

Integrated Three-Dimensional MR Neurography: Innovations for Plexus and Peripheral Nerve Imaging

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Introduction

Magnetic resonance neurography (MRN) has emerged as an indispensable imaging technique for comprehensive evaluation of plexus and peripheral nerve disorders [1, 2]. The clinical utility of MRN depends critically on three fundamental technical requirements: (1) high spatial resolution, (2) homogeneous fat suppression, and (3) effective vascular suppression.

This article reviews integrated 3D MR neurography techniques and addresses technical challenges. The SPACE sequence incorporates advanced acceleration (DL CS CAIPI¹), fat suppression (C-FOCI, f-Dixon¹), and vascular suppression (MSDE¹, DANTE¹). Additionally, DESS with deep learning reconstruction¹ provides complementary imaging capabilities. Here we present practical protocol implementations and clinical applications that optimize imaging quality for plexus and peripheral nerve evaluation.

Integrated 3D SPACE: Combined acceleration, fat suppression, and vascular suppression

(1) Spatial resolution requirements for 3D MR neurography

High-resolution imaging is essential because peripheral nerves are thin, elongated structures composed of multiple fascicles, and pathologic changes may be subtle or focal. High-resolution 3-Tesla MRN substantially enhances nerve visualization and directly influences diagnostic accuracy and subsequent therapeutic decisions, making improved spatial resolution not merely a technical advancement but a clinically significant improvement in patient care [3]. Achieving high-resolution images of peripheral nerves

requires extended acquisition times. However, recent technological advances in the 3D SPACE sequence address this limitation through an integrated combination of three complementary techniques: parallel imaging with controlled aliasing (CAIPI), compressed sensing (CS), and deep learning (DL) reconstruction.

Parallel imaging with controlled aliasing (CAIPI)

Parallel imaging (PI) exploits differences in receiver coil sensitivity to reconstruct images from undersampled k -space data, reducing acquisition time. However, as acceleration increases, so does the g -factor penalty — noise amplification arising from the geometry and sensitivity profiles of the receiver coil array. CAIPIRINHA (Controlled Aliasing In Parallel Imaging Results In Higher Acceleration), also known as CAIPI, strategically shifts the phase-encoding pattern across slices in 3D acquisitions, reorganizing the aliasing artifacts that result from undersampling into regular, predictable patterns favorable for GRAPPA-based reconstruction [4]. This controlled aliasing pattern reduces g -factor penalties and enables higher acceleration factors while preserving signal-to-noise ratio.

Incoherent sampling and compressed sensing

Compressed sensing (CS) uses the inherent sparsity of medical images — the principle that images contain redundant information. Unlike uniform k -space undersampling, CS uses variable-density, pseudorandom patterns: Low frequencies are densely sampled to preserve contrast and overall image structure, while high-frequency data are undersampled irregularly [5]. This pseudorandom undersampling pattern produces incoherent, noise-like aliasing artifacts rather than coherent folding artifacts. Iterative reconstruction algorithms can then suppress these noise-like artifacts more effectively under data-consistency constraints, which enforce agreement between the reconstructed image and measured k -space

¹ Work in progress. The applications are currently under development and are not for sale in the U.S. and in other countries. Their future availability cannot be ensured.

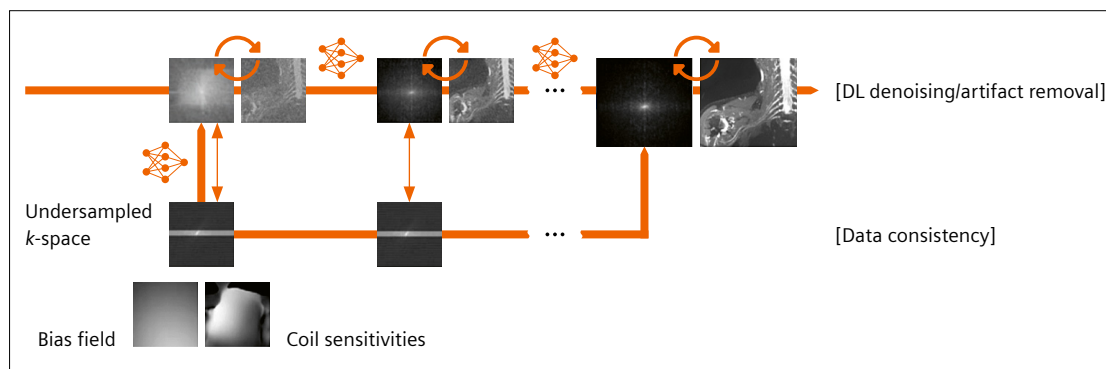
data. However, when pushed to very high acceleration factors, conventional iterative CS may introduce image smoothing — a critical limitation in neurography, where subtle fascicular details and focal signal abnormalities are diagnostically important.

