to loom. (Brunie L, 1993) However, one of the first uses of the term "image-guidance" in the medical literature with reference to radiation treatment was in a 1994 paper by Adler's group describing the Cyberknife ™ prototype. (Schweikard A, 1994) With the introduction of the Cyberknife ™ stereoscopic imaging coupled to a robotically-mounted compact linear accelerator, the concept of "Image-guidance" was realized. Early iterations of Cyberknife ™ 's image-guidance system included a c-arm fluoroscopic-guided system, but ultimately settled on the x-ray stereoscopic system currently in use.

In the early 1990's, 5 Cyberknife ™ beta prototype systems were installed at Stanford, University of Pittsburgh-Shadyside, Newport Beach, UT Southwestern, and Cleveland Clinic. The first robotic image-guided radiosurgery treatment in the world was performed using prototype Cyberknife ™ in June 1994 at Stanford University. By 1999, the device gained United States Food and Drug Administration (FDA) clearance for radiation treatment of lesions of the head and neck. Within a year of the first brain treatment, the first extra-cranial treatment of spinal tumors was successfully treated at Stanford using image-tracking of implanted gold fiducials. Shortly thereafter, using a technique of respiratory-breath-hold and image-guidance of implanted gold

fiducials, Cyberknife ™ treatment of pancreas tumors and lung tumors was pioneered through early feasibility studies. By 2001, the Cyberknife ™ system gained US FDA clearance for treatment anywhere in the body, followed by approval across other global sites including Europe (2002), South Korea (2003), Taiwan (2004), and Japan (2008). Over the next 5 years between 2002-2007, multiple enhancements in the Cyberknife ™ system were developed that helped to launch the era of Image-guided and Stereotactic Body Radiotherapy (SBRT) by introducing improvements in the efficiency and ease of extracranial body treatments including Synchrony Respiratory Tracking (2002) allowing treatment of lesions that move with respiration during active breathing; XSight ™ Spinal Tracking (2004) permitting treatment of spinal lesions without the need for implanted fiducials; 4D Optimization of the planning system (2005); and XSight ™ Lung Tracking (2007) permitting the treatment of some lung tumors without implanted fiducials.

Cyberknife ™ robotic radiosurgery has not only improved upon existing techniques of precision therapy, but pioneered new opportunities that have transformed the world of modern radiotherapy by creating a platform to extend the reach of radiation across disciplines. Over the past 2 decades, over 1500 Cyberknife-related contributions have been added to the academic literature covering nearly every anatomic region and extending beyond oncologic treatment to include functional applications, vascular anomalies, and cardiac dysrhythmias.

The field of image-guide robotic radiosurgery emerged from neurosurgery and radiation medicine by combining concepts of image-guidance, stereotaxy, and robotics to address the need to accurately target key areas within the neurological axis. In many ways the advances of robotic radiosurgery have mirrored innovations in other industries, first offering a tool to improve efficiency, then leading to the application of the technology beyond the neuraxis to extracranial body sites. With the innovations of Synchrony, robotic radiosurgery crossed new frontiers and transcended barriers of motion management. Over the past 2 decades, the lives of thousands of patients have been changed and numerous contributions to academic medicine have been made. As the technology of image-guided robotic radiosurgery matures, it is ever more important to continue to extend the concepts founded in this extraordinary technology and to create new possibilities.

References

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