Prospective Motion Correction in Pediatric Neuroimaging with KinetiCor

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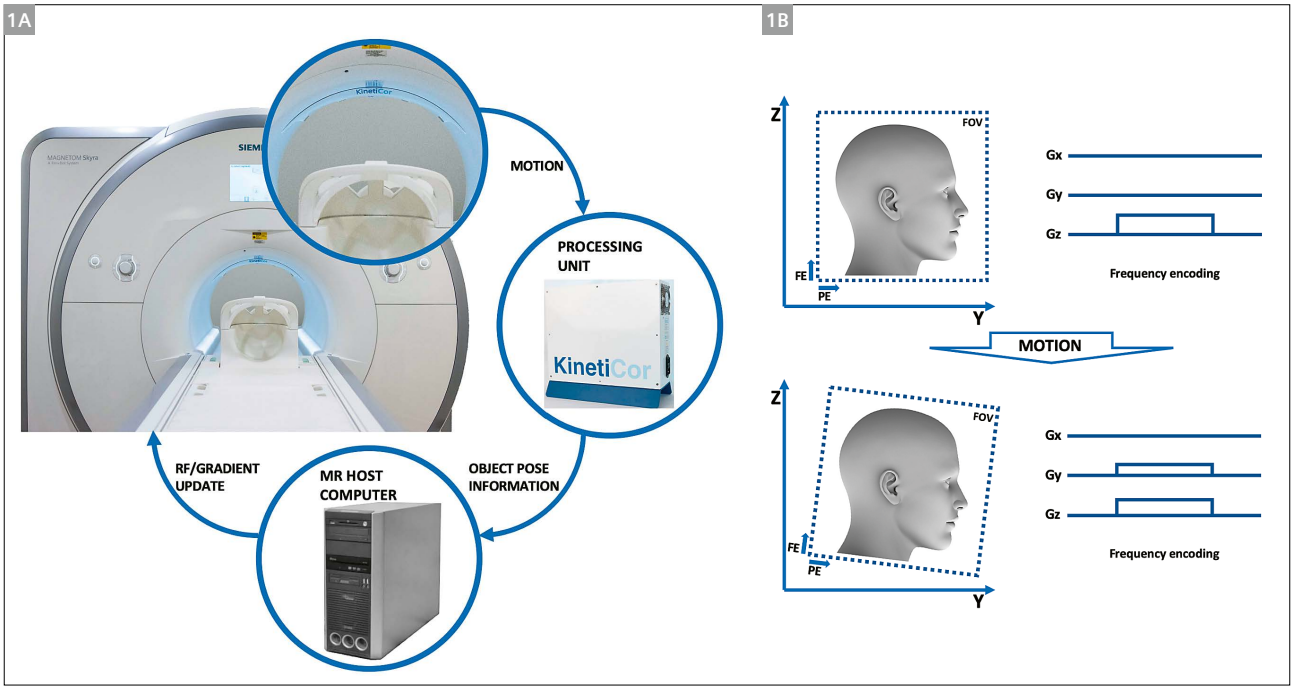
During MRI, unwanted motion can displace or destroy image encoding, leading to non-diagnostic images. The problem of motion in MRI is particularly prevalent in clinical pediatric[1] imaging. In addition to challenges related to comfort, scanner-induced anxiety, and length of the exam, which affect patients of all ages, children may be unable to cooperate either as a result of a medical condition (e.g., autism spectrum disorder) or because they are too young to follow instructions [1, 2]. To obtain diagnostic images, many hospitals have a low threshold for imaging patients with sedation or general anesthesia. In fact, the rate of sedation for MRI in children between the ages



1 Schematic illustration of the KinetiCor system[2]. **(1A)** Illustrates the main components including the quad-camera, processing unit, MR Host computer, and feedback loop to the scanner. **(1B)** Illustrates prospective motion correction (PMC) based on updating coordinate positions, scanner gradients, and adjusting the field of view.