Deep learning reconstruction

Deep Resolve Boost employs learned iterative networks to improve reconstruction. Rather than applying hand-crafted mathematical rules like in traditional reconstructions, the variational network framework implements iterative reconstruction as stacked neural network layers [6]. Each layer in the network alternates between enforcing data consistency in k -space and applying learned image refinements that suppress artifacts while preserving fine anatomic detail (Fig. 1). This iterative refinement through learned layers allows the network to progressively improve the reconstructed image over multiple passes, adapting to

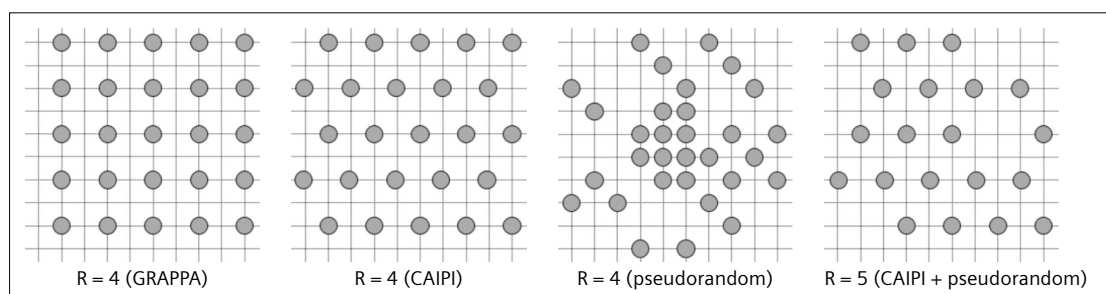
the specific undersampling pattern. Because the acquisition still relies on parallel imaging, performance ultimately remains constrained by coil geometry and g -factor penalties.

In contrast, CS-based DL reconstruction extends the acceleration strategy beyond conventional parallel imaging by incorporating incoherent undersampling and learned regularization into the reconstruction process. CS-based DL reconstruction learns a more flexible image prior from data, enabling more effective suppression of noise and undersampling artifacts while better preserving subtle anatomic structures. DL CS CAIPI reconstruction further combines the complementary strengths of parallel imaging, compressed sensing, and deep learning [7]. It allows imaging to move into higher acceleration ranges where aliasing is expected, but it designs the sampling pattern so that the aliasing becomes easier for the DL reconstruction algorithm to handle (Fig. 2). The result is high acceleration ($R \geq 5$) with preserved fine structural detail — essential



1 Schematic diagram of Deep Resolve.

Similar to conventional iterative compressed sensing, which alternates between data consistency (k -space term) and image regularization (denoising term), the variational network mimics this structure through stacked convolutional neural network (CNN) layers. Each layer enforces data consistency in k -space and applies learned CNN-based image refinement — replacing hand-crafted denoising with learned denoising from training data. Through multiple iterations, the network progressively reconstructs high-quality images while maintaining fidelity to measured k -space data.



2 k -space sampling patterns for different acceleration strategies.

$R = 4$ GRAPPA shows uniform, regular sampling that is favorable for parallel imaging reconstruction with predictable aliasing. $R = 4$ CAIPI demonstrates controlled phase-encoding shifts across slices that reorganize aliasing patterns while maintaining GRAPPA reconstruction efficiency. $R = 4$ pseudorandom sampling introduces variable-density, incoherent undersampling that transforms aliasing into noise-like artifacts that are suitable for compressed sensing and deep learning suppression. $R = 5$ CAIPI + pseudorandom (hybrid) combines the structured CAIPI pattern with pseudorandom variable-density undersampling, enabling higher acceleration while preserving the benefits of both parallel imaging and incoherent artifact suppression. The gray circles represent sampled k -space points.

for resolving small nerve fascicles and detecting focal pathology. These advances enable high-resolution 3D nerve imaging within clinically tolerable scan times, allowing better detection of subtle focal abnormalities and superior coverage of complex plexal structures.

Clinical implications for 3D MR neurography

MR neurography requires simultaneous achievement of high spatial resolution, adequate signal-to-noise ratio, and large field-of-view coverage. Conventional imaging approaches face inherent limitations in meeting all three requirements within acceptable scan times. The integrated DL CS CAIPI approach overcomes these constraints by enabling high acceleration ($R \geq 5$) while preserving image quality, allowing high-resolution 3D imaging within clinically tolerable scan times. Representative imaging protocols with acquisition parameters and expected scan times are summarized in tables 1–3. The approach

