PHILIPS

mDIXON XD

MR software

The next generation **fat-free imaging**

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For more than 30 years, MR researchers and clinicians have demonstrated the clinical value of fat suppression in MR imaging. More recently, robust fat-free imaging with the mDIXON family of imaging methods has shown to be a useful clinical tool for a variety of clinical applications. With the introduction of Philips mDIXON XD, fat-free image quality has taken a leap forward. It opens the way for high performance oncology imaging with large fields of view and high resolution, brain imaging with both motion- and fat-free image quality. It also allows new applications such as cardiac and vascular imaging.

In this white paper, the basic concepts of mDIXON will be introduced and related to other Dixon-based techniques. We will discuss how mDIXON improves overall imaging performance. We will also discuss the benefits of mDIXON XD, which takes mDIXON imaging to the next level of image quality and diagnostic confidence.

Introduction and background

Dixon imaging

In 1984, W. Thomas Dixon, Ph.D. published a paper entitled “Simple Proton Spectroscopic Imaging”[1], in which he introduced what is now commonly referred to as the Dixon method. By sampling two echoes with a slightly different echo delay derived from the difference between the chemical shift frequency of water and fat, this method allowed for the creation of separate water and fat images, even in the presence of sizeable magnetic field inhomogeneities. It was used initially to study fat related disorders, such as fatty liver disease[2,3]. Due to the lack of available water and fat image reconstruction software on early commercial MRI systems, this method was performed by radiological interpretation of the two sampled echo images, rather than by interpretation of separate water and fat images.

As clinical MRI moved to higher magnetic field strengths with improved magnet field homogeneity, spectral pre-saturation methods were the dominant tool for creating fat suppressed images (SPAIR for example). However, with today’s prevalence of high field MRI magnets (1.5T, 3.0T and beyond), magnetic field perturbations such as local magnetic susceptibility, which increases linearly with the magnetic field strength, can potentially render suboptimal routine spectrally selective fat suppression pulses in virtually every anatomic region of the human body. This has stimulated research and development within both the academic and MR system manufacturer environments to revisit the original Dixon method to improve fat suppression and fat quantification.

How it works

The original Dixon data acquisition[6] can be TSE based (acquired as a multi-repetition / multi-acquisition) or gradient echo based (acquired as a multi-echo acquisition). In the original work performed by Dixon[1], a multi-repetition single spin echo sequence was used to generate two sets of images with different TE values. The relative timing of TE1 and TE2 was based on the frequency difference between water and fat molecules. This frequency difference scales with the main magnetic field strength by 140 Hz/T. In the original Dixon study, which was performed on a 0.35T system, this meant that water and fat signals would be in-phase every 20 msec. The first echo of the spin echo sequence TE1, which is based on the timing of the 90° and 180° RF pulses, aligns the water and fat signals (zero phase difference). This is commonly referred to as in-phase. By acquiring the second echo of the spin echo sequence TE2 with an offset readout gradient, the relative phase between water and fat signal is in opposition (180° phase difference). This is commonly referred to as opposed phase. The resultant acquired images were then used to create water only images (via the sum of in- and opposed phase images) and fat only images (via the difference between in- and opposed phase images).

Limitations of Dixon imaging

A key limitation of the original Dixon method and some of the more recently derived Dixon methods is the requirement of discrete acquisition parameters. The main ones are the timing of the echo times within the image acquisition protocol, as well as the increase of the number of echoes for SE sequences (usually going from two to three) to improve the BO inhomogeneity correction and generate true water and fat images[5]. This restricts the ability to fully optimize the Dixon acquisition for scan time, spatial resolution, and anatomical coverage[6]. Furthermore the Dixon method relies on the assumption that there is only one fat peak and one water peak. In fact, the typical fatty acid molecule contains seven primary 1H spectral peaks, resulting in a much more complex modulation of the MRI signal[1]. This will have very significant implications when looking at optimizing water/fat separation accuracy.

