Image fusion pitfalls for cranial radiosurgery

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Abstract

Stereotactic radiosurgery requires imaging to define both the stereotactic space in which the treatment is delivered and the target itself. Image fusion is the process of using rotation and translation to bring a second image set into alignment with the first image set. This allows the potential concurrent use of multiple image sets to define the target and stereotactic space. While a single magnetic resonance imaging (MRI) sequence alone can be used for delineation of the target and fiducials, there may be significant advantages to using additional imaging sets including other MRI sequences, computed tomography (CT) scans, and advanced imaging sets such as catheter-based angiography, diffusor tension imaging-based fiber tracking and positon emission tomography in order to more accurately define the target and surrounding critical structures. Stereotactic space is usually defined by detection of fiducials on the stereotactic head frame or mask system. Unfortunately MRI sequences are susceptible to geometric distortion, whereas CT scans do not face this problem (although they have poorer resolution of the target in most cases). Thus image fusion can allow the definition of stereotactic space to proceed from the geometrically accurate CT images at the same time as using MRI to define the target. The use of image fusion is associated with risk of error introduced by inaccuracies of the fusion process, as well as workflow changes that if not properly accounted for can mislead the treating clinician. The purpose of this review is to describe the uses of image fusion in stereotactic radiosurgery as well as its potential pitfalls.

Key Words: Image fusion, radiosurgery, stereotactic

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INTRODUCTION

Stereotactic radiosurgery involves the application of a 3 dimensional radiation dose to a target, often in a single session of treatment. Unlike conventional operative neurosurgery there are no visual cues to confirm the location of important structures and it is necessary to have a high level of confidence in the location of the target and critical surrounding structures.[1]

Stereotactic radiosurgery systems share in common that imaging is used to define both the target (and surrounding critical structures) as well as the stereotactic space that serves as a reference between the location of the cranium or stereotactic head frame and the target located within.

In some cases (most notably the Gamma Knife manufactured by Elekta, Sweden) a single sequence

from an magnetic resonance imaging (MRI) scan may be used to define both the target location as well as the stereotactic space. Stereotactic space is determined by the fiducials on the localizer of the stereotactic head frame. Although this approach offers simplicity there may be benefits associated with including additional imaging sets in the planning process. For example, MRI distortion may cause inaccuracies in defining both the target and the stereotactic space.[12] In addition, a single imaging sequence may not provide the best available 3 dimensional definition of a lesion.

Image fusion is a technique that allows multiple imaging sets to be combined and used for radiosurgery planning and is associated with a number of potential advantages including integration of multiple types of diagnostic images that may provide different information concerning the target or critical structures as well as allowing the use of geometrically precise computed tomography (CT) imaging to detect the fiducial localizers and define stereotactic space.

What is image fusion?

Image fusion involves rotation and translation of a second image set to bring it into alignment with the first image set. For example, a patient may have undergone pre- and postcontrast CT brain, various MRI sequences, and positron emission tomography (PET). It may be desirable to register these image sets to each other to obtain maximal information concerning the neuroanatomy and lesion. When an image set is rotated and translated to bring it into alignment with another image set this is referred to as a rigid transformation. Planning systems for radiosurgery currently use rigid transformation, although deformable image fusion has been developed.[14]

The use of image fusion allows multiple MRI sequences, CT scans, PET, and angiography to be incorporated into treatment planning.

