TimTX TrueShape and *syngo* ZOOMit Technical and Practical Aspects

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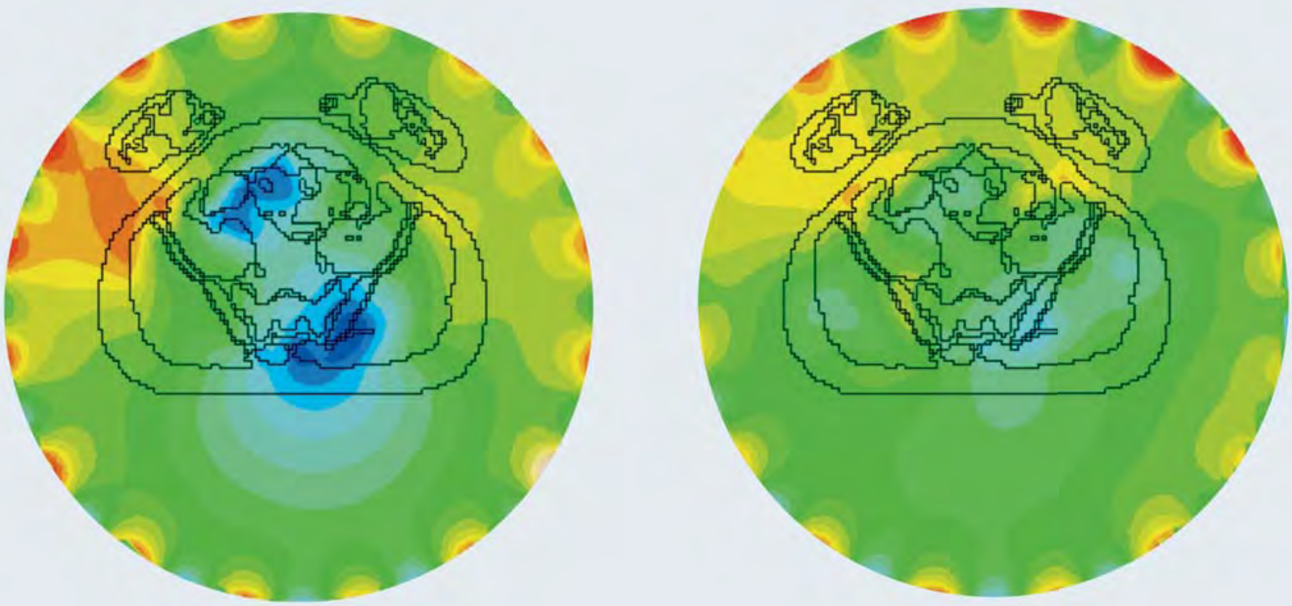