mDIXON: The Generalized Two-Point Solution

Technical note

One of the key limitations of the original Dixon method is the restriction of the echo times for the two echoes sampled (known as two-point Dixon) in a dual echo gradient echo imaging acquisition. The echo timing must be such that the in- and opposed phase water and fat images are acquired, based on the frequency difference between water and fat protons. This allows for the creation of water only (W) or fat only (F) images via a simple addition or subtraction of the in- and opposed phase images (IP and OP, respectively[1]):

$$W = IP + OP$$

$$F = IP - OP$$

When moving to higher field strengths, the timing for these two echo times decreases, making it increasingly difficult to maintain high spatial resolution and clinically relevant image signal-to-noise ratio (SNR). Creation of three-point methods have allowed for more flexibility in the choice of echo times[4], but have restricted the ability to optimize other relevant imaging characteristics, such as spatial resolution and, most importantly, total scan time due to the required increase in TR[7].

The mDIXON image reconstruction method is a generalized solution based on the semi-flexible two-point method and removes the need to use field strength dependent TE values[9]. For mDIXON, the complex composite signal in image space S, sampled at echo times t_n, with $n = 1, \ldots, N_E$, is modeled by[7]

$$S_n = (W + Fe^{i\Theta n})\, e^{i\phi n}$$

W and F denote the real or complex water and fat signal in image space, respectively.
The dephasing angle Θ is given by

$$\Theta_n = 2\pi\, \Delta f t_n$$

where Δf commonly represents the resonance frequency offset of the dominant spectral peak of fat with respect to water. φ denotes a phase error, and $\phi = e^{i\phi}$. a corresponding phase or, that is usually attributed to field inhomogeneity, in which case it is proportional to both the field strength offset ΔB_0 and the echo time TE.

However, unlike three-point Dixon methods, two-point methods do not rely on a linear relation between ϕ and TE.

The generalized nature of the mDIXON methodology allows the user to create fully optimized imaging protocols based on shortest imaging time and optimized spatial resolution, for example, without the restriction of magnetic field dependent TE values imposed by the Dixon method.

The dual echo gradient echo method (mDIXON FFE) uses a bipolar gradient readout for the two acquired echoes. Having the ability to use arbitrary TE values, allows a significant increase in scanning efficiency compared to field strength dependent Dixon based methods that use fixed TE values[7]. This results in optimized spatial resolution, field of view, and anatomical coverage compared to fixed TE-based Dixon imaging, especially for applications such as high resolution abdominal imaging within a single breathhold.

For TSE based imaging, the multi-repetition spin echo imaging sequence is used. With the ability to use two echo times with arbitrary TE values, mDIXON TSE becomes a very efficient acquisition method with improved sharpness (thanks to reduced TSE train length) compared to Dixon TSE, which must perform three repetitions to accommodate the use of three TE values. This increases the total image acquisition time by 30% compared to mDIXON TSE[5].

Benefits of the Philips mDIXON imaging method

Philips researchers originally developed a methodology known as modified DIXON, or mDIXON, which provides the clinical user with more flexibility in optimizing their mDIXON imaging protocols, specifically in balancing the resultant spatial resolution and scan time with the acquisition of only two echoes with unrestricted TE values [7]. While the initial focus was on gradient echo imaging for fat-free abdominal imaging in breathholds[8], mDIXON has now been integrated into more routine imaging methods such as fat-free turbo spin echo imaging (mDIXON TSE).

The main benefit of mDIXON for FFE sequences, compared to frequency-selective fat-suppression methods like eTHRIVE, is its greater scanning efficiency. Data is not acquired during the application of the SPAIR fat suppression pulse used in eTHRIVE, whereas the mDIXON data is acquired continuously. Furthermore fat has a more uniform low signal intensity in the mDIXON images compared to the eTHRIVE images.

