High-resolution, Anatomically-accurate Diffusion-weighted Imaging of Orbital and Sinonasal Lesions with RESOLVE

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Diffusion-weighted imaging is a core sequence in clinical routine imaging for many anatomical regions including the brain, abdomen, breasts, and pelvis [1, 2]. Conventionally, diffusion-weighted imaging is acquired using a single-shot diffusion-weighted echo planar imaging (EPI) sequence with the primary advantages of insensitivity to motion-induced phase errors and relatively short acquisition times. However, this sequence also suffers from lower spatial resolution as well as susceptibility-based, geometric distortions in certain regions (such as fluid/air interfaces). This has posed challenges for high-quality, diffusion-weighted imaging of the eyes, ears, nose, and throat.

RESOLVE (REadout Segmentation Of Long Variable Echo trains) [3, 4] is a multi-shot, diffusion-weighted sequence with a readout-segmented EPI sampling scheme. This sequence includes a 2D non-linear correction for motion-induced phase errors together with GRAPPA [5] functionality. The significantly shortened EPI echo spacing (as only a subset of raw data points in the readout direction is sampled with each shot) enables a significant reduction in the level of susceptibility and blurring, making it possible to acquire diffusion-weighted images of higher resolution.

In this paper, we review four of the recently published studies from our Institution where RESOLVE was shown to be clinically effective in the diffusion-weighted imaging of sinonasal and optic pathologies. We additionally demonstrate the clinical value that RESOLVE brings to the detection and characterization of the diseases in these regions.

RESOLVE in the imaging of sinonasal lesions

Our first evaluation of RESOLVE in the imaging of sinonasal lesions involved a comprehensive comparison of image quality relative to conventional single-shot EPI (SS-EPI) (see Table 1 for the imaging parameters of these two sequences) in 32 patients with sinonasal lesions [6]. Image quality was evaluated qualitatively by two head and neck radiologists with decisions made on consensus where there is divergence. In addition, a quantitative evaluation of the geometric distortion was also performed.

RESOLVE ADC maps had significantly higher ratings compared to SS-EPI on the scales of image quality, lesion conspicuity, and image distortions (Table 1 and Fig. 1). During the analyses, we also observed that RESOLVE was capable of revealing the otitis media of five patients (e.g., via the effusion of mastoid cells) more clearly than SS-EPI. RESOLVE also exhibited the orbit, skull base, and upper neck with significantly reduced distortion, ghosts, and blurring. The delicate structures of the orbit, such as the globe, optic nerve, extraocular muscle, and lacrimal gland...

<table>
<thead>
<tr>
<th></th>
<th>Conventional SS-EPI</th>
<th>RESOLVE</th>
</tr>
</thead>
<tbody>
<tr>
<td>TR (ms)</td>
<td>8000</td>
<td>4700</td>
</tr>
<tr>
<td>TE (ms)</td>
<td>88</td>
<td>66</td>
</tr>
<tr>
<td>Echo spacing (ms)</td>
<td>1.08</td>
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</tr>
<tr>
<td>FOV</td>
<td>240 x 240 or 220 x 220</td>
<td>240 x 240 or 220 x 220</td>
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<tr>
<td>Matrix</td>
<td>154 x 192 or 164 x 164</td>
<td>154 x 192 or 192 x 192</td>
</tr>
<tr>
<td>Slice / Gap (mm)</td>
<td>4.0 / 0.6</td>
<td>4.0 / 0.6</td>
</tr>
<tr>
<td>b-values (s/mm²)</td>
<td>0, 1000</td>
<td>0, 1000</td>
</tr>
<tr>
<td>Averages</td>
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<td>1</td>
</tr>
<tr>
<td>GRAPPA factor</td>
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<td>1</td>
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<tr>
<td>Readout segments</td>
<td>-</td>
<td>7</td>
</tr>
<tr>
<td>Total acquisition time (min)</td>
<td>2:34</td>
<td>2:55</td>
</tr>
</tbody>
</table>

Table 1: Imaging parameters of the SS-EPI and RESOLVE sequences as used in Zhao et al. (2016) [6].
could be visualized with RESOLVE. The image qualities of the nasopharynx and upper neck were also improved by the introduction of RESOLVE, which resulted in significantly reduced ghosts and distortions and enabled us to observe nasopharynx disease and neck lymph nodes.