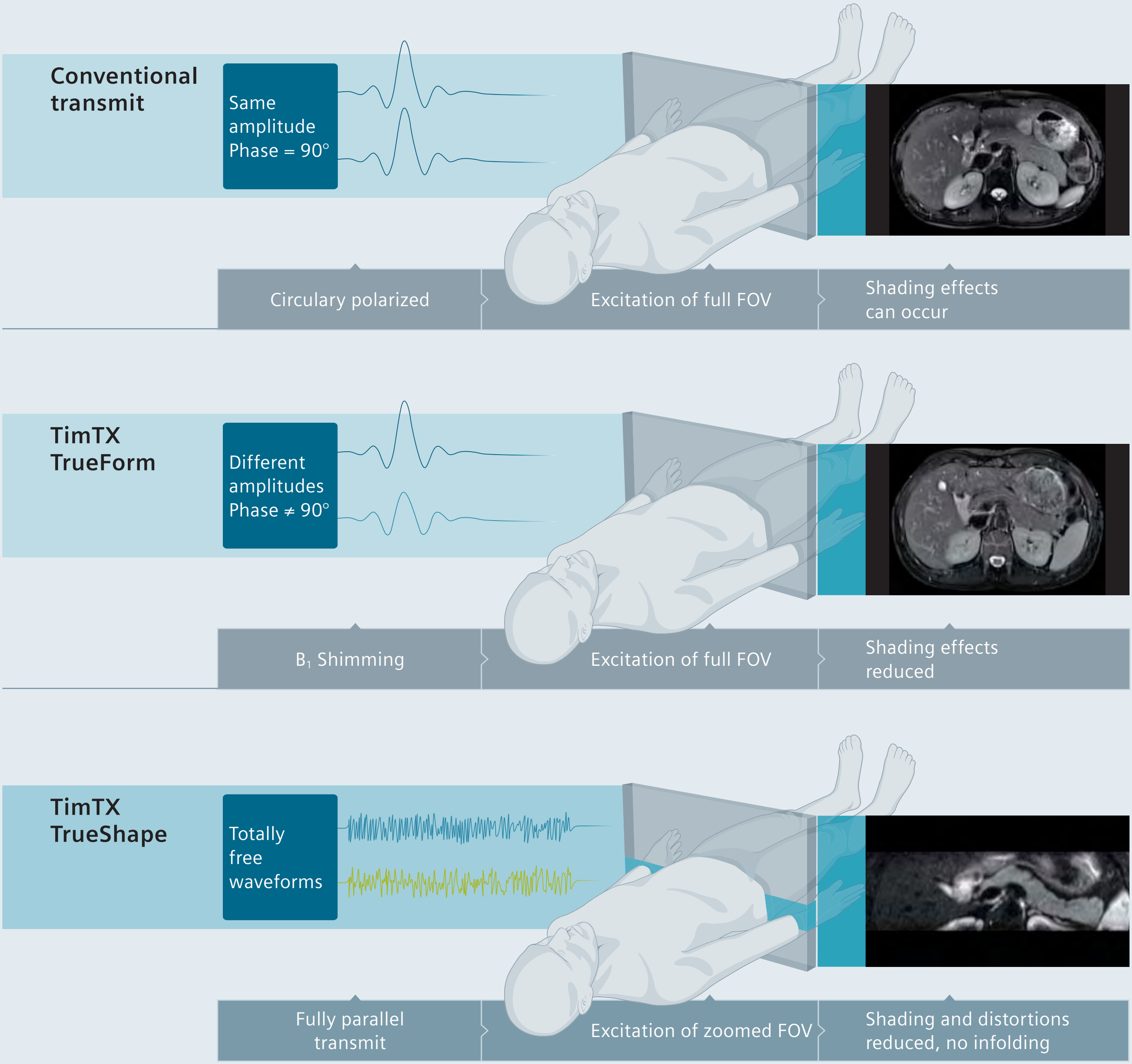
1 B_1 homogeneity with circular polarization (left) and with TimTX TrueForm (right) for a typical anatomical region (pelvis) where B_1 inhomogeneity can occur at 3T. Note the blue-colored areas with the conventional CP excitation. The dielectric shading effects are practically eliminated on the right side, while the example shown on the left would have been of non-diagnostic quality at least for these specific anatomical regions because of potential contrast variations.

At the RSNA 2011, Siemens was the first to introduce sequence techniques for clinical MR systems that take full advantage of parallel transmission: zooming without aliasing. This application, called *syngo* ZOOMit*, is enabled by the technology platform TimTX TrueShape. TimTX TrueShape is the first platform in the MR industry to make full use of the dynamic capabilities of a transmit array system. And *syngo* ZOOMit is the first fully dynamic application based on TimTX TrueShape.

The purpose of this article is to provide some background information about the new dynamic parallel transmission techniques (pTX), compare them to the existing static B_1 shimming, and point out potential applications based on dynamic pTX.

Background – from parallel receive to parallel transmit

The implementation of multi-channel radio frequency (RF) receive systems and receive array coils in the early 1990s marked a revolution in MR imaging. This technology offered the very attractive combination of high signal-to-noise ratio (SNR) from small coil elements with the large coverage of large coils. Starting with 2 and 4 RF channels in the 90s, systems with up to 8 RF channels were available around the year 2000. Multi-channel RF received a further boost with the advent of parallel acquisition techniques (PAT) at this time. A variety of parallel acquisition techniques were developed, such as SMASH [1], SENSE [2], 2