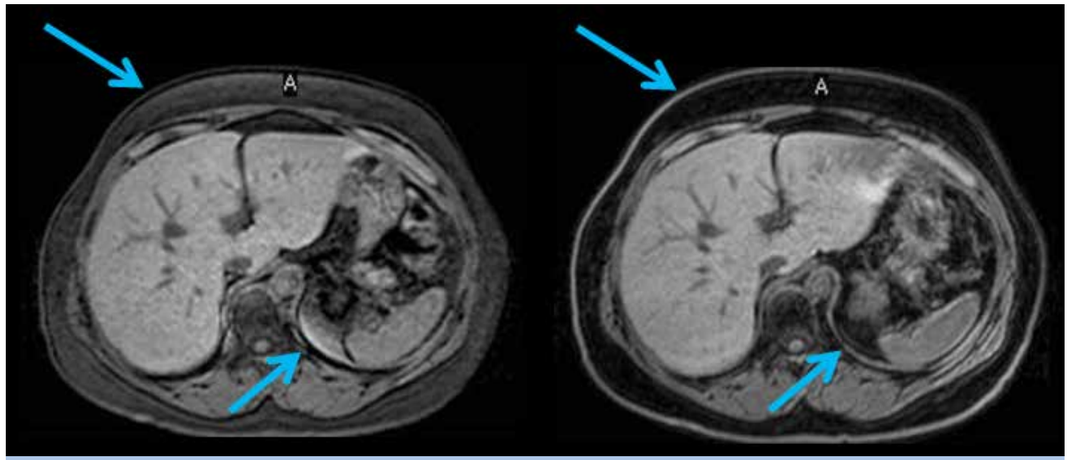


Image 1: Comparison of eTHRIVE (left) versus mDIXON (right) on the same volunteer acquired with the same field of view, anatomical coverage, spatial resolution and breathhold time. Achieva 1.5T, image resolution 1.5 x 1.5 x 2.0 mm, scan time 0:19 min

Increase in both speed and sharpness

For TSE sequences, the key benefit of mDIXON TSE over similar Dixon TSE methods has to do with total imaging time. mDIXON TSE maintains equivalent scan times as traditional methods of fat suppression (SPIR, SPAIR). Furthermore mDIXON TSE does not suffer from time consuming inversion recovery techniques such as STIR fat suppression. Although both mDIXON TSE and Dixon TSE use a multi-acquisition scheme that acquires one set of echoes per TE, Dixon TSE requires a set of three acquisitions with fixed TE values. This increases the scan time compared to mDIXON TSE which only requires two acquisitions and allows flexible TE values. For mDIXON TSE the echo spacing's of the acquired echo train can be shortened, providing additional improvements in both imaging time and image sharpness. The mDIXON TSE 2-echo technology delivers a 30% increase in speed and up to 30% increase in sharpness compared to conventional 3-echo Dixon TSE techniques.