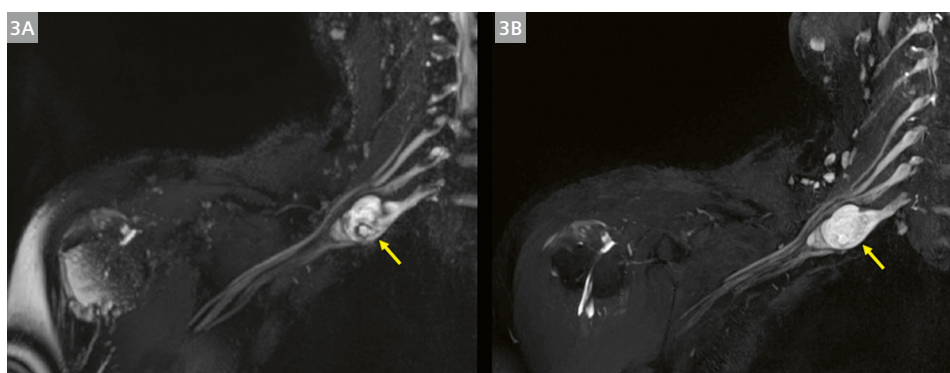
directly translates to superior visualization of nerve anatomy. This enables confident detection of pathologic changes, from nerve compressions and signal abnormalities to mass lesions (Fig. 3), while the ability to resolve individual nerve fascicles and small branch nerves enhances diagnostic accuracy.

(2) Fat suppression challenges

Uniform fat suppression is fundamental in MR neurography. Incomplete fat suppression obscures abnormal T2 hyperintensity and compromises nerve-to-background contrast, frequently resulting in diagnostic errors [8]. Fat suppression techniques used in MR neurography can be broadly categorized into three groups: chemical shift selective fat saturation (CHESS), inversion recovery techniques such as short inversion time inversion recovery (STIR), and chemical shift-based Dixon techniques.

Sequence	STIR SPACE	Deep Resolve STIR DANTE SPACE ¹	Deep Resolve f-Dixon DANTE SPACE ¹
Deep Resolve Boost & Sharp	No	Yes (research sequence)	Yes (research sequence)
Orientation	Coronal	Coronal	Coronal
Field of view, mm ²	300 × 300	300 × 300	300 × 300
Slice thickness, mm	1	0.9	0.9
No. of slices	120	120	120
Matrix size	352 × 352	352 × 352	352 × 352
Pixel resolution, mm ²	0.85 × 0.85	0.43 × 0.43 (interpolated)	0.43 × 0.43 (interpolated)
TR/TE, ms	2800 / 171	3000 / 251	3000 / 362
TI, ms	250	250	N/A
Inversion RF pulse	Product inversion pulse	C-FOCI	C-FOCI
Bandwidth, Hz/pixel	330	836	862
Turbo factor	130	120	120
Total acceleration factor	4 (CAIPI 2 × 2)	12 (CAIPI 3 × 2, CS 2)	12 (CAIPI 3 × 2, CS 2)
Gadolinium contrast	Enhanced	None	None
Fat suppression	STIR, CHESS	STIR	Fast Dixon
Blood suppression	MSDE	DANTE	DANTE
B ₀ shim	Standard neck	Advanced	Advanced
B ₁ shim	Volume-selective	TrueForm	TrueForm
No. of averages	1	2	2
Total scan time, min:sec	5:22	4:57	4:57

Table 1: Representative 3D MR neurography sequences and acquisition parameters for brachial plexus.



3 Clinical application of deep learning-enhanced SPACE with optimized fat suppression.

Compared to STIR SPACE (3A), Deep Resolve CS CAIPI STIR SPACE with C-FOCI fat suppression (3B) demonstrate improved visualization of the brachial plexus and schwannoma involving the inferior trunk (arrow) with increased detail sharpness and reduced noise, while C-FOCI provides homogeneous fat suppression in the shoulder region. The acquisition time is about 10% shorter than standard STIR SPACE. Both images are MIP reformats with 1 cm thickness.

Sequence	STIR SPACE	Deep Resolve STIR DANTE SPACE ¹	DESS	Deep Resolve DESS ¹	Deep Resolve 3D EPI DESS ¹
Deep Resolve Boost & Sharp	No	Yes (research sequence)	No	Yes (research sequence)	Yes (research sequence)
Orientation	Coronal	Coronal	Coronal	Coronal	Coronal
Field of view, mm ²	400 × 400	400 × 400	400 × 400	400 × 400	400 × 400
Slice thickness, mm	1	1	1	1	1
No. of slices	160	160	160	160	160
Matrix size	384 × 384	384 × 384	448 × 269	400 × 400	400 × 400
Pixel resolution, mm ²	0.52 × 0.52 (interpolated)	0.52 × 0.52 (interpolated)	0.89 × 0.89	0.50 × 0.50	0.50 × 0.50
TR/TE, ms	2800 / 171	2800 / 166	12.27 / 4.41	12.27 / 4.41	13.0 / 4.40
TI, ms	250	250	N/A	N/A	N/A
Flip angle, °	T2 Var	T2 Var	23	23	23
Bandwidth, Hz/pixel	343	352	302	338	962
Turbo factor	130	130	N/A	N/A	5 (EPI factor)
Total acceleration factor	4 (CAIPI 2 × 2)	6 (CAIPI 3 × 2)	None	4 (CAIPI 2 × 2)	4 (CAIPI 2 × 2)
Gadolinium contrast	Enhanced	None	None	None	None
Fat suppression	STIR, CHESS	STIR, CHESS	Water excitation	Water excitation	Fast water excitation
Blood suppression	MSDE	DANTE	N/A	N/A	N/A
B ₀ shim	Standard	Standard	Standard	Standard	Standard
B ₁ shim	TrueForm	TrueForm	TrueForm	TrueForm	TrueForm
No. of averages	1.4	2	1	1	1
Total scan time, min:sec	5:30	4:56	5:13	2:46	2:20