To evaluate extent of geometric distortions, key anatomical landmarks (bilateral frontal-internal points, lateral points, and back points of the maxillary sinus, bilateral back points, of the inferior nasal concha, and bilateral frontal-lateral points of the sphenoid sinus) were identified and their coordinates were marked on the T2w TSE, T1w TSE, and the B0 images for SS-EPI and RESOLVE. The differences in the coordinate locations (in mm) between the T2w and the other images (T1w, SS-EPI, and RESOLVE) were measured and compared. Our findings indicated that while some minimal residual distortions remain with RESOLVE (relative to the T1w images), the extent of the deviation from the T2w images was, on average, 3 times higher for SS-EPI compared to RESOLVE [6].

We also evaluated for differences in ADC as well as signal-to-noise ratio (SNR) and contrast-to-noise ratio (CNR) between RESOLVE and SS-EPI using regions-of-interest (ROIs) carefully matched to the lesions together with ROIs placed in the brainstem. There were significantly lower ADC values for RESOLVE compared to SS-EPI for the lesions while the ADC values for the brainstem were similar (Table 2). For us, the elevated lesion ADCs seen for SS-EPI is likely the result of the more inhomogeneous ADC maps due to susceptibility and ghosting artifacts which are prevalent in conventional diffusion-weighted imaging of the nasal cavity. This is bolstered by the finding of similar ADC values in the brainstem.
SNR was lower for RESOLVE compared to SS-EPI, however, there were no significant differences for CNR. This finding is not surprising as SS-EPI has more efficient k-space coverage compared to RESOLVE [7] which necessitates the loss of the advantage of a short acquisition time. However, the higher SNR of SS-EPI does not translate to increased resolution or image quality. In contrast, RESOLVE has the potential to achieve higher resolution with reduced susceptibility artifacts and T2* blurring compared to SS-EPI. Critically, there is no difference in the CNR ratio, consistent with a previous study on breast cancer [7].

Following our establishment of the improved image quality provided by RESOLVE in sinonasal lesions, we sought to investigate the clinical utility of RESOLVE; specifically, we tested if the addition of RESOLVE may improve the differentiation of benign and malignant sinonasal lesions over DCE-MRI [8].

This study involved 98 patients (61 females, mean age 47 years) who underwent RESOLVE and DCE-MRI examinations. 58 patients had histologically-proven malignant lesions while the remaining 40 were established as benign (see Fig. 2 for a case example). The images were post-processed and the data analyzed by an experienced radiologist who was blinded to the histopathological results [8]. Parameters derived from DCE-MRI included several parameters uptake characteristics (see [8] for more details).

Logistic regression and receiver operator characteristic (ROC) curve analyses were performed, first with DCE-MRI parameters alone, followed by DCE-MRI together with RESOLVE ADC values. With DCE parameters alone, accuracy of classification was 70.4 (ROC curve AUC: 0.69, sensitivity 57.5%, specificity 79.3%). When ADC was added to the analysis, the diagnostic accuracy increased to 85.7 (AUC 0.87, sensitivity 85.0%, specificity 86.2%).

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RESOLVE in the imaging of optic neuritis

Acute optic neuritis (ON) is one of the most common optic neuropathology in young adulthood. It is often associated with multiple sclerosis (MS) or neuromyelitis optica (NMO) but can also occur in isolation [9]. The diagnosis of ON is currently based solely on clinical and neuro-ophthalmological examination [10]. However, MRI is also used for the assessment of the inflammatory changes in the optic nerve as well as to rule out structural lesions and other compressive or inflammatory orbital lesions.

Diffusion-weighted imaging of the optic nerve in patients with ON have been shown to predict clinical outcome [11, 12]. However, these studies were based on SS-EPI diffusion which is more prone to susceptibility artifacts in the topic area compared to RESOLVE (Fig. 3). We thus sought to evaluate the role of RESOLVE in detecting acute ON relative to fat-suppressed contrast-enhanced T1w TSE imaging [13].
The final study population consisted of 42 patients with ophthalmological symptoms who have undergone an evaluation for ON by a neuro-ophthalmologist and an MRI within 4 weeks of their acute presentation. 8 patients had neither a clinical history nor positive findings of ON during the ophthalmological examination while the remaining 34 were diagnosed as having left, right, or bilateral ON. Out of the total of 84 optic nerves evaluated, 41 were considered clinically positive and 43 negative.