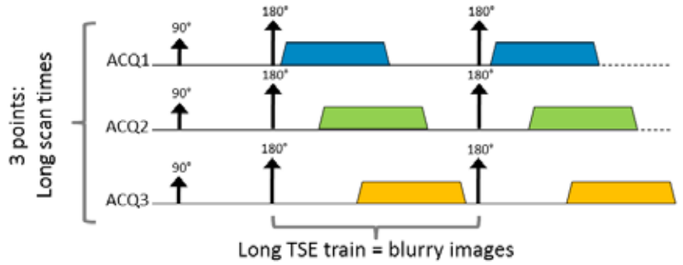


Image 2: Graphical representation of 3 point Dixon TSE

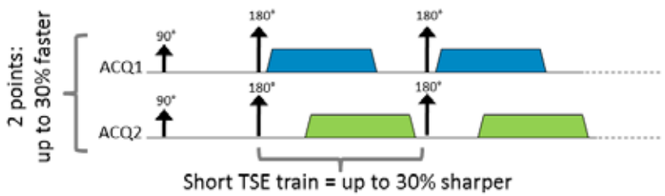


Image 3: Graphical representation of 2 point mDIXON TSE

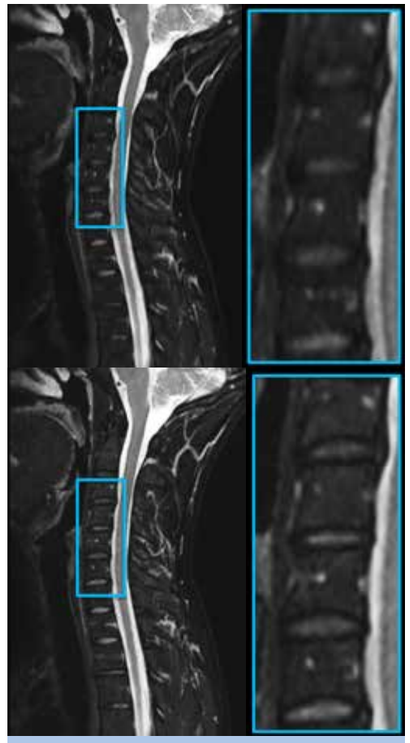


Image 4: Comparison of conventional 3 point Dixon method (top) versus Philips 2 point mDIXON method (bottom) on the same volunteer acquired with the same field of view, anatomical coverage, and spatial resolution. Scan time for the conventional 3 point Dixon method is 4:30 minutes whereas it is only 3:09 minutes for the Philips 2 point mDIXON method. Note the increase in image sharpness with the acquisition of the 2 point mDIXON method.

Next generation fat-free imaging: mDIXON XD

As was pointed out in the last section, mDIXON provides higher scanning efficiency and dramatically improved fat-free images when compared to traditional spectral fat suppression methods. mDIXON has been recognized over the past few years as the technology of choice in the clinical MRI environment[6]. The logical next step is to expand the utility of mDIXON to address the challenges faced every day in the clinical setting. For virtually all anatomies, there is a significant need for uniform, complete, and consistent fat-free imaging, even in the case of large fields-of-view, challenging patients or anatomies, and high resolution scans, as well as a reduction of artifacts due to patient motion. mDIXON has been brought to a new level of performance, called mDIXON XD, through advancements in acquisition, calibration and reconstruction methodologies. It provides improvements in image resolution, field of view and motion correction, with expanded anatomical coverage including cardiovascular applications.

mDIXON XD incorporates a 7 peak fat model, realizing additional improvements in the level of fat-free imaging[10–13].

This is especially important when working with today's higher magnetic field strengths. Unlike acquiring data at 0.35T, at fields of 1.5T and 3.0T water fat modulation becomes increasingly complex at shorter echo times. This can lead to errors in the assignment of fat and water during the image reconstruction, resulting in incomplete or erroneous fat suppression. This is especially true when performing clinically relevant fat-free imaging at higher spatial resolution[13]. Moreover the improved B0 correction implemented in mDIXON XD allows for fat-free imaging over large fields of view.

The improved correction relies on a smart inclusion of magnet and anatomy specific data, that are used as input for the mDIXON XD reconstruction. This a priori knowledge helps remove the corresponding phase effects and improves the overall water-fat separation performance. Hence, mDIXON XD delivers a reconstruction that is tailored, adapted and optimized for each individual magnet and anatomy.