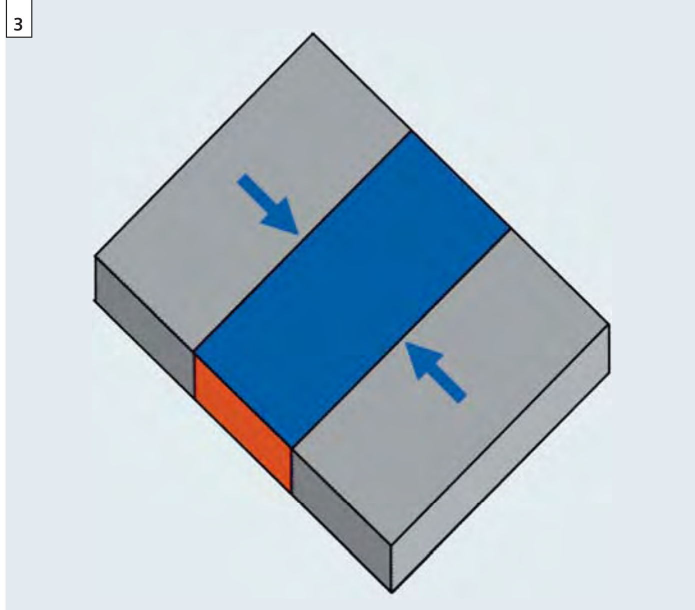
2 **(Top)** Conventional transmit (circular polarization) with severe shading effect due to B_1 inhomogeneities; **(Middle)** B_1 Shimming with TimTX TrueForm (different amplitude/phase settings on the two channels of the RF body coil), eliminating the B_1 shading and resulting in homogeneous image contrast; **(Bottom)** Fully dynamic pTX with TimTX TrueShape (arbitrary waveforms of the two RF channels as well as the gradients), resulting in a zoomed image with higher image quality and shorter scan time.

*This product is still under development and not yet commercially available. Its future availability cannot be ensured.

and GRAPPA [3]. PAT on the receive side offers shorter scan times, higher temporal and/or spatial resolution as well as reduced blurring and distortion artifacts in single-shot imaging. PAT is an integral part of many exams today. Applications like contrast-enhanced 3D liver dynamics, MR angiography or diffusion-weighted imaging (DWI), to name just a few, would not be possible in a clinical setting without PAT. In addition, with the availability of flexible scalable coil technology, PAT can be applied in any body region, ranging from a dedicated brain scan to a whole-body examination.

Tim (Total imaging matrix) was the first RF system that was specifically designed for maximizing the benefits from PAT. Introduced in 2003, the MAGNETOM Avanto, the first MR system which enabled high-quality whole-body scanning in a clinical setting, offered up to 32 RF channels. Today, up to 128 RF channels are available as a product.

In parallel to the development of these new receive technologies (multi-channel coils, Tim, PAT), further efforts were undertaken over the last decade to increase the field strength beyond 1.5 Tesla, in order to gain even higher SNR – which could be invested in, for example, higher spatial resolution or even faster imaging with PAT. But 3 Tesla field strength, besides the obvious advantage of higher SNR, also showed the disadvantage of a lower B_1 homogeneity in some body regions. This is where the so-called B_1 shimming, based on multi-channel transmit technology, came in, as a remedy to B_1 inhomogeneities.



3 *syngo* ZOOMit: Zooming the FOV in the phase-encoding direction.

From circular polarization to B_1 shimming

Ideally, circular polarization is the best way to perform conventional slice-selective imaging. The benefit of circular polarization (CP) over linear polarization (LP) manifests itself in a more homogeneous B_1 distribution over the object, a lower specific absorption rate (SAR), and higher SNR in the receive path. Technically, the circular polarization is achieved by feeding two ports of the transmit coil with identical amplitudes and a phase shift of 90 degrees (Fig. 2, top).

It turns out that at high field strengths, such as 3T, the 'ideal' circular polarization is not necessarily the optimum anymore. The reason is that at such high frequencies, the wavelength of the MR signal approaches the dimensions of the object. At 3T, the wavelength is approximately 26 cm. It is therefore smaller than, for example, the dimensions of the abdomen. This can result in interferences of the B_1 field and signal shading. The critical point here is that not only the signal intensity is altered (which can be corrected for with post-processing), but, most critically, also the contrast behavior can be altered.

A remedy to this RF shading effect is B_1 Shimming. The two ports of the transmit coil are fed with different amplitudes and a phase shift ≠ 90 degrees (see Fig. 2, middle). With a 2-channel transmit system, this results in an 'elliptical' excitation. This can potentially, including the interaction with tissue characteristics, result in a more homogeneous B_1 distribution than the conventional circular polarization (Fig. 1). At 3T, mainly abdominal and pelvic imaging is critical, the head is still smaller than the MR wavelength. At ultra-high field strength such as 7T, B_1 shading is also very severe in the head region as a consequence of even shorter wavelengths.