[1]MR scanning has not been established as safe for imaging fetuses and infants less than two years of age. The responsible physician must evaluate the benefits of the MR examination compared to those of other imaging procedures. Note: This Siemens Healthineers disclaimer does not represent the opinion of the author.
[2]The BioMatrix Kinetic Sensor is released with 3T MAGNETOM Vida and 1.5T MAGNETOM Sola. With MAGNETOM Skyra and MAGNETOM Prisma the KinetiCor system is work in progress, it is currently under development and is not for sale in the U.S. and in other countries. Its future availability cannot be ensured.

of 6 months and 6 years exceeds 90% [3, 4]. Although sedation and general anesthesia are an effective means of reducing patient motion they are not devoid of risks. Acute medical complications associated with sedation and anesthesia may occur and can range from mild medication reactions to severe life threating cardiopulmonary events [5]. Recently, concerns for long-term of effects of anesthetic medication on cognitive function also have been raised [6–8]. Finally, the cost of sedation and its effect on workflow also need to be considered, as the use of sedation can nearly triple the cost of the exam [9].

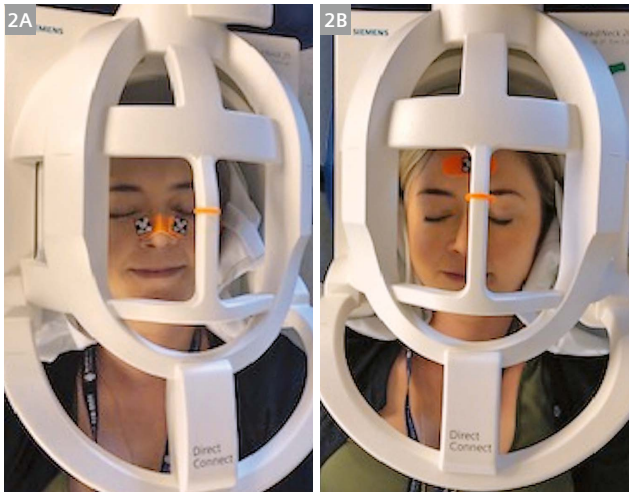
Recent advances in MRI hardware and pulse sequences have enabled faster acquisition of images. In conjunction with child-life specialists and other behavioral techniques, these have contributed to increasing the success rate of awake MRI in children [3]. However, these techniques have limited impact in some of our most vulnerable patients, including younger children and those with developmental disabilities. Motion correction strategies have therefore emerged as promising alternatives to mitigate motion artifacts in these patients. In particular, prospective motion correction (PMC) strategies are well suited for clinical practice, since they avoid delays that can result from "off line" processing of images and are therefore easy to integrate into the clinical workflow [1].

Prospective motion correction with KinetiCor

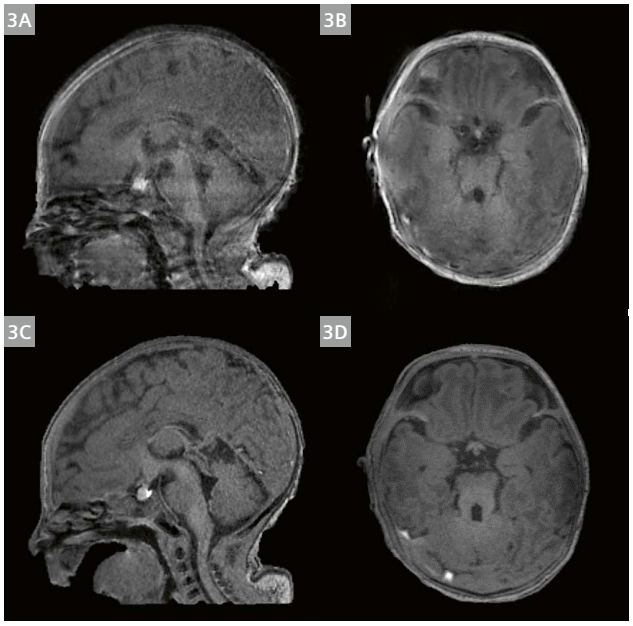
The MRI-compatible KinetiCor tracking system consists of a quad-camera that is embedded in a plastic molding and affixed securely to the bore of the MRI system. The camera is connected to the processing unit which is located in the equipment room alongside the scanner electronic cabinets. The camera system is connected to the processing unit through a shielded twisted power cable and 4 pairs of optical fibers (Fig. 1). For motion tracking in adults, KinetiCor provides a two-winged marker that is designed to be placed on the bridge of the nose. When the marker is visible, the tracking system continuously records rigid head motion with six degrees of freedom (translations in x, y, and z axes and rotations around x, y, and z axes). The camera system has been tested to have a spatial tracking accuracy of at least 100 microns for translation and 0.1 degrees for rotation with a recording rate of 60 Hz (60 frames per second). The motion estimates from the camera system are sent in real time to a motion correction framework that uses these data to update the field of view, RF pulses, and gradients, so that the imaging volume coincides with the new head position [10, 11].