Use of CT scanning in treatment planning

The incorporation of CT scanning into planning offers several potential advantages when compared with MRI alone. While MRI is almost always superior for visualizing the lesion, the calculation of dose requires an electron density map and knowledge of the surface contour of the head. A CT scan provides information concerning the electron density of the head and thus calculations incorporating the CT data can explicitly use this data to calculate the dose.[2]

CT scanning is also useful in radiosurgery planning because CT is geometrically accurate, whereas MRI is associated with image distortion [Figure 1]. Imaging distortions associated with MRI arise from the magnet (magnetic field inhomogeneities) as well as the patient (chemical shifts and susceptibility). Methods are available to correct distortions resulting from
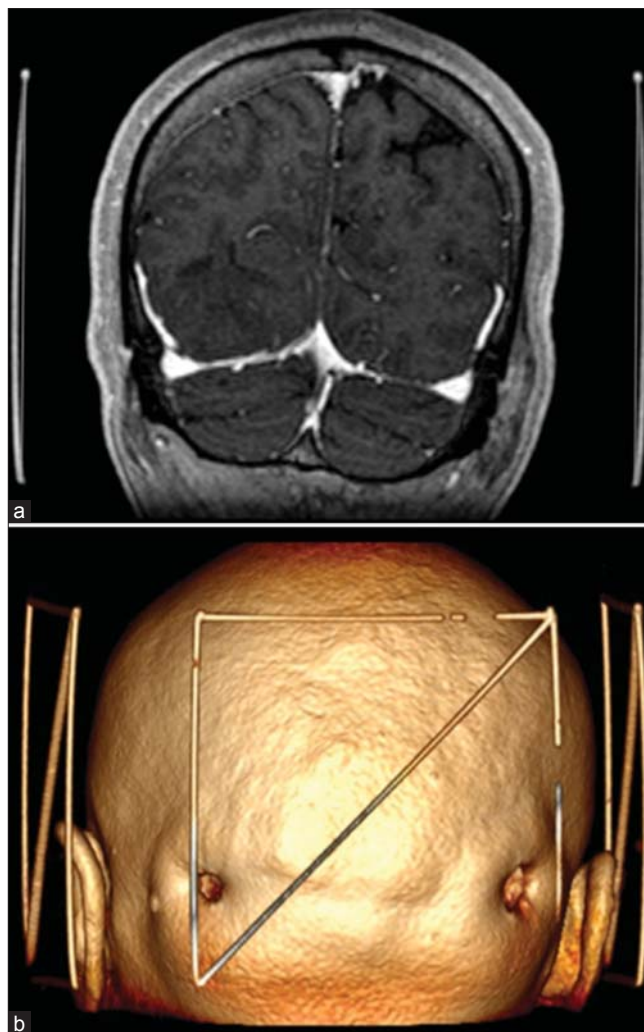

Figure 1: MRI of patient in a Leksell Frame reveals warping of the fiducials. (a) 2D example (b) 3D example

field inhomogeneities,[5] however, methods to reduce distortions due to patient susceptibility and chemical shifts will not completely eliminate them, and typically decrease signal-to-noise ratio with potential degradation of the image.

Use of CT to MRI fusion eliminates the need to rely on the potentially distorted MRI imaging of fiducials in order to define stereotactic space at the cost of relying on the veracity of the fusion. In the 1990s an early report using this technique, a phantom study, showed that the use of CT-MRI fusion with localization of the CT scan was significantly more accurate than using MRI alone.[4] Kondziolka showed that use of MRI versus CT for localization can vary the location of the target by approximately 2 mm.[9] Watanabe *et al.* also noted a variation of 2 mm secondary to MRI distortion.[17]

Many radiosurgery units now use 3 T rather than 1.5 T MRI, and at 3 T the field within the coil is more sensitive to inhomogeneities.[11] This may further increase the risk of inaccurate localization of the target or fiducials,

although there is some empirical evidence that disputes this concern, at least for a well calibrated scanner.[15]

A question remains as to whether the extent of distortions expected in today's MRI environment translate into clinically relevant effects. Pollock has shown that for vestibular schwannoma radiosurgery more conformal plans led to an increased risk of failure to control the tumor, possibly due to errors in stereotactic localization of the target using MRI alone.[12] Indeed distortion is greatest at tissue interfaces and the bone cerebrospinal fluid (CSF) interface of the internal auditory meatus can therefore be problematic as was demonstrated in their report.