Table 2: Representative 3D MR neurography sequences and acquisition parameters for lumbosacral plexus.

CHESS relies on the resonance frequency difference between fat and water, but it becomes unreliable in regions with B_0 inhomogeneity, such as the brachial plexus and lumbosacral plexus, or in off-center extremity imaging. STIR remains one of the most robust fat suppression methods because it nulls fat based on the T1 relaxation time rather than spectral separation, making it insensitive to B_0 inhomogeneity. However, conventional STIR has disadvantages including lower signal-to-noise ratio and longer scan times.

In optimized 3D STIR SPACE, a C-shaped frequency offset corrected inversion (C-FOCI) pulse improves fat suppression by providing relatively uniform fat inversion across both B_0 and B_1 inhomogeneity [9]. This is particularly relevant in the neck–shoulder region, where field inhomogeneity commonly impairs uniform fat suppression. Combined with DL reconstruction, C-FOCI STIR SPACE achieves high-resolution imaging with robust fat suppression and clinically acceptable scan times (Fig. 3).

Dixon imaging is another widely used fat suppression strategy in MR neurography. It separates water and fat based on their precession frequency differences and provides homogeneous fat suppression with minimal

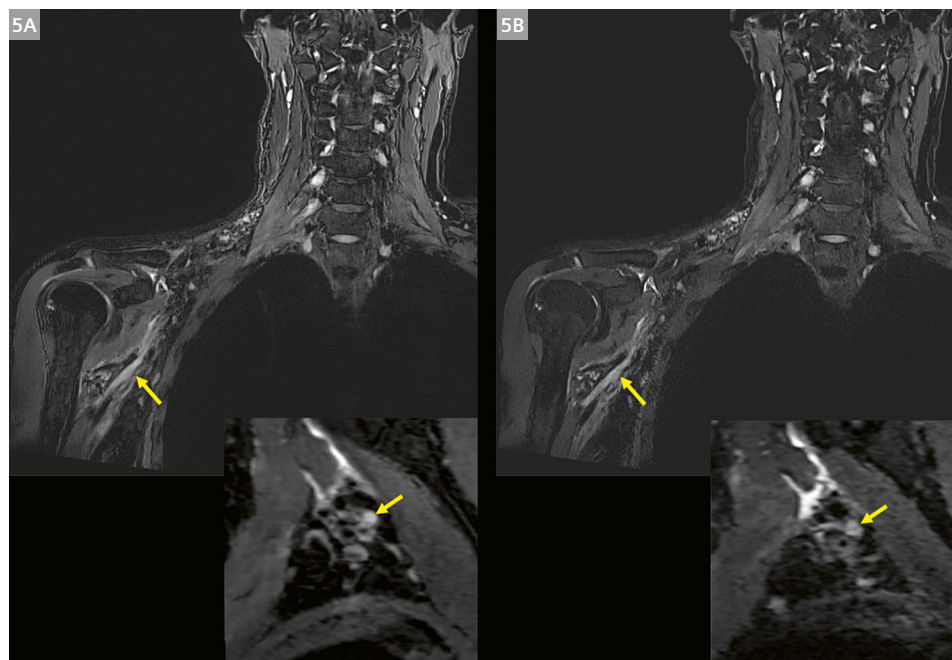
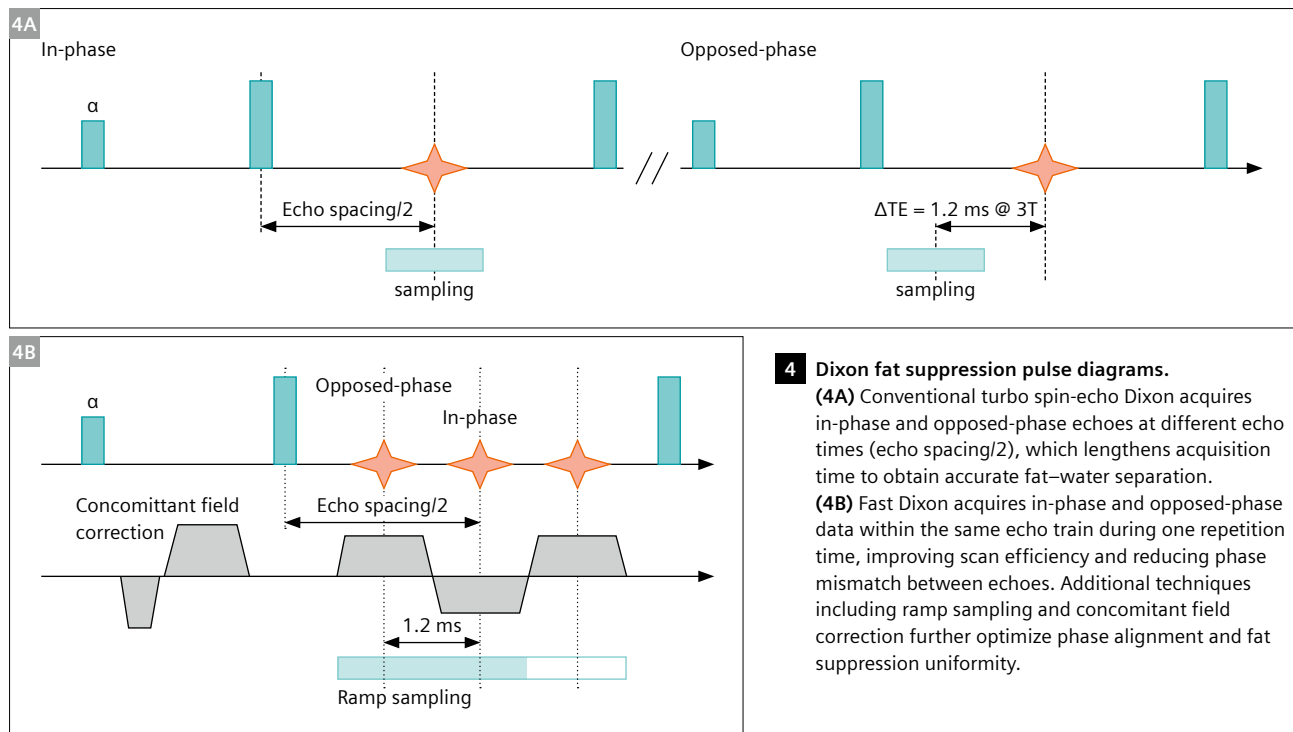
signal-to-noise penalty. Because Dixon is relatively insensitive to B_0 and B_1 inhomogeneity, it is particularly useful for large field-of-view plexus imaging and off-center extremity imaging [10].