The MRI examination included RESOLVE (TR 4700 ms, TE 70 ms, slice thickness 2.9 mm, gap 10%, 25 slices, bandwidth 723 Hz/px, matrix 192, FOV 220 mm, averages 1 to 2, b-value 1000 s/mm², diffusion directions 3, TA 2.5–5.3 minutes) and post-contrast T1-weighted TSE (CE-T1) in 3 orientations: axial (TR 643 ms, TE 12 ms, slice 2 mm), oblique sagittal (TR 713 ms, TE 12 ms, slice 2 mm) and coronal (TR 568 ms, TE 11 ms, slice 3 mm). The RESOLVE and CE-T1 images were reviewed separately by two independent neuroradiologists who were blinded to the clinical history and diagnosis by the neuro-ophthalmologist. Each optic nerve was evaluated for optic neuritis and marked as ‘positive’ (+), ‘negative’ (-) or indeterminate.

This study found, as expected, that the accuracy of fat suppressed CE-T1 for acute optic neuritis was higher than diffusion ADC. For the two readers, the sensitivity, specificity and accuracy of CE-T1 for acute ON neuritis were 68.3/85.4%, 79.1/93.0% and 82.1/83.7%, respectively. For RESOLVE, they were 82.9/82.9%, 81.4/83.7% and 82.1/83.3%, respectively [13]. Nevertheless it should be noted that the sensitivity and specificity of RESOLVE were high and helped in the resolution of a number of patient cases. In our study, there were 3 cases of bilateral acute atypical ON with no obvious enhancement on CE-T1 but with high signal on DWI with decreased ADC values (Fig. 4). Moreover, for patients contraindicated for contrast injection, DWI can inform on molecular motion and thus play an important role in diagnosis and patient management. Beyond diagnosis of acute ON, it is also important to be able to differentiate between different clinical types. Acute ON usually precedes the onset of MS or NMO. While NMO can be distinguished from MS at a biochemical level by the presence of the antibody to the astrocyte water channel protein aquaporin 4 (AQP4) [14], it can still commonly be misdiagnosed as MS. As the treatment and prognosis for NMO are distinct from MS [15], it is important to help clinically differentiate between them. We evaluated the possibility that diffusion MRI with RESOLVE may help differentiate between MS- and NMO-related acute ON. We also investigated if MR diffusion parameters may help predict findings on optical coherence tomography (OCT) at six months post the acute attack [16].

34 patients, 19 diagnosed with MS-ON and 15 with NMO-ON, and 16 normal controls were studied (see [16] for more information on patient selection criteria). RESOLVE was acquired on all participants with the following parameters (TR 4700 ms, TE 70 ms, slice thickness 2.9 mm, gap 10%, 25 slices, bandwidth 723 Hz/Px, matrix of 192, FOV 220 mm, voxel size of 1.1 x 1.1 x 2.9 mm³, 2 averages, b-value of 0, 1000 s/mm², 3 diffusion directions, 7 readout segments, TA 5.3 minutes) (Fig. 5).

Figure 3: RESOLVE (3A: b1000, 3B: ADC) shows reduced distortion and greater anatomical detail of the optic area compared to SS-EPI (3C: b1000, 3D: ADC) [13].

Figure 4: 21-year-old male with bilateral optic neuritis and no light perception. CE-T1 axial and coronal (4A, B) showed no obvious contrast enhancement while RESOLVE b1000 and ADC (4C, D) showed apparent diffusion restriction, bilaterally.
Summary and conclusions

We reviewed four recent papers from our institution which evaluated the role of RESOLVE in the imaging of lesions within the sinonasal and optic regions. Compared to conventional SS-EPI, RESOLVE is a breakthrough in terms of achieving high-resolution, low distortion diffusion-weighted imaging of these challenging regions. With RESOLVE, small anatomical structures can be better visualized without the marked susceptibility distortion typically present for conventional diffusion in these areas [6].

With the improvement to diffusion imaging quality provided by RESOLVE, this opens up opportunities to quantitatively assess the role of diffusion in the clinical diagnoses of orbital and sinonasal lesions. We have shown that RESOLVE ADC values can improve the accuracy to differentiate between malignant and benign sinonasal lesions over and above CE-T1 [8]. For optic neuritis, the most common optic neuropathy in young adults, RESOLVE ADCs have a high accuracy in differentiating between normal and affected optic nerves and complements T1-CE in the diagnostic process. RESOLVE ADCs may also help differentiate between multiple sclerosis related optic neuritis and neuromyelitis optica related optic neuritis as well as predict optic nerve atrophy [16]. This can help support better diagnosis of these diseases and also help predict the prognosis of these patients.

References


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