Role of CT MRI fusion versus MRI alone in other areas of stereotactic neurosurgery

In other areas of stereotactic neurosurgery – particularly in deep brain stimulation – there has been a divergence of opinion concerning whether it is more accurate to use a CT/MRI fusion with CT localization versus using MRI alone. The issue is not completely resolved. Recently Chen *et al.* compared the use of CT scanning with image fusion versus use of MRI alone in planning for deep brain stimulation of the subthalamic nucleus and found the microelectrode track to be longer in those patients in whom CT scanning is utilized in the planning, suggesting better localization of the target with this method.[3]

An analysis performed concerning the accuracy of deep brain stimulation using MRI alone for both fiducial registration and targeting found that the implanted stylettes differed from their planned location by an average of 1.8 mm (95% CI, 1.5–2.1).[15] Although a component of this error may relate to mechanical inaccuracies of the ring and arc system on the stereotactic head frame, it is likely that a proportion of this error would be due to imaging distortions causing errors in target position and frame localization – and thus radiosurgery is at risk of these errors.

MRI to MRI fusion

A number of scenarios exist where combining multiple different MRI sequences is of benefit. For example, in treatment of trigeminal neuralgia we typically give a 90 Gy point dose to the cisternal segment of the trigeminal nerve. Given the small diameter of the nerve it is critically important to make sure that the nerve is accurately targeted. To this end we typically fuse four MRI sequences consisting of two types of MRI (a standard stereotactic Spoiled Gradient Echo (SPGR) or Magnetization Prepared Rapid Acquisition Gradient Echo (MPRAGE) sequence as well as a Fast Imaging Employing Steady sTate Acquisition (FIESTA) or Constructive Interference Steady State (CISS) sequence) each acquired in each of the coronal and axial planes [Figure 2]. Increased confidence concerning the true location of the nerve can be obtained when the target is convergent on the four imaging sequences.

Likewise MRI to MRI fusion can be helpful in delineating vestibular schwannoma contours as well as the location of the cochlea. FIESTA sequences provide excellent resolution of the cochlea and tumor, however, a nerve or vessel closely applied to the surface of the tumor may not be readily distinguished without reference to other sequences [Figure 3].

Fusion of other imaging modalities

In occasional patients the incorporation of PET scanning may yield additional information. For example, hypofractionated stereotactic radiotherapy (SRT) may be indicated in some cases of recurrent glioblastoma.[6] Incorporation of the PET may help distinguish between active tumor versus postoperative changes or radiation necrosis.

Image fusion of cerebral angiography can also be performed to enhance planning of arteriovenous malformations (AVMs). We have found that in some cases this significantly clarifies the extent of the target volume [Figure 4]. We recommend the use of nonsubtracted catheter-based digital angiography reconstructed into axial slices so that the bony anatomy can be fused with the CT images (a subtracted angiogram lacks mutual information with which to perform a fusion). The alternative is to perform angiography with the patient in a stereotactic head frame, though this is unnecessary if the above suggestion is followed.

Other advanced imaging sets may also be fused such as the use of Diffusion Tensor Imaging (DTI) to allow fiber tracking[8] and delineation of the location of the corticospinal tract.

Workflow issues and effects

Image fusion can benefit workflow. Patients are now often imaged with MRI a few days prior to their planning scan with CT. This reduces the time taken on the day of CT planning, as well as identifying occasional patients that may no longer be suitable for stereotactic radiosurgery before deploying the resources associated with stereotactic radiosurgery planning and treatment.

Each component of the radiosurgical treatment process is susceptible to errors and the overall accuracy of the treatment cannot be better than the weakest link in this chain.[13] In a phantom study using BrainLab Novalis (BrainLab, Germany) Rahimian found that the MRI geometrical inaccuracy was only 0.22+/–0.1 mm, whereas the inaccuracy of the autofusion was 0.41+/–0.30 mm making the fusion process a potential source of significant error.