From a clinical perspective, dielectric shading can negate the advantage of a 3T system and there was intense debate in the first years of 3T MRI as to whether such a scanner would ever be fully operational as a clinical whole-body system. If a robust and homogeneous image quality could not be assured in the abdomen, what would be the clinical use of such a scanner? A solution was therefore urgently needed to take advantage of the higher field strength, without negating the MR scanner's daily clinical usability. In the first days, clinicians tried to manipulate the B_1 distribution by applying heavy dielectric cushions on the patients – with limited success and practicability. So, B_1 shimming became a key to the further success of 3T MRI.

In 2007, Siemens pioneered B_1 shimming with the **TimTX TrueForm** technology (TrueForm RF design). This technology was first implemented in the MAGNETOM Verio, which also happened to be the first open-bore system available at 3 Tesla (Tim coil technology had already been introduced at this time point also for 3T). TimTX TrueForm offers 2-channel transmit array functionality for B_1

shimming. It works with anatomy-specific settings, optimized for improved B_1 homogeneity [4]. This approach has the advantage that no time is required, for example, for patient-specific B_1 mapping and adjustments (which can easily require 1 minute for each body region to be examined). And, more importantly, the workflow of an MRI exam compared to a 1.5T scanner is completely unchanged. Routine one-station exams (also with small table movements due to automatic table positioning to isocenter), multi-region exams, breath-hold versus gated sequences, especially TimCT (scanning during continuous table move) – all this is not affected. TimTX TrueForm is virtually invisible for the user – apart from the improvement in image quality.
As important as B_1 Shimming is at 3T and above – this type of B_1 Shimming is still a conventional approach with 'static' excitation pulses, i.e. the combination of a sinc (sin(x)/x) RF pulse with a static slice-select gradient to excite a slice, which works irrespective of how one determines the required settings (anatomy-specific or based on previous B_1 mapping). In fact, it is 'only' a repair mechanism to counteract the effects of the shorter wavelength at high field and to compensate for effects introduced by the human body itself.
But it was soon realized that parallel transmission technology (pTX) can offer a much greater potential than only B_1 shimming. Dynamic pTX can be used to enable new applications.

Beyond simple B_1 shimming: dynamic parallel transmission with TimTX TrueShape

TimTX TrueShape is a new transmit platform introduced for the MAGNETOM Skyra. It features a new RF body coil and two independent transmitters that are fully integrated into the Tim 4G DirectRF architecture, i.e. both transmitters are situated in the TX-Box at the magnet side, directly adjacent to the receivers. While it is also possible to perform patient-specific B_1 Shimming for dedicated examinations, extensive testing has shown that the anatomy-specific B_1 Shimming (already introduced in 2007) shows comparable results to patient-specific B_1 shimming for clinical applications. The potential of this technology platform lies elsewhere – in enabling entirely new applications.
With TimTX TrueShape equipment, 'fully dynamic' parallel transmission is made available for a clinical whole-body system. It enables the fully flexible and independent switching of arbitrary RF waveforms on the two RF channels, simultaneously with arbitrary gradient shapes on 1, 2 or all 3 gradient channels (Fig. 2, bottom). By this means, it is possible to excite arbitrarily shaped volumes (instead of a 'simple slice'), or, more generally, to spatially control the magnitude as well as the phase of the excitation. The first clinical application to take advantage of this technology is 'zoomed' imaging.

syngo ZOOMit: The 'Optical Zoom' in MR imaging

It is a well-known phenomenon in MR imaging that if the field-of-view (FOV) is smaller than the object, aliasing (fold-over artifacts) will occur. This is not an issue in the readout direction, since it can be overcome by frequency oversampling 'for free', i.e. without an increase in scan time, nor a penalty in SNR. But oversampling in the phase-encoding direction comes at a cost: more phase-encoding steps directly result in longer scan times, longer echo trains, etc. These disadvantages make the use of phase oversampling unfavorable in many cases. And if phase oversampling is not possible at all (e.g. because of too-long scan times or echo trains), the only way to zoom into an image is a simple magnification – the analogy to a **digital zoom** of a camera that does not really

syngo ZOOMit offers distinct advantages:

Higher image quality:

- **Less distortion and blurring artifacts**
  For the zoomed FOV, the same spatial resolution can be achieved with shorter echo trains. This is a similar effect as (and can additionally be combined with) the echo train shortening with iPAT (then called ZOOPPA). It is especially valid for zoomed echo-planar-imaging (EPI; used for DWI and functional MRI), or similar for single shot TSE (HASTE).
- **Less motion and flow artifacts**
  Regions outside the FOV (with organs that may be moving, or vessel pulsation) are not excited, do not contribute to the MR signal, and hence reduce artifacts.
- **Increased spatial resolution in region of interest**
  Only the reduced FOV (zoomed) needs to be encoded.