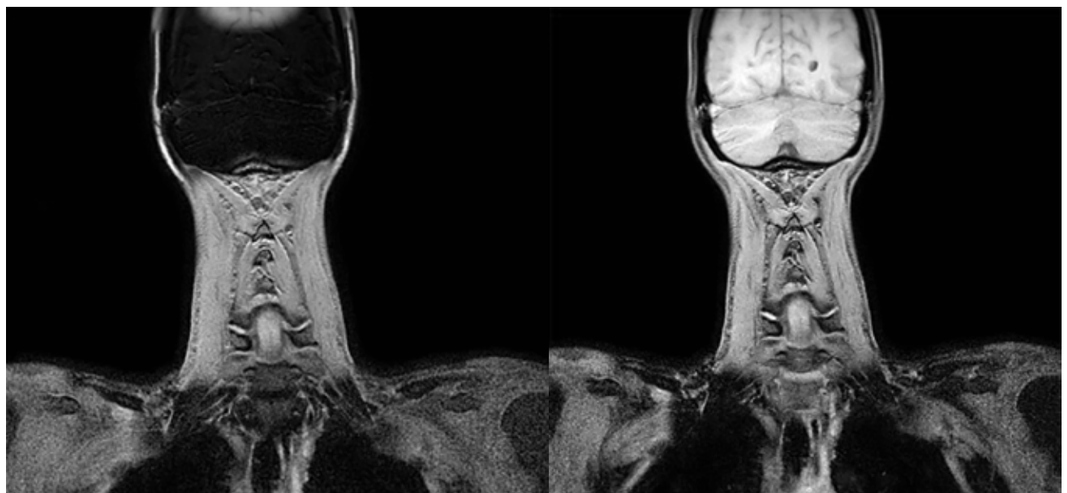


Image 6: Comparison of 1 peak spectral fat model (left) versus 7 peak spectral fat model (right) on the same volunteer acquired with the same field of view, anatomical coverage, spatial resolution and scan time. Note the fat swap in the brain region when the 1 peak spectral fat model is used.

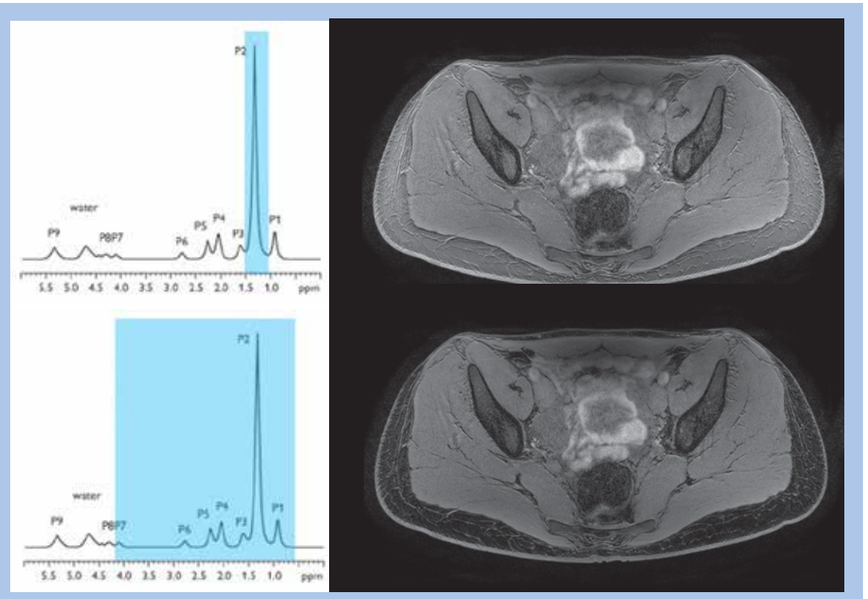
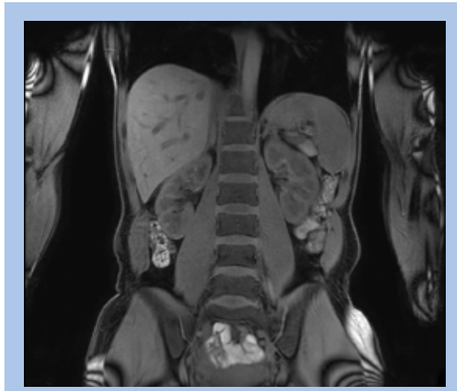
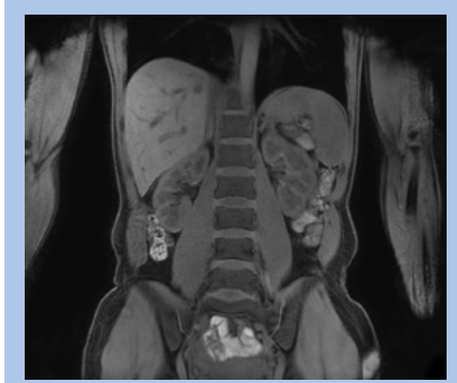
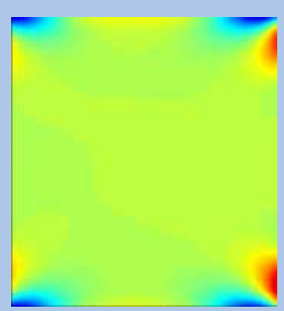


Image 5: Comparison of 1 peak spectral fat model (top) versus 7 peak spectral fat model (bottom) on the same volunteer acquired with the same field of view, anatomical coverage, spatial resolution and scan time. Note the improvement in fat-free imaging at these sub-millimeter image resolutions.