From a practical perspective, the image fusions can be performed by radiation therapists or physicists prior to the physician performing contouring of the target and critical structures, and in our view it is mandatory for the treating physician to carefully review any image fusions prior to proceeding with contouring of structures since
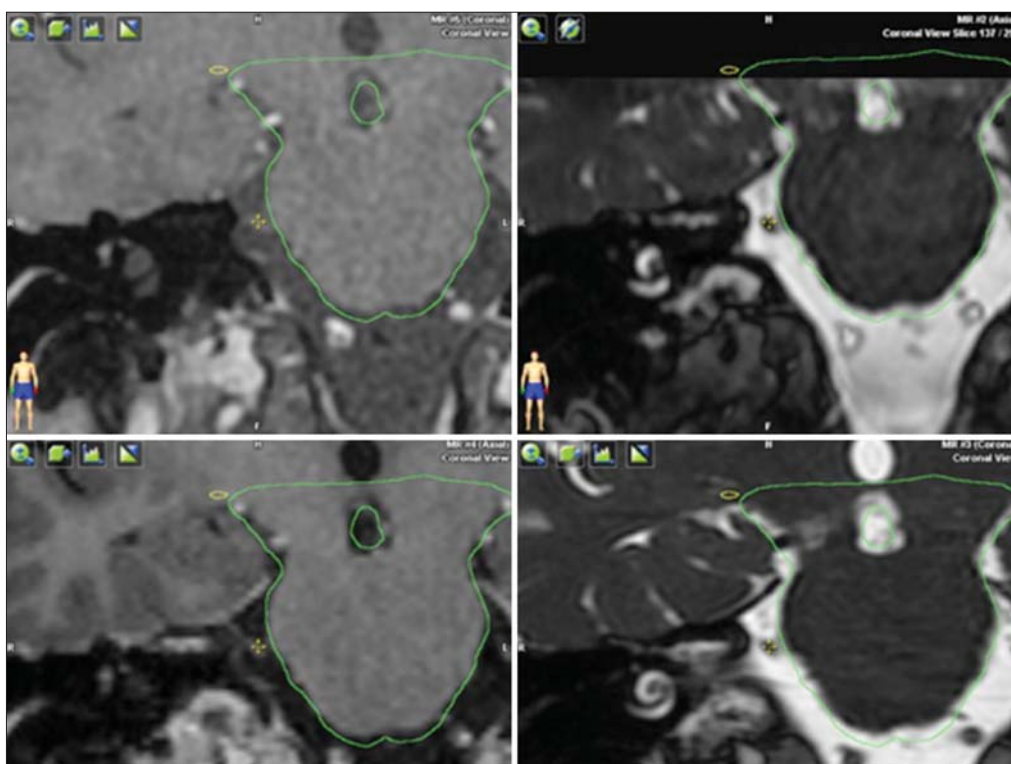
Figure 2: Incorporation of multiple separate MRI sequences to allow visualization of the right trigeminal nerve
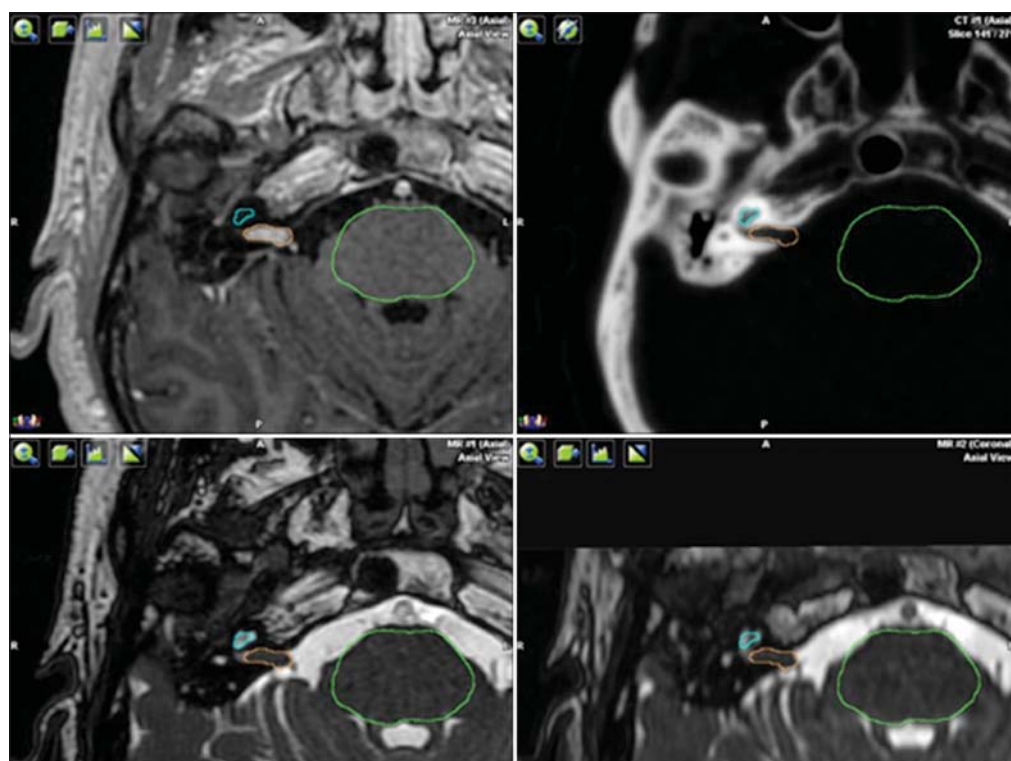

