BRAINLAB

EXACTRAC FRAMELESS RADIOSURGERY

Clinical White Paper

Radiosurgery stands as a unique field in medical practice, presently encompassing the disciplines of neurosurgery, radiation oncology and medical physics. Despite initial skepticism, radiosurgery's utility over time has clearly become a key component in the neurosurgical armamentarium[1]. In the last decade, improvements in imaging and computing have led to the development of frameless image-guided radiosurgery, a precise non-invasive variant offering improved patient comfort and treatment flexibility in addition to radiosurgical accuracy[2-4]. This evolution eliminated the requirement of the invasive frame-based patient fixation technique as the relationship between the immobilization device and the patient anatomy is no longer crucial. However, abandoning the head frame unavoidably raises intra-fraction motion issues which necessitate recurrent verification of correct patient positioning throughout the treatment[5]. Only techniques providing this capability truly permit Frameless Radiosurgery.

DEFINITION

Radiosurgery was originally defined by Leksell as "a single high dose fraction of radiation, stereotactically directed to an intracranial region of interest"[6]. Although this definition was recently stretched to include treatments up to five fractions[7], the localization accuracy and precision implicit in the word "stereotactic" remains of utmost importance for radiosurgical interventions today.

Radiosurgery relies on stereotactic image localization, thereby enabling co-identification of a virtual target in the treatment planning computer with the actual target position in the patient anatomy. To use this paradigm optimally and position the patient with the highest possible accuracy and precision, all errors, from image acquisition over treatment planning to mechanical aspects of treatment delivery, must be systematically optimized[8,9].

FRAME-BASED RADIOSURGERY

In conventional frame-based radiosurgical approaches, the patient is immobilized with an invasive head frame and positioned before treatment by inferring the location of internal anatomy from external coordinates provided during the localization process[10]. The entire patient positioning workflow is built around the assumption that the external coordinates correctly represent the isocenter location.

Frame-based radiosurgery depends critically on maintenance of the spatial relationship of the frame to the skull. Any slippage or deformation of the frame between planning and treatment will result in a positioning error and is important to exclude carefully at the time of treatment[11]. Although a depth helmet has been routinely employed to monitor for frame slippage[12], it provides only indirect or limited information that may not necessarily be correlated with the internal target position. The depth-helmet technique relies on potentially imprecise skin markings and depth measurements, which are particularly difficult in patients with certain hair types or loose skin[13].
Even though the head frame itself is in general an efficient immobilization device and frame slippage or frame deformation rarely occurs, many patients consider head frame placement to be a traumatic experience. Frame-placement involves risk of bleeding and infection, as well as requires pre-medication. Furthermore, the care of patients wearing head frames creates a clinical resource burden on the day of treatment, requiring dedicated nursing and physician support. Frame-based treatment also requires treatment planning to be completed following frame placement on the day of treatment, making it less feasible to incorporate advanced dose planning techniques[3,13].

FRAMELESS RADIOSURGERY

Moving from frame-based radiosurgery to frameless radiosurgery by no means implies the act of trading an invasive head frame for a relocatable frame or mask. While a variety of non-invasive relocatable frame and mask systems have been utilized for fractionated stereotactic treatment[14-16], their immobilization capability and overall target localization accuracy have been considered to be lower than an invasive frame-based system[17].

The somewhat unfortunate term "frameless radiosurgery" actually implicates the adoption of image-guided technologies and computer-driven optimizations of every step in the designated radiosurgery workflow in an attempt to minimize every individual error and thereby maximize the total radiosurgical accuracy[18,19]. As a consequence, the invasive head frame needs to be replaced by a non-invasive immobilization device, since metallic frames typically cause too many artifacts during the image-guided procedure.

The challenge of frameless radiosurgery is to compensate for the slight loss of immobilization by reducing other potential errors accumulating at each step in the radiosurgery procedure. Rather than manually driving the couch and positioning the patient indirectly by matching surface marks with laser crosshairs, an infrared camera system can be implemented to maneuver the patient in the field-of-view of the image-guided system to initiate the positioning process based on visualization of the internal anatomy[20]. Dedicated software subsequently calculates the three-dimensional deviations from the expected target position and corrects them by moving and rotating the couch on which the patient is immobilized in six directions (6D)[21].