Conventional turbo spin-echo Dixon imaging requires echoes that are acquired at different echo times or in separate acquisitions, which may increase scan time and introduce phase errors between echoes during motion. These phase mismatches can result in incomplete fat suppression or water–fat swapping, particularly in regions affected by respiratory or vascular motion. Fast Dixon (f-Dixon) overcomes these limitations by acquiring opposed-phase and in-phase data within the same echo train [11]. This approach improves scan efficiency and reduces phase mismatch between echoes (Fig. 4). Additional strategies, such as ramp sampling and concomitant field correction, further improve acquisition efficiency and phase alignment.

In recent SPACE development, f-Dixon provides robust fat suppression directly integrated into the 3D acquisition. f-Dixon SPACE offers more homogeneous fat suppression compared to STIR while preserving brighter nerve signal without prolonging scan time (Fig. 5).

Sequence	DESS	Deep Resolve DESS ¹	Deep Resolve 3D EPI DESS ¹
Deep Resolve Boost & Sharp	No	Yes (research sequence)	Yes (research sequence)
Orientation	Coronal	Coronal	Coronal
Field of view, mm ²	200 × 200	200 × 200	200 × 200
Slice thickness, mm	1	1	1
No. of slices	112	112	112
Matrix size	192 × 192	192 × 192	192 × 192
Pixel resolution, mm ²	1.04 × 1.04	0.52 × 0.52 (interpolated)	0.52 × 0.52 (interpolated)
TR/TE, ms	12.27 / 4.41	12.27 / 4.41	18.0 / 4.80
Flip angle, °	23	23	23
Bandwidth, Hz/pixel	338	338	500
EPI factor	N/A	N/A	10
Total acceleration factor	None	4 (CAIPI 2 × 2)	4 (CAIPI 2 × 2)
Gadolinium contrast	None	None	None
Fat suppression	Water excitation	Water excitation	Fast water excitation
B_0 shim	Standard	Standard	Standard
B_1 shim	TrueForm	TrueForm	TrueForm
No. of averages	1	1	1
Total scan time, min:sec	5:29	1:45	1:12

Table 3: Representative 3D MR neurography sequences and acquisition parameters for extremity regions (knee/elbow).