Tailoring solutions to the needs of every patient

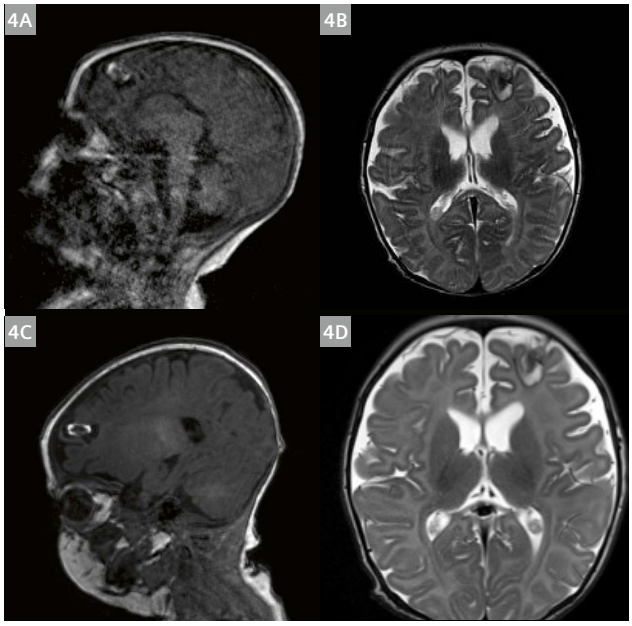
Simply put, one size doesn't fit all. Pediatric imaging, and certainly pediatric neuroimaging, illustrates this principle. The size of the brain of a term born infant is approximately 25% of the size of an adult. Brain growth is the fastest in the first year of life, resulting in doubling of brain volume (and head size) by 12 months of age [12]. During infancy and early childhood, fast growth will continue until the head reaches approximately 90% of its adult size by the age of 6 years [13, 14]. In practical terms, this means that the conventional two-winged marker that is used for PMC in adults is not suitable for imaging our youngest patients. The two-winged marker would cover most of the face of a newborn and would not couple appropriately with the facial structure of newborns or young infants. To address this, we have modified the two-winged nasal marker to a single flat marker than can be placed on the forehead (Fig. 2). A fortuitous advantage to the use of a single marker is that it can be used to track motion when patients use MRI-compatible video goggles which obscure the eyes and nose of the patient. In doing so, the single marker has enabled us to perform PMC in some of the most challenging patients we encounter (ages 3–7 years), who are at very high-risk for non-diagnostic examinations when imaged without sedation or anesthesia.



2 Images of an adult volunteer using the 64-channel head coil with the **(2A)** two-winged nose marker and the **(2B)** single-forehead marker.



3 PMC in a 4-week-old infant[1] with abnormal prenatal head ultrasound who underwent MRI with feed and wrap technique. **(3A)** Sagittal and **(3B)** axial MPRAGE images show moderate motion artifacts. **(3C)** Sagittal and **(3D)** axial MPRAGE with PMC show substantial improvement in image quality, allowing for clear identification of hypoplasia and dysgenesis of the superior cerebellar vermis (3C) and a "molar tooth configuration" of the superior cerebellar peduncles (3D).



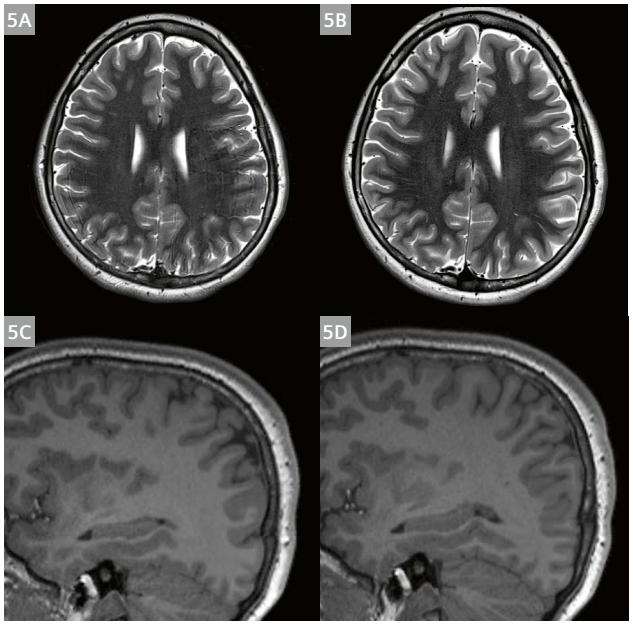
4 PMC in a 12-week-old infant[1] who obtained an MRI for follow-up of a perinatal intraparenchymal hemorrhage. **(4A)** Sagittal MPRAGE shows severe motion artifact; while a region of T1 shortening is identified at the site of the hematoma, anatomic detail is distorted and is overall non-diagnostic. **(4B)** Axial T2 image through the site of the hemorrhage shows mild motion artifact, with acceptable depiction of the region of encephalomalacia and chronic blood products. **(4C)** Sagittal MPRAGE with PMC and **(4D)** axial T2 obtained with PMC show virtually no motion artifacts and provide superior evaluation of the site of the hemorrhage as well as the rest of the brain parenchyma.