Figure 3: Use of multiple image sets for defining vestibular schwannoma and adjacent cochlea

the implied accuracy of a carefully segmented structure may be misleading in the context of a poor image fusion. Having said this, the automatic image fusion is reliable in the vast majority of cases.[7,16]

There is a theoretical concern that a long chain of image fusions may increase the total error. For example, a FIESTA or T2 sequence may be fused to an SPGR with gadolinium, which in turn is fused to a CT with contrast

which is then in turn fused to the reference (noncontrast) CT set. The total error is the root mean square of each of the component errors. Thus we would advocate using the minimum necessary number of fusions away from the fusion root (base imaging set) as possible, as well as constant referencing of the contoured 3 dimensional volume to all available imaging sets.

Because of the inherent spatial inaccuracies of MRI, it is generally accepted that when manually checking the fusion one concentrates on the area to be treated rather than on surface contours or remote anatomy.

It has become practice in some institutions to accept the MRI brain performed at an outside institution on referred patients for incorporation into planning with a locally acquired CT scan. There are two possible drawbacks with this approach. A stereotactic MRI should be performed on an MRI scanner that has undergone appropriate acceptance checks and quality assurance to ensure appropriate accuracy for stereotactic radiosurgery.
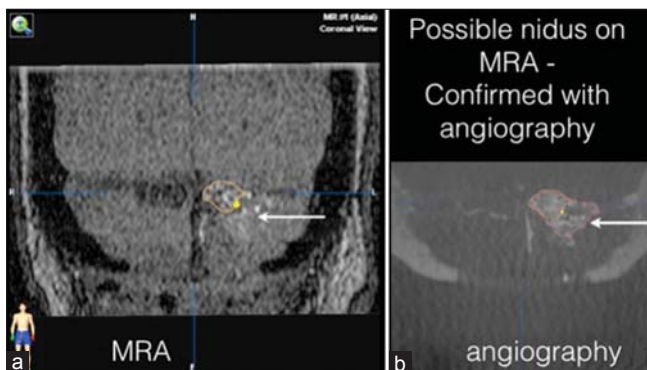