- 5** **Comparison of fat suppression techniques in radial neuropathy (arrow).** Deep Resolve f-Dixon SPACE¹ (**5A**) and Deep Resolve STIR SPACE¹ (**5B**) demonstrate comparable spatial resolution and fat suppression quality. f-Dixon preserves superior nerve signal intensity compared to STIR without increasing acquisition time, providing improved visualization of affected nerve segments, particularly evident on oblique sagittal reformatted images.

(3) Vascular suppression requirements

Vascular suppression is critical in MR neurography, as slow-flowing venous structures produce high-signal linear appearances that can obscure or mimic peripheral nerves — which is particularly challenging in the pelvis and extremities, where nerves course adjacent to abundant vascular structures [1]. In the brachial plexus, small branch nerves are closely associated with subclavian, axillary, and cervical vessels [12].

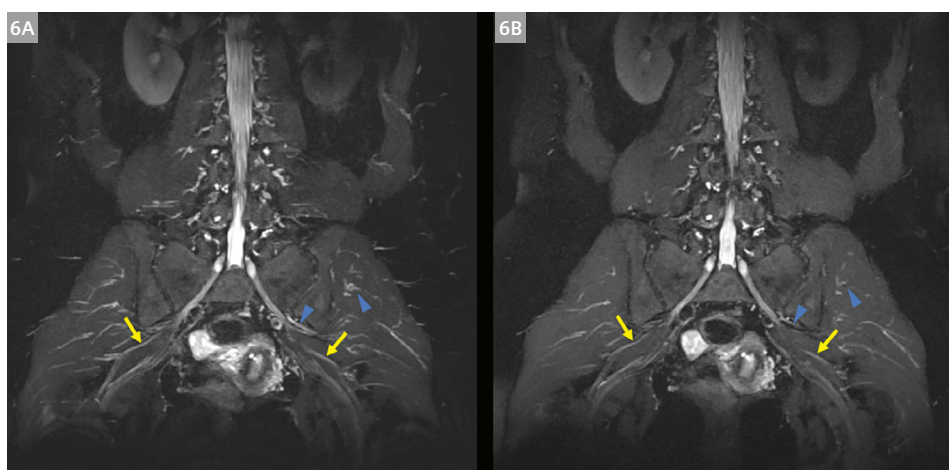
Contrast-enhanced 3D STIR SPACE remains a robust vascular suppression technique. After gadolinium administration, the shortened T1 relaxation time of blood approaches that of fat, allowing STIR to suppress both fat and vascular signal simultaneously. This improves visualization of small branch nerves and the maximum intensity projection (MIP) image quality [12]. However, this approach has limitations: It obscures rather than highlights lesions with blood–nerve barrier disruption, and requires gadolinium administration.

Non-contrast black-blood preparation techniques offer an alternative option: Motion-sensitized driven equilibrium (MSDE) uses motion-sensitizing gradients to dephase flowing spins, but its performance may be limited by signal-to-noise ratio loss, B_1 sensitivity, motion artifacts, and image blurring [13]. As an alternative, delay alternating with nutation for tailored excitation (DANTE) employs trains of low flip-angle pulses to attenuate flowing spins with more effective suppression of slow flow [14]. In lumbosacral plexus imaging, DANTE-prepared STIR SPACE demonstrates superior suppression of slow-flowing venous structures with improved visualization of nerve anatomy [2] (Fig. 6).

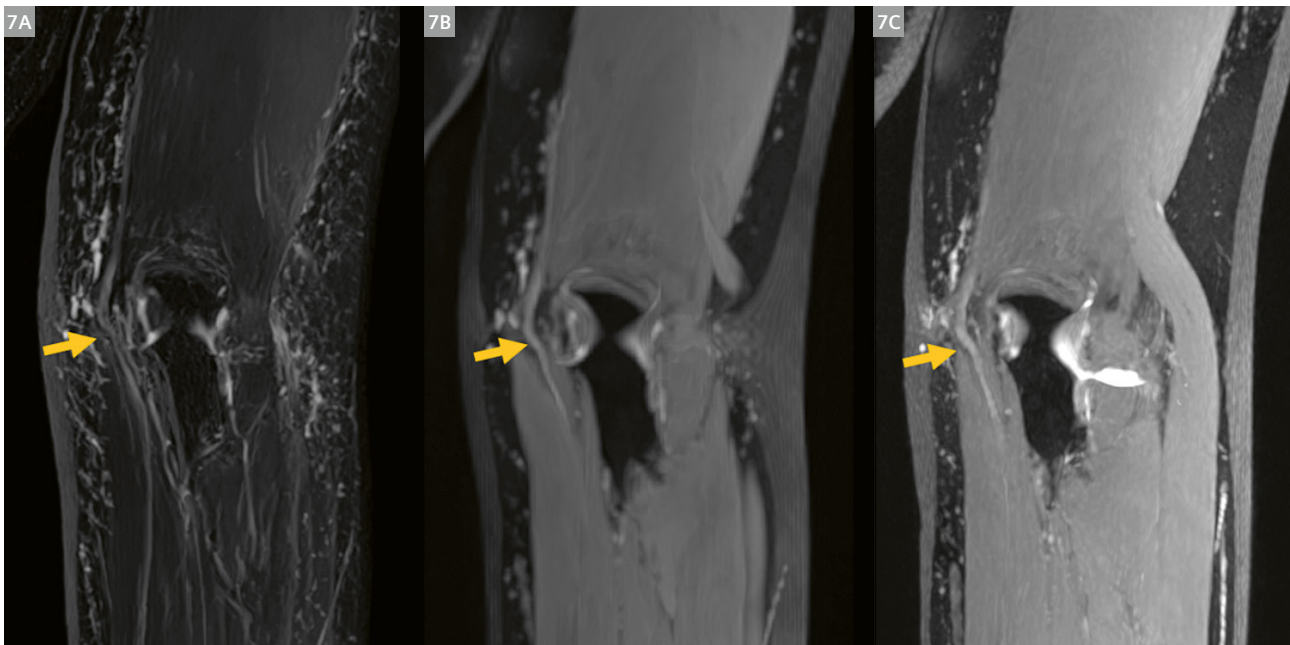
DESS: An alternative to 3D SPACE sequences for MR neurography