Special population: newborns and young infants

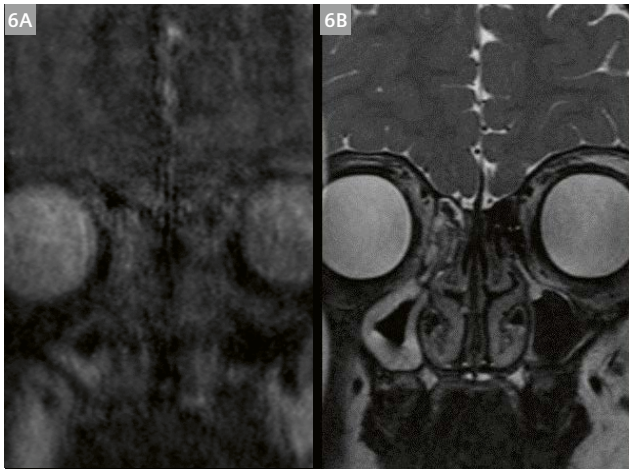
A patient population that is frequently imaged at children's hospitals are infants less than 12 months of age[1]. Imaging during natural sleep using the "feed and swaddle technique" has a high success rate, approaching 80% [15]. Despite the overwhelming success, some infants have trouble falling asleep or are intermittently disrupted by the sound of the MRI scanner. Other patients are jittery or have slow "bobbing" head movements, which introduces artifacts. The small size of the brain and the subtle nature of some abnormalities in this age range, such as some congenital malformations, may require high-resolution imaging that is highly susceptible to motion. With the use of the pediatric marker, we have successfully improved quality of scans in newborns and young infants imaged during natural sleep (Figs. 3 and 4). Images have been acquired using a 3T MR scanner (MAGNETOM Prisma, Siemens Healthcare, Erlangen, Germany)[2].

High resolution imaging

Protocols that rely on high-resolution sequences with lengthy acquisitions, such as epilepsy and neuro-oncology protocols, stand to benefit the most from PMC. These protocols are often degraded by motion even in reasonably compliant children and adolescents, resulting in repeat acquisitions and low-quality images. The epilepsy protocol for instance takes approximately 30 minutes of gradient time and includes: 3D MPRAGE, 3D T2 SPACE FLAIR, (35 direction) diffusion tensor imaging, high-resolution 2D T2 TSE and 2D TSE fat-suppressed FLAIR, with acquisitions that require 6 minutes, 6 minutes, 4 minutes, 5 minutes, and 4 minutes, respectively. Since the differential diagnosis for pediatric epilepsy is broad high-quality imaging is crucial, as the radiologist needs to exclude tumors, prior injury, and brain malformations as potential causes. Some of these, in particular cortical malformations, can be difficult to detect and present as subtle areas of blurring of the gray-white junction or other alterations of the gray-white interface that can easily be obscured by motion artifacts (Fig. 5) [16].



5 PMC in a 10-year-old patient with new onset generalized seizures obtained with the aid of MRI compatible video goggles. No abnormality was identified. **(5A)** T2-weighted image shows mild ringing which decreases image quality, while remaining borderline diagnostic. Repeat **(5B)** axial T2 image with PMC shows resolution of artifacts, allowing for better evaluation of the parenchyma. **(5C)** Sagittal MPRAGE shows overall good image quality although mild ringing artifact noted in the posterior parietal lobe. Repeat **(5D)** MPRAGE with PMC shows resolution of ringing artifact.