Figure 4: Contours of a posterior fossa AVM. (a) Initial contouring performed using MRA images failed to discern what was (b) clearly additional nidus on the fused angiography images

An outside MRI may lack such checks and may also have failed to perform appropriate sequences. Thicker sliced sequences on MRI contoured in the plane of acquisition may be misleading as the slices may have averaged the abnormal signal over the full thickness of the slice and partial voluming may be observed [Figure 5].[10]

An additional concern with the use of outside MRI, which may also be relevant to in-house acquired MRI, is the issue of time between scan and treatment. Image fusion and frameless radiosurgery have created the possibility that the scan date is days or weeks prior to treatment. Given the propensity of some tumors to enlarge rapidly, a delay between acquisition of the planning MRI and delivery of the treatment may result in a part of the lesion not receiving adequate dose without this being detected. This may be of particular relevance to melanoma or other hemorrhagic metastases, which can expand very rapidly. In cases where we have stereotactically drained a cystic metastatic lesion followed by radiosurgery to the residual cyst wall we elect to treat the patient with stereotactic radiosurgery within 24 hours of cyst aspiration to minimize the possibility of cyst recurrence over time.

Fusion for follow-up
During the follow-up of a patient there are some cases where there is uncertainty regarding whether a tumor has enlarged or not. In such cases, the posttreatment images may be fused with those obtained prior to treatment and use spyglass or other imaging tools to compare accurately the size of a lesion.

CONCLUSIONS

There is a surprising paucity of research assessing the accuracy of image fusion technology and its effect on
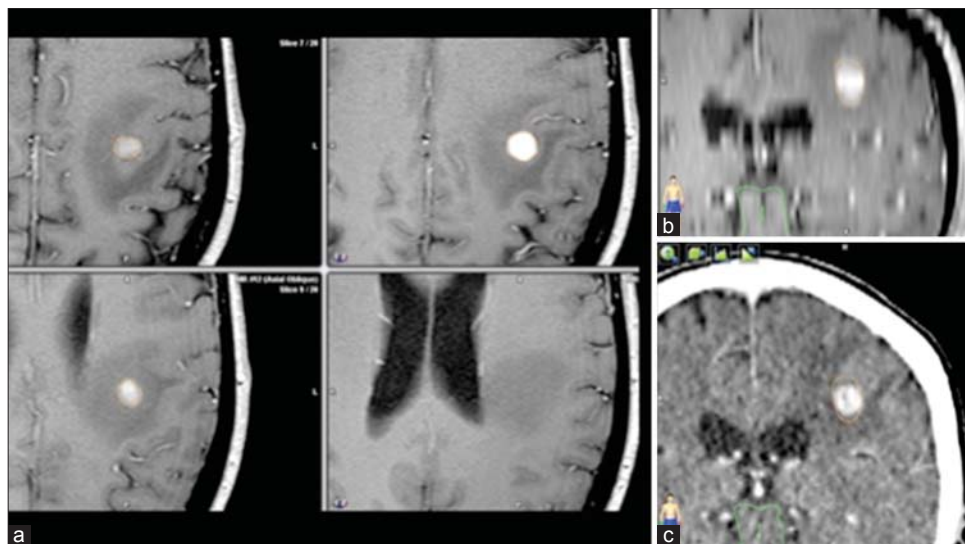

Figure 5: Use of thick sliced MRI for contouring. (a) Observe the appearance looks satisfactory in the plane of acquisition – axial. (b) On coronal reformat the lesion appears to have an elongated shape in the superior inferior dimension. (c) CT with contrast provided for comparison showing the shape of the lesion is in fact spherical

patient outcome. Image fusion is critical to performance of radiosurgery if CT scanning is to be used, and may be advisable in many cases, even when the MRI is used for localization. A thorough knowledge of the issues surrounding its use may prevent inadvertent poor targeting of a lesion, and may therefore maximize both the effectiveness and the safety of radiosurgery procedures.

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