Diffusion-weighted reversed fast imaging with steady-state precession (DW-PSIF) has been a favored gradient-echo-based MR neurography technique because peripheral nerves appeared relatively bright due to its heavily T2-weighted contrast and diffusion gradient-based vascular suppression [15]. However, dual echo steady state (DESS) is increasingly used as an alternative, providing high-resolution 3D coverage with improved image quality and intrinsic vascular suppression.

DESS is a gradient-echo steady-state sequence that generates images from the combination of two echoes: a free induction decay component and a spin-echo-like component. Compared with STIR SPACE, DESS generally provides lower nerve-to-background contrast; normal nerves may be less conspicuous because their signal can be similar to adjacent soft tissue. Therefore, DESS is not ideal when the primary goal is to make normal nerves appear bright against a uniformly suppressed background. However, DESS offers two important advantages for MR neurography: efficient fat suppression using water excitation, and intrinsic vascular suppression related to its gradient-echo steady-state mechanism. Moving blood spins experience phase mismatch between the two echoes, whereas relatively stationary nerve tissue maintains phase coherence. Additionally, the short T2* relaxation of deoxy-hemoglobin in venous blood contributes to venous signal loss [2]. These mechanisms make DESS particularly relevant for lumbosacral plexus and extremity peripheral nerve imaging, where STIR SPACE still fails to completely suppress vessel signals (Fig. 7).