COMPARISON

Immobilization only contributes a fraction to the total radiosurgical accuracy, which stems from all individual errors accumulated at each step in the radiosurgery process[22]. Typical for frame-based radiosurgery are image registration errors, external coordinate misplacement, laser misalignment, and geometric and mechanical errors of the positioning hardware and delivery system[23]. Most of these errors occur randomly during the manual frame-based patient positioning procedure, and are not easily traceable, which impedes the relation to unexpected treatment outcome and toxicity.

A systematic evaluation of the accuracy of frame-based radiosurgery was undertaken by Maciunas et al. for several commercial radiosurgery frames. Imaging-associated errors contributed significantly to the reported overall average uncertainty of 2.28 mm[24]. The American Association of Physicists in Medicine (AAPM) reported a similar value for the overall localization uncertainty, namely 2.4 mm[25].

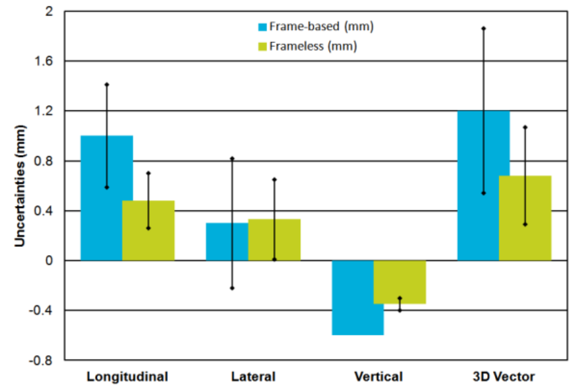

Figure 1: Comparison of the total uncertainties associated with frame-based and frameless radiosurgery for a phantom[26]. Frameless radiosurgery is significantly more accurate in the longitudinal and vertical directions, which leads to a 50% improvement in overall three-dimensional accuracy when compared to frame-based techniques.

As frame-based radiosurgery is still considered to be the gold standard for many neurosurgical practices, the reported accuracies provide growing momentum for evaluating frameless technologies. In order to achieve comparable and preferably even better accuracy than frame-based techniques, true frameless radiosurgery should compensate for the reduced immobilization accuracy associated with a non-invasive fixation device. This is realized by reducing human interference during patient positioning and optimizing the radiosurgery workflow by direct visualization of the internal target.

A direct comparison of the uncertainties associated with frame-based and frameless radiosurgery was undertaken by Gevaert et al. and is presented in Figure 1[26]. By performing an end-to-end test with a metal target hidden in a phantom, the authors were able to quantify the total error accumulated at each step in the radiosurgery process. Repeating the same test several times for both the frame-based and frameless radiosurgery procedure revealed an average three-dimensional positioning uncertainty of 1.2 mm for frame-based radiosurgery versus 0.68 mm for frameless radiosurgery.

Extracting target treatment margins from phantom data is not as straightforward as involuntary patient motion during treatment; although limited by the relocatable mask, it cannot entirely be excluded and is potentially larger for frameless as compared to the frame-based technique. However, the advantage of the frameless approach is the possibility of real-time monitoring, which is required to achieve the necessary set-up precision.

BENEFITS

A significant advantage of image-guided frameless radiosurgery over frame-based radiosurgery is that the relationship between the immobilization device and the cranial skeletal anatomy need not be preserved from treatment planning to actual treatment. Instead, imaging at the time of treatment is used to directly determine the position of the target in stereotactic space.

Rather than restricting physician intervention to the immobilization step, frameless radiosurgery offers physicians control over the entire positioning procedure by providing image fusion evaluation tools. A clear documentation of the constant evaluation of the patient position, performed before and during treatment, enables physicians to qualify treatments and assists in explaining unexpected toxicity.

A non-invasive fixation also permits flexible treatment schedules and unlocks the potential of fractionated radiosurgery protocols. But perhaps the greatest benefit of frameless radiosurgery is to offer patients an improved level of comfort and restrain their needless anxiety.