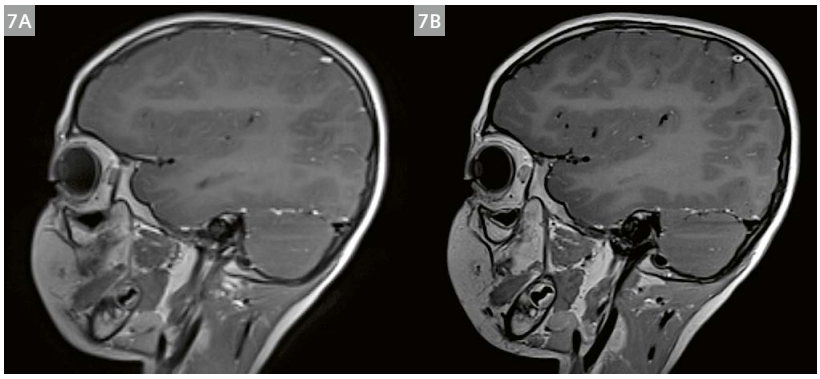
6 PMC in high-resolution cranial nerve imaging with T2 SPACE in a 5-year-old girl with poor sense of smell. **(6A)** Coronal reformat from T2 SPACE image through the anterior cranial fossa is non diagnostic. **(6B)** Coronal reformat from a repeat T2 SPACE acquisition with PMC shows substantial improvement and shows absence of the olfactory bulbs.

Cranial nerve imaging also relies on high-resolution sequences. At Boston Children's Hospital, we use a high-resolution 3D T2 SPACE or CISS sequences to outline cranial nerves or small lesions that are located at the interface of the parenchyma and cerebrospinal fluid. Despite routine utilization of targeted regions of interest (e.g., specific cranial nerves) the acquisitions often exceed 6 minutes and are frequently motion degraded. Since cranial nerves move rigidly with the skull, PMC works well to improve anatomic detail (Fig. 6). We are currently undergoing optimization of PMC for other high-resolution 2D spin-echo acquisitions used for imaging orbits, skull base, and skull.

A final niche application of PMC is to maximize the chances of obtaining diagnostic images after the administration of gadolinium-based contrast agents. Gadolinium-enhanced T1-weighted images are often obtained last on brain MRI protocols, to avoid the possible confounding effects of contrast (T1 shortening and the T2* effects) on other pulse sequences. Even compliant children can become restless during long scans and their ability to cooperate with crucial post-contrast images is often suboptimal. In recent years, there has been a growing concern regarding the long-term effects of gadolinium deposition in tissues, including the brain [16]. PMC can help obtain high-quality post-contrast images, ensuring that the administration of contrast serves its purpose and is not in vain. At Boston Children's Hospital we use T1-SPACE and occasionally T1-MPRAGE for our gadolinium-enhanced whole-brain imaging, both of which profit from PMC. Given that contrast-enhanced images are often obtained to monitor disease activity of serious conditions (tumors, infection, demyelination), improving image quality directly affects patient care.

Challenges

Despite a successful initial experience with the KinetiCor system several challenges remain to be addressed. PMC with KinetiCor is more effective in 3D-sequences; artifacts resulting from through-plane motion on 2D sequences remain a challenge, particularly when acquiring sequences in the coronal plane. The system is unable to correct non-rigid motion, which precludes utilization in the infra-hyoid neck, cranio-cervical junction, and spine. Another



7 PMC in postcontrast sagittal T1 SPACE in a 10-year-old boy with concern for meningitis. No abnormal enhancement was seen. **(7A)** Sagittal T1 SPACE is of diagnostic quality and shows only mild motion artifact (subtle blurring and mild ringing). **(7B)** Repeat sagittal T1 SPACE with PMC shows resolution of ringing and blurring.

important limitation is that the skin marker is susceptible to skin motion and can result in spurious motion estimates that do not reflect true head motion. Improved filtering algorithms and markerless detection are under development, which are expected to mitigate or resolve this issue.

Conclusion

PMC is emerging as a promising technique to improve image quality in pediatric neuroradiology. In conjunction with child-life specialists, faster sequences, and audio-visual/behavioral techniques, PMC could contribute to decreasing the need for sedation and general anesthesia in vulnerable populations, including young children and those with cognitive disabilities who are unable to remain motionless during MR imaging acquisitions.

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