B0 correction algorithm – Philips conventional





Improved B0 correction algorithm – 3D full FOV

Image 7: Comparison of conventional Philips B0 correction algorithm (top) versus improved B0 correction algorithm (bottom) on the same volunteer acquired with the same field of view, anatomical coverage, spatial resolution and scan time. Note the artifacts at the edges of the field of view when conventional B0 correction algorithm is used. Ingenia 3.0T, image resolution 1.5 x 1.5 x 4.0 mm, scan time 0:16 min

mDIXON XD for TSE

Using the maximum water-fat shift (minimum band width) is preferred in TSE imaging to gain signal-to-noise. However, if the resultant chemical shift artifact is not corrected, these high water-fat shifts may lead to a suboptimal tissue delineation in anatomic areas where both water and fat are present (like cartilage). mDIXON XD includes a water-fat shift correction algorithm ensuring high signal-to-noise and more enhanced visualization of the cartilage.

In recent years, motion has been addressed via MultiVane-like technologies (known as Propeller), which have helped tremendously to reduce MRI's motion sensitivity. However, fat suppression incorporated into such motion correction schemes was based on either standard spectral fat suppression with very high sampling bandwidths, impacting image SNR, or three-point Dixon methods[14–16]. mDIXON XD for TSE combined with MultiVane XD results in a fat-free image with improved sharpness and increased SNR compared to a standard fat-free mDIXON TSE approach[17].

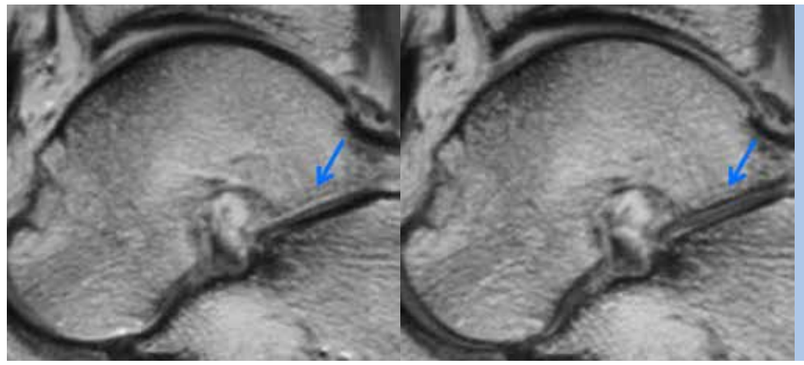


Image 8: Comparison of an uncorrected water-fat shift of 2.3 pixels (left) versus a corrected water-fat shift of 2.3 pixels (right) on the same volunteer acquired with the same field of view, anatomical coverage, spatial resolution and scan time. Note the apparent shift of the cartilage in the un-corrected image.