Higher speed:

- **Faster scan times**
  For the zoomed FOV, the same spatial resolution can be achieved with fewer phase-encoding lines. This is a similar effect as (and can be combined with) the scan time reduction with iPAT. It is especially valid for zoomed 3D TSE (*syngo* SPACE).

increase spatial resolution. For many imaging techniques, e.g. DWI or 3D data sets, one would therefore like to simply 'zoom' into the object in the phase-encoding direction (the one that is critical). It can be seen as the MR analogy to the **optical zoom** of a camera. A smaller quadratic FOV or only a reduced FOV in phase-encoding direction ('stripe') is excited (Fig. 3). Consequently, there will be no signal from the non-excited regions and only the small stripe needs to be encoded. The encoding time can be decreased while maintaining spatial resolution, or the spatial resolution can be increased - or a combination thereof.

The Details: How does *syngo* ZOOMit work?

In conventional imaging, a slice is excited by playing out a sinc (sin(x)/x)-shaped RF pulse in the presence of a static gradient plateau. The reason for the sinc shape of the RF pulse is the fact that the Fourier transform of a sinc is a rectangle. By this means we achieve a rectangular slice profile of a defined slice thickness. For further explanation it is useful to introduce the concept of the '**excitation k-space**' [5]. Analogous to the receive k-space, 'movement' on a k-space trajectory is done with the gradients - the gradient amplitude defines the 'speed' in k-space, while the gradient slew rate defines the 'acceleration' in k-space. In a similar way as the signal is read out in receive k-space on the trajectory defined by the gradients (with multiple RF receive channels), the RF pulse is modulated during the trajectory (possibly with multiple TX channels).

For a conventional slice excitation (in z-direction), we first 'move' to +z with the z-gradient (Fig. 4, bottom left). During the plateau of the z-gradient (Fig. 4, bottom right) which 'moves' us from +z to -z, we play out the RF pulse - which consequently looks like one 'spoke' in excitation k-space, positioned at x = y = 0 (since no x- or y-gradient was used), ranging from +z to -z (due to the z-gradient plateau). This RF pulse is amplitude-modu-

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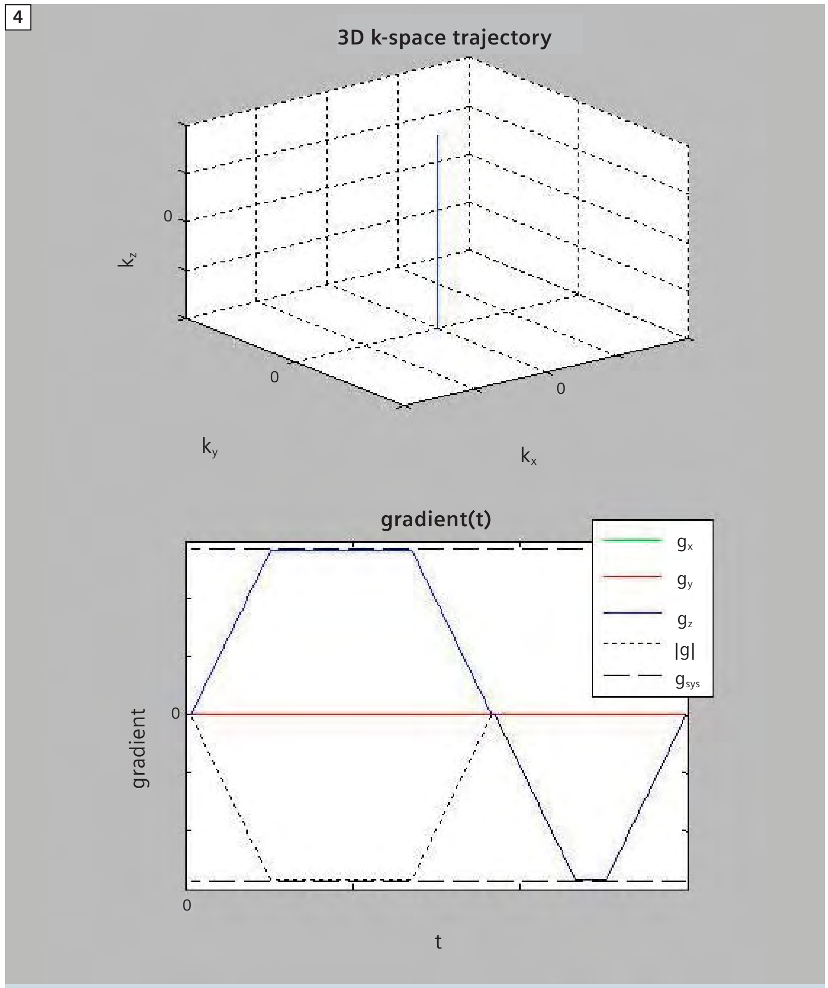

4 Conventional slice selection: One spoke, at x = y = 0, ranging from +z to -z. The RF is played out during the plateau of the z-gradient (left part of the graph).