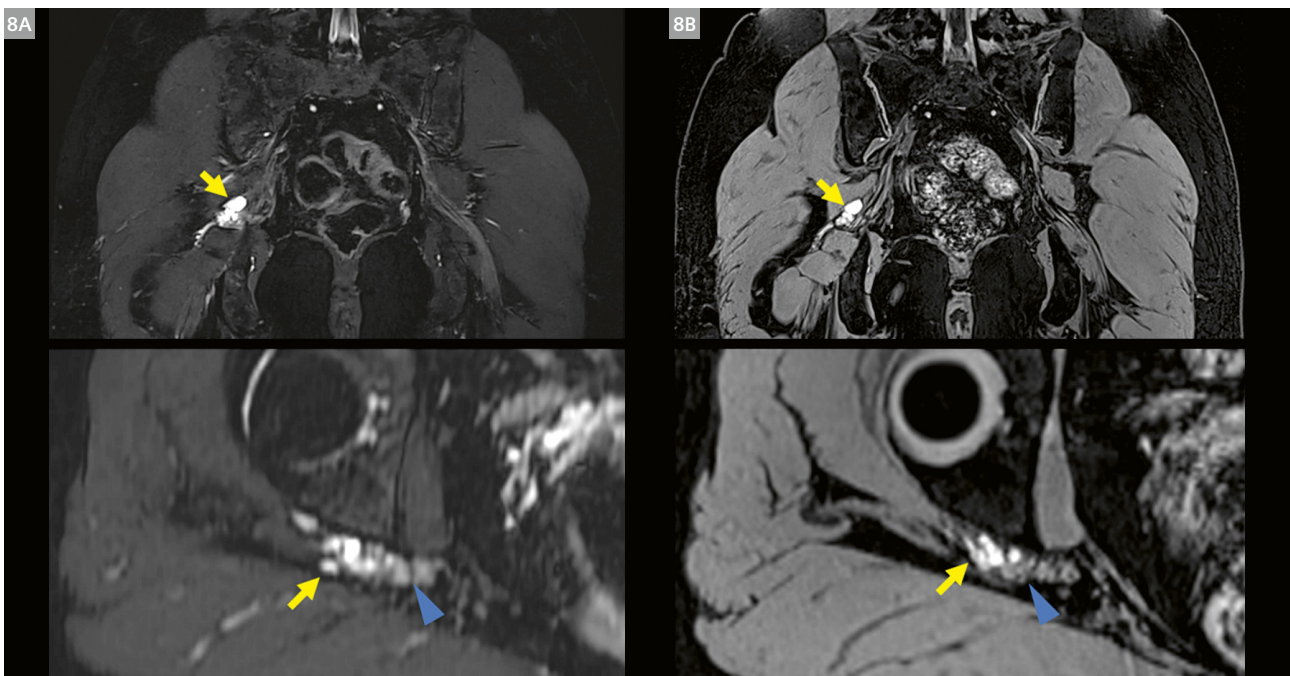


6 Comparison of vascular suppression techniques in non-contrast lumbosacral plexus (LSP) MRN. (6A) MSDE-prepared STIR SPACE¹ and (6B) DANTE-prepared STIR SPACE¹ demonstrate different vascular suppression performance. DANTE provides superior suppression of slow-flowing venous structures, particularly the superior gluteal vein and muscular veins (arrowheads), compared to MSDE. Both images successfully depict sciatic nerve anatomic variants — the left sciatic nerve demonstrates Beaton and Anson type B variant, while the right sciatic nerve shows the type C variant (arrows).



7 Comparison of vascular suppression and image quality in ulnar neuropathy.

Coronal MIP reformats (1 cm thickness) of three different sequences: **(7A)** f-Dixon DANTE-prepared SPACE (4:33 min), **(7B)** DESS (5:18 min), and **(7C)** Deep Learning-enhanced DESS (1:31 min). Both DESS sequences (7B, 7C) demonstrate superior vascular suppression compared to SPACE (7A), with effectively suppressed vessel signals and clear visualization of the affected neuropathy segment. DL-enhanced DESS (7C) achieves significantly shorter acquisition time while providing markedly improved signal-to-noise ratio and image sharpness compared to conventional DESS.



8 Deep Resolve 3D EPI DESS for lumbosacral plexus imaging.

Compared to STIR SPACE **(8A)**, Deep Resolve 3D EPI DESS¹ **(8B)** provides superior visualization of the relationship between the paralabral cyst (arrow) and right sciatic nerve bundle (arrowheads), with markedly improved conspicuity of individual nerve fascicles. The enhanced sharpness and reduced noise of DL reconstruction enable confident assessment of nerve bundle compression and fascicular involvement, demonstrating the potential clinical value of Deep Resolve DESS.¹

Deep Resolve 3D DESS

DL reconstruction combined with dedicated undersampling strategies such as CAIPIRINHA or CS substantially improves acceleration in DESS [16]. Deep Resolve DESS reduces noise, improves perceived sharpness, and increases confidence in the visualization of small nerve branches [17]. Importantly, acquisition time can be reduced to approximately 25%–50% of conventional DESS protocols (Tables 2 and 3). Although DL reconstruction does not fundamentally change the contrast mechanism of DESS, it effectively enhances nerve visualization through noise reduction and improved image sharpness, allowing better differentiation of normal nerves from adjacent soft tissue. Deep Resolve DESS is especially useful in the lumbosacral plexus or upper extremities, where the magnetic field is inhomogeneous and the complex anatomy makes nerve branches difficult to separate from surrounding muscles and adjoining vessels.

Deep Resolve 3D EPI DESS

CAIPIRINHA-accelerated 3D echo-planar imaging (EPI) substantially reduces acquisition time compared with conventional 3D gradient-echo imaging, with further improvement in image quality through deep learning reconstruction [18]. With appropriate selection of segmentation, a moderate EPI factor, CAIPIRINHA sampling, and multishot design, potential artifacts such as distortion, blurring, and residual phase error can be minimized while preserving the advantages of EPI-based acquisition [19].

By incorporating an echo-planar readout into the DESS framework, EPI DESS maintains DESS-type contrast while potentially enabling shorter scan times, broader anatomic coverage, or higher spatial resolution. Although Deep Resolve 3D EPI DESS has not yet been systematically evaluated in MR neurography, a segmented 3D readout design could potentially benefit lumbosacral plexus and extremity peripheral nerve imaging through improved acquisition efficiency (Fig. 8).

Conclusion

Advanced 3D MR neurography has been transformed through integrated technical innovations that address high spatial resolution, homogeneous fat suppression, and effective vascular suppression. SPACE with DL CS CAIPI acceleration and optimized fat/vascular suppression techniques, combined with complementary DESS-based approaches and deep learning reconstruction, provide efficient, high-quality imaging of plexus and peripheral nerve anatomy.

The integration of these technological advances provides flexible and efficient imaging protocols that substantially improve visualization of peripheral nerve anatomy and pathology. These innovations enhance diagnostic confidence in the evaluation of plexus and peripheral nerve disorders, ultimately improving patient management and clinical outcomes.

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