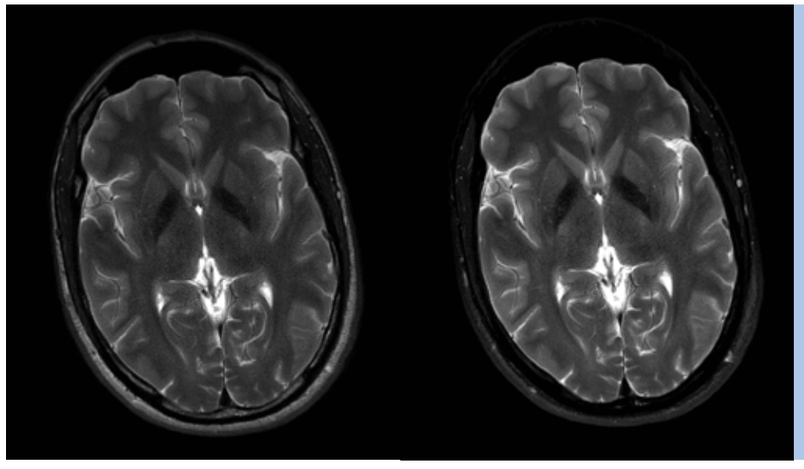


Image 9: T2w mDIXON XD combined with MultiVane XD provides in-phase (left) and fat-free (right) images with superior tissue sharpness (compared to standard MultiVane acquisition). Ingenia 3.0T, image resolution 0.6 x 0.6 x 4.0 mm, scan time 3:12 min

mDIXON XD for vascular imaging

An area of active research is the utility of mDIXON XD FFE for contrast-enhanced peripheral MRA angiography. Recently published work[19] has shown that using mDIXON XD FFE, instead of the standard single echo FFE acquisition protocol, enables subtraction-less (single-pass) MRA by utilizing the water-only mDIXON images as opposed to standard MRA technology which relies on the subtraction of a pre- and post-contrast scan. mDIXON XD reduces any artifact that could arise from the subtraction step in standard MRA (e.g. resulting from misalignment between the pre and post contrast scan due to motion), resulting in more robust MRA. This new approach improves vessel-to-background contrast by 30-36% allowing better depiction of small peripheral vessels compared to standard pMRA[19].

Conclusion:

For over 30 years MR researchers and clinicians have shown that fat suppression in MR imaging is a tool that has many clinical uses. Achieving robust fat suppression performance continues to be the focus of many investigations. The mDIXON family of imaging methods has show to be an exceptionally useful clinical tool for a variety of clinical applications.

With the introduction of mDIXON XD, fat suppressed image quality has taken a leap forward, expanding applications to larger fields of view and higher resolution with enhanced image sharpness. It also improves motion corrected image quality.

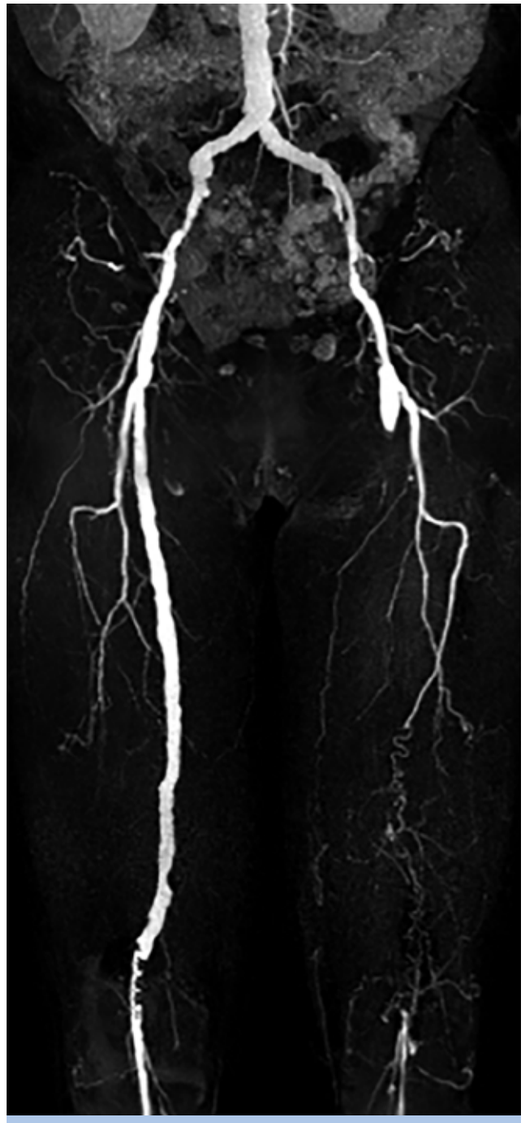


Image 9: Example of mDIXON XD for peripheral vascular imaging. Ingenia 1.5T, image resolution 2.1 x 1.8 x 1.5 mm, scan time 0:14 min per station

Another member of the mDIXON family: mDIXON Quant

In addition to mDIXON XD FFE and mDIXON XD TSE, there is now mDIXON Quant, which enables accurate and reproducible quantification of fat deposition in the liver in a single breathhold. In addition to the quantification result, which can be shown in convenient color maps, the corresponding T2*/R2*, water, in-phase, opposed phase, and fat images can also be provided without the need for additional scanning.