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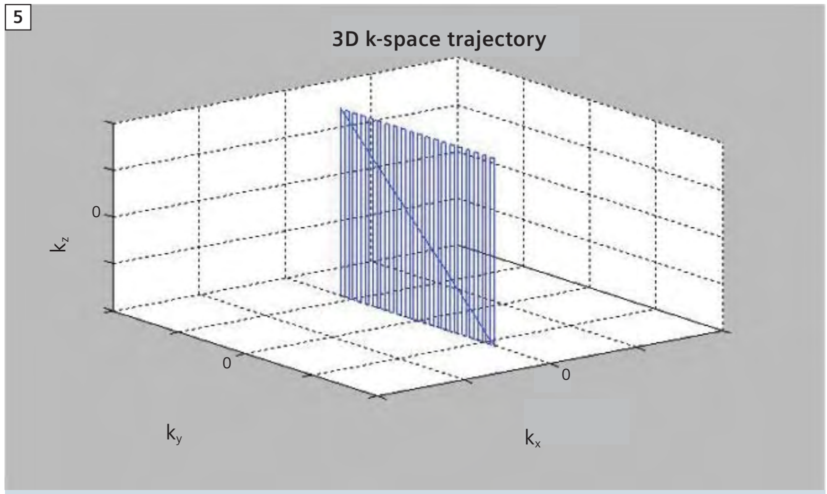

5 *syngo* ZOOMit. Multiple spokes, each of them slice-selective, aligned along the y-direction (zoom direction in this example).

lated with a sinc function. The result of this excitation is a slice with defined thickness in z-direction and 'infinite' extension in x and y.
In order to 'zoom', i.e. to reduce the extension of the slice in one direction in-plane, we need to implement an encoding in, for example, y-direction. This combination is achieved by using multiple slice-selective spokes (each of them similar to conventional slice selection). The different spokes are aligned along y-direction (the 'zoom direction') at x = 0 (x being the readout direction that is not affected). The spokes are modulated in amplitude and phase in a way that a FOV selection in y is realized. The trajectory in excitation k-space is similar to an EPI readout in receive k-space. In the analogy, the RX readout gradient pulses correspond to the TX slice-select gradients, the RX phase-encode blips correspond to the TX 'zooming' blips along y-direction, while the RX echoes correspond to the TX sinc pulses.
Figure 5 shows the 'EPI trajectory' of *syngo* ZOOMit in the excitation k-space. For the complete transmission diagram (RF and gradients, including additional pTX mechanisms), see Figure 6.

The benefits of Tim 4G for dynamic pTX

The accurate excitation of arbitrarily shaped objects places high demands on the system hardware. It is imperative that the gradients have highest fidelity for an exact definition of the excitation k-space trajectory.
Tim 4G's **DirectRF** offers full 'digital in / digital out' of the transmitter and the receiver. Both the TX-Box and the receivers are situated directly at the magnet, as close as possible to the RF body coil and the local RX coils, but far enough from the bore in order to reduce any risk of RF interferences and to minimize the bulk and weight of the coils on the patient.
A major benefit of the integration of the TX-Box and receivers are the short cables with defined cable lengths. This makes the whole architecture installation-independent (everything can be pre-tuned in the factory) and reduces potential phase shifts between the signals of the different components that might be the consequence of varying siting conditions with potentially different cable lengths.
The **Real-time Feedback Loop** for the RF data and the **Real-time Data Transfer** between the components offers several advantages, e.g. high stability of the B_1 field and very tight control between transmitter, receiver and the RF body coil. The architecture guarantees highest accuracy, synchronicity, stability and signal purity in the complete chain.