INNOVATION THROUGH TRADITION

ExacTrac is a genuine image-guided positioning system that teams up with iPlan RT treatment planning to offer a frameless radiosurgery solution that allows unlimited intra-fraction positioning verification[27]. ExacTrac builds on the experience of two decades of frame-based radiosurgery and was designed in response to clinicians' needs for treatments that integrate the highest standards of accuracy and precision in an efficient and flexible workflow[28].

CONFIDENTLY RESTRAIN YOUR MARGINS

Over the last few years, dose escalation has become a common strategy to enhance the therapeutic effect of a radiosurgical treatment. However, this implies the need for ever smaller target margins in an attempt to limit radiation-induced toxicity[29]. As a result, accuracy in localization of the isocenter became essential for effective treatments, as an error of 1 mm can result in dosimetrical inaccuracies on the order of 10% or more during delivery[30].

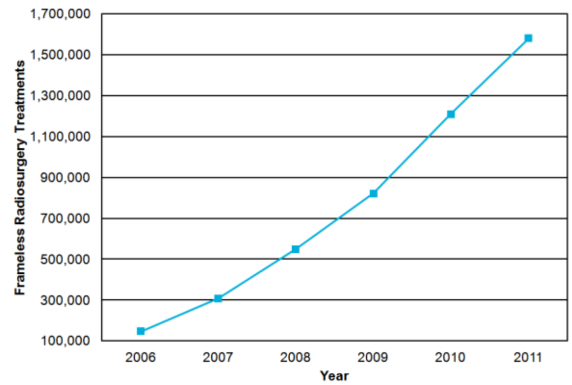

Figure 2: Graphical representation estimating the incremental annual number of ExacTrac frameless radiosurgery treatments.

The usability of ExacTrac and the trust in its capabilities are reflected by a widespread adoption and a rapid increase in the annual number of frameless radiosurgery treatments as indicated in Figure 2.

Only an end-to-end test of the entire frameless radiosurgical workflow can quantify the combined localization error accumulated during the imaging, planning and positioning phases. Hiding a metal target in a rigid phantom and simulating a complete typical treatment is a simple and straightforward end-to-end test which has been undertaken by several independent groups over the last decade to identify the ExacTrac localization accuracy[5,26,27,31-38].

An overview of the results is presented in Figure 3. The average reported mean localization error is 0.8 mm, which is a remarkable result, especially if one considers that the earliest reports on the sub-millimeter accuracy of ExacTrac date back to as early as 2003[38]. ExacTrac achieves this level of accuracy and precision by controlling the motion of the treatment couch with six degrees of freedom (6D).

RELY ON THE AUTOMATIC FUSION

The most important step in the image-guided frameless radiosurgery workflow is the fusion of "live" localization images to digitally reconstructed radiographs or simulation images to determine the deviation from the desired patient position.

A reliable and fast fusion algorithm is required to ensure a smooth workflow and enable frequent positioning verification. The fusion algorithm implemented in ExacTrac has been reported to automatically achieve a correct fusion without manual correction in nearly all frameless radiosurgery cases[32,34,38-40].

High quality imaging for localization and simulation is a necessity for reliable image fusion. For the localization images, ExacTrac accredits superior contrast resolution in optimal exposure conditions to the unique configuration of the X-ray system. The fixed configuration of X-ray tubes and flat-panel detectors eliminates any potential spatial uncertainty caused by mechanical movement. Further, the large source-to-detector distance reduces the solid angle of the radiation beam and hence reduces potential geometric distortion. Finally, the large isocenter-to-detector distance reduces the potential body scattering to the detectors and hence increases the contrast to noise ratio[41].

The simulation images are constructed from the planning CT set and influence the localization accuracy, depending on the CT quality and slice thickness. Therefore, in order to maximize positioning accuracy, imaging artifacts should be prevented and the slice thickness should be less than 5 mm[37,40,42].

TREAT WHAT WAS PLANNED

The fusion of the localization and simulation images determines the deviation from the desired patient position. During this crucial step in the frameless radiosurgery workflow, a dedicated algorithm will translate and rotate the localization image set with six degrees of freedom to realize the best match with the simulation image set. The resulting six shifts need to be applied to the current patient position in order to position the target exactly at the isocenter.