How does mDIXON Quant differ from mDIXON XD?

Because of the need for accurate and reproducible fat quantification, mDIXON Quant has different goals than mDIXON XD, which focuses on speed and fat-free performance. mDIXON Quant is a low flip angle, multi-echo, multi-peak method including T2* and novel eddy current compensation that delivers accurate and reproducible quantification of fat deposition in the liver in a single breathhold over a wide range of echo times, fields of view, and resolutions[23].

What is the clinical need driving mDIXON Quant?

Hepatic steatosis, or fatty liver is a condition characterized by accumulation of tryglicerides in hepatocytes. It is associated with a wide range of conditions. While excessive alcohol consumption is a common cause of fat deposition in the liver, physicians are increasingly finding fatty liver not related to alcohol, called Non-Alcoholic Fatty Liver Disease (NAFLD). It affects 30% to 40% of the adult population depending on ethnicity and gender[20] , and over 50% of obese children[21]. In some cases simple steatosis can progress to non-alcoholic steatohepatitis (NASH) and cirrhosis. While NAFLD is multifactorial, it is most often caused by obesity and can be associated with risk factors for metabolic dysfunction, Type 2 diabetes, and cardiovascular diseases.
A healthy liver has up to 5%-6% fat content. Fat content from 5% to 33% is graded as mild, 34% to 66% moderate, and over 67% severe steatosis.
Recent research has shown that NAFLD and resultant diseases such as Type 2 diabetes can be reversible[22], and treatment options have been investigated. Therefore, there is a clinical need for diagnosing and monitoring liver fat content.

How flexible is mDIXON Quant?

mDIXON Quant differs from other MR fat quantification methods because there is virtually no restriction on the echo times. This provides full flexibility in choosing other parameters, such as resolution, field of view and scan time. Another important aspect is the full flexibility in output image selection. The user can choose any combination of images: fat fraction, T2*, R2*, water, in-phase, opposed phase, and/or fat. This allows the radiologist to review only the minimum number of images required for diagnosis.

What about color fat fraction maps?

mDIXON Quant creates a color fat fraction map that visually conveys the amount of fat in the liver, and enables convenient comparison of images acquired at different times.

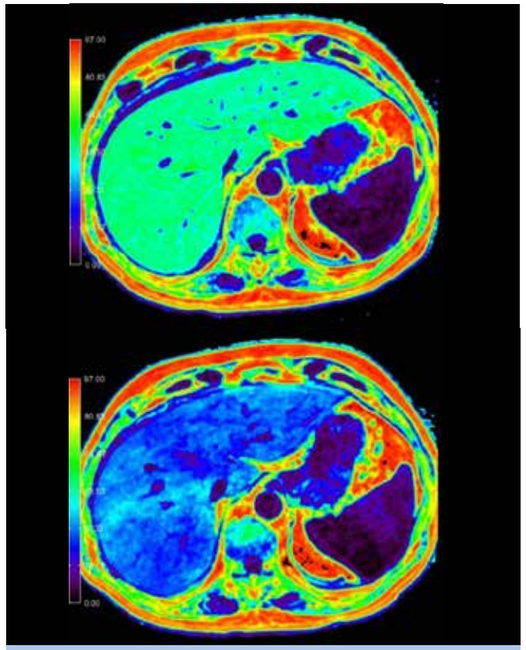


Image 10: mDIXON Quant of a patient 2 weeks after cessation of alcohol consumption shows a fat fraction of ~50 (top). Follow-up 2 weeks later (4 weeks after cessation of alcohol consumption) shows a decrease of fat fraction to ~30% (bottom). Courtesy: Dr. S. Hussain, University of Nebraska Medical Center, Omaha, Nebraska, USA

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