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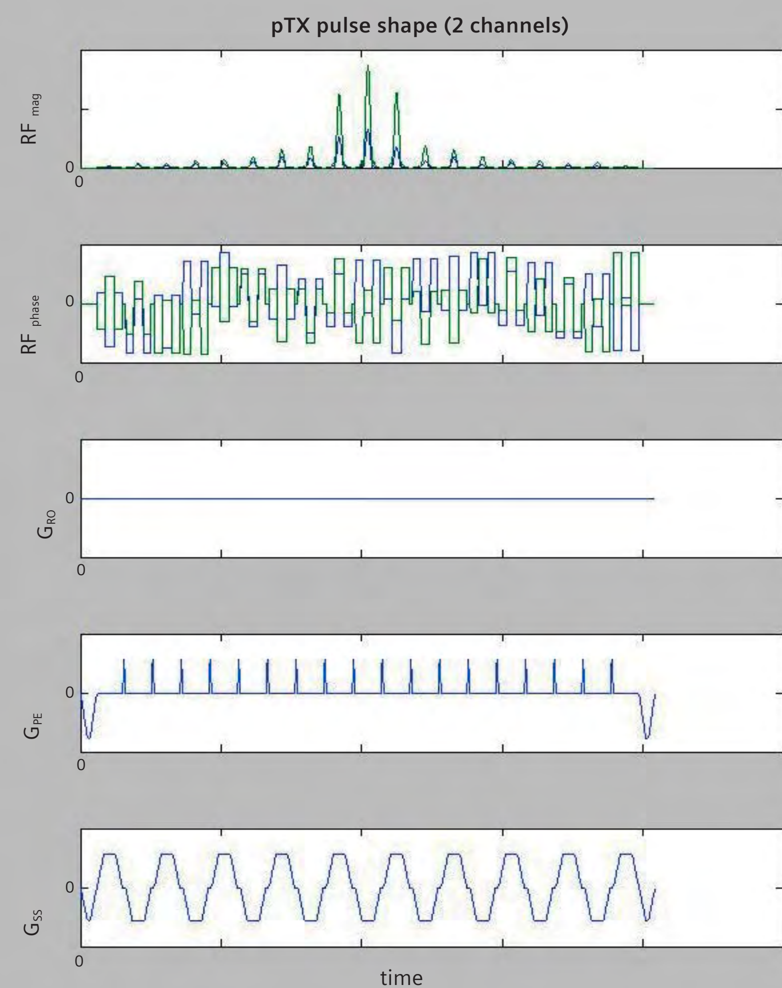


6 Typical sequence diagram of *syngo* ZOOMit. Excitation RF pulses with free modulation of amplitudes and phases on 2 TX channels, simultaneous use of two gradient channels.

Software and sequences for dynamic pTX

TimTX TrueShape incorporates new software, setting the stage for fully dynamic pTX. This includes the user interface (e.g. for graphic positioning of the zoomed FOV), new sequence parameters, and the underlying architecture and algorithms for the inline waveform calculations as well as SAR monitoring.

syngo ZOOMit is the first product application, but the TimTX TrueShape architecture is prepared for extended pTX applications in the future like variable pTX acceleration with 8+ channels or arbitrarily shaped excitation. It is also open for researchers who want to develop their own applications.
Pulse sequences allowing for zooming are (currently) derived from the EPI and the SPACE sequences. The option is completed by optimized protocols for body, cardiac, neuro and MSK imaging.

Potential advantages of dynamic pTX for zoomed imaging

While zoomed imaging can in principle also be performed with conventional scanners [6, 7], the following unique 'treasures' can utilize the benefits of dynamic parallel transmission for *syngo* ZOOMit:

Focused B_1 Shimming

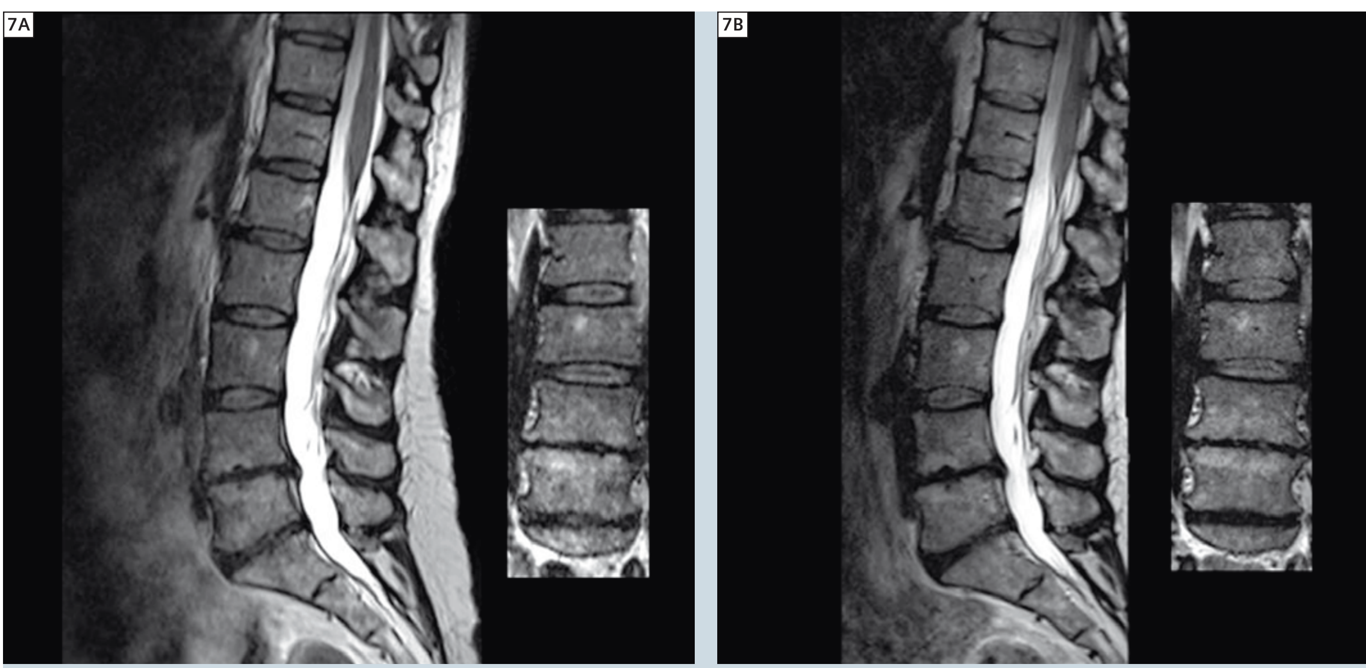
With the current product implementations in the market, a global B_1 Shimming of the whole imaging volume is performed.
syngo ZOOMit offers a local B_1 Shimming, focused on the zoomed FOV. 'Concentrating' the B_1 shim optimization on a small volume increases the accuracy of the local shim and increases B_1 homogeneity.

B_1 mitigation

In conventional imaging, the flip angle is proportional to the B_1 field. With B_1 Shimming, a higher B_1 homogeneity and, consequently, higher flip angle homogeneity can be achieved.
However, even after ('static') B_1 Shimming, B_1 homogeneity might not be perfect. B_1 mitigation is a 'dynamic' application to improve flip angle homogeneity beyond what can be achieved with B_1 Shimming alone. This is achieved with sophisticated excitation pulses, typically multiple excitation 'spokes' in the excitation k-space [8, 9].
Since *syngo* ZOOMit incorporates multiple spokes (Fig. 5). These spokes can be modified to achieve – simultaneously to the zooming – a B_1 Mitigation in the zoom direction (in addition to focused B_1 Shimming), for higher flip angle homogeneity.

B_0 compensation

The main magnetic field B_0 has imperfections/inhomogeneities. Furthermore, local magnetic field inhomogeneities are induced by the patient (susceptibility effects). B_0 homogeneity can be improved with conventional (high-order) B_0 Shimming.
B_0 compensation with dynamic pTX pulses is an additional means to compensate for remnant B_0 inhomogeneities relevant for the RF excitation. With sophisticated excitation pulses, the phase of the spins can locally be altered to counteract and compensate the phase shift due to B_0 inhomogeneities [9]. This will improve the accuracy of the zoomed FOV



7 Comparison of a conventional SPACE acquisition **(7A)** (sagittal orientation and coronal MPR shown) with a zoomed SPACE **(7B)** in the same volunteer at same resolution. By simply zooming the FOV, a reduction of scan time of one third was achieved.

(exact shape, profile steepness) and can potentially also improve fat suppression.

Transmit SENSE (TX-SENSE)

In general, the more advanced the excitation is, the more time it can take for the excitation pulse. A zoomed image (restriction in 2 dimensions, y, z) is more 'complex' than the excitation of a slice (restriction in only 1 dimension, z). Transmit SENSE, possible with multichannel TX systems, is a remedy against too-long excitation pulses. The duration of the excitation pulse can be shortened and thus also concurrent B_0 effects (that scale with the pulse duration).