However, a conventional treatment couch only supports four patient shifts: three translations and one rotation around the anteroposterior axis in the plane parallel to the ground, which is denoted as the yaw or isocentric table rotation. The rotations around the longitudinal and lateral axis, respectively denoted roll and pitch, cannot be accomplished with a conventional treatment couch.

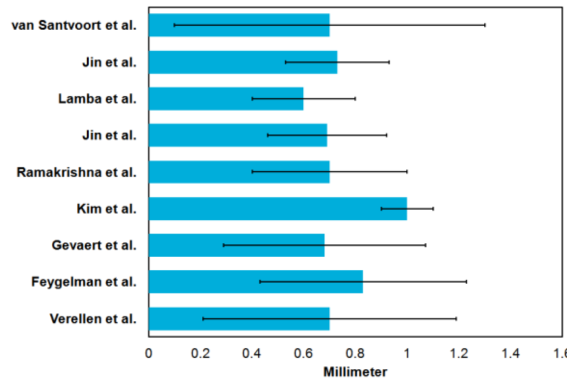

Figure 3: Results from hidden target tests published in the last decade by several independent groups[5,26,27,31-38]. The mean of the localization errors represents the systematic error, or the accuracy of the localization method. The standard deviation represents the random error, the precision, or the uncertainty of the localization method.

The errors introduced by ignoring rotations can be as high as 4mm[43]. But even half a degree deviation in roll and pitch can result in under-dosage of the target and overexposure of the surrounding normal tissue[44]. These effects become even more pronounced during treatments targeting multiple metastases at once and in case there is close proximity of organs at risk, as in spinal treatments.

In order to enable true frameless radiosurgery and achieve sub-millimeter accuracy, ExacTrac complements the standard couch with a robotic tilt module that fulfills corrections in pitch and roll. Because the isocenter is used as the rotational origin in the ExacTrac fusion algorithm, the rotations are decoupled from the translations and both sets of shifts can be safely and independently applied[28,45,46].

VERIFY AT ALL COUCH ANGLES

Even in the earliest days of radiation oncology, it was recognized that targeting from multiple directions reduces dose spillage into the normal tissue, enabling radiosurgery to be an effective treatment[47]. Although radiosurgery evolved owing to developments of image-guided techniques and innovative dose delivery approaches, technology did not alter that early concept.

From a treatment planning perspective, frame-based and frameless radiosurgery plans are identical since both utilize several non-coplanar arcs or beams to target a lesion from multiple directions and various couch angles and restrain the dose to the normal tissue[48]. As true frameless radiosurgery requires repeated verification of the patient position throughout the entire treatment, it should permit imaging at all couch angles.

All mechanical motion inherently produces additional inaccuracies and this paradigm also applies to movements of the treatment couch. The need to detect and correct these errors is depicted in Figure 4, where it is presented that couch motion causes shifts beyond the typical treatment margin of 1 mm[36].

Because ExacTrac is decoupled from the linear accelerator, it allows for verification of the patient position at all couch angles. Moreover, ExacTrac offers the opportunity to correct detected shifts at any couch angle, making it perfectly suited for true frameless radiosurgery.

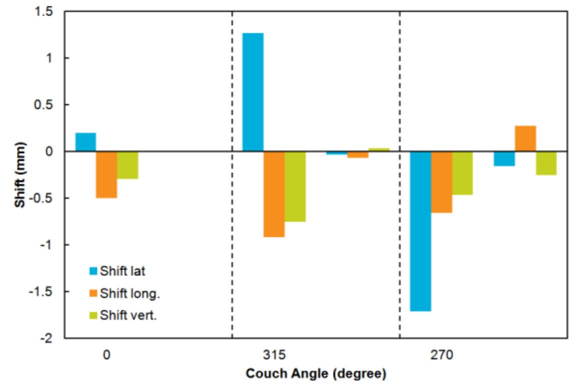

Figure 4: Verification of the patient position at various couch angles demonstrates that the couch rotation produces deviations greater than 1 mm. At treatment couch angles of 315 and 270 degrees, ExacTrac is able to detect (first set of values) and correct (second set of values) shifts from the isocenter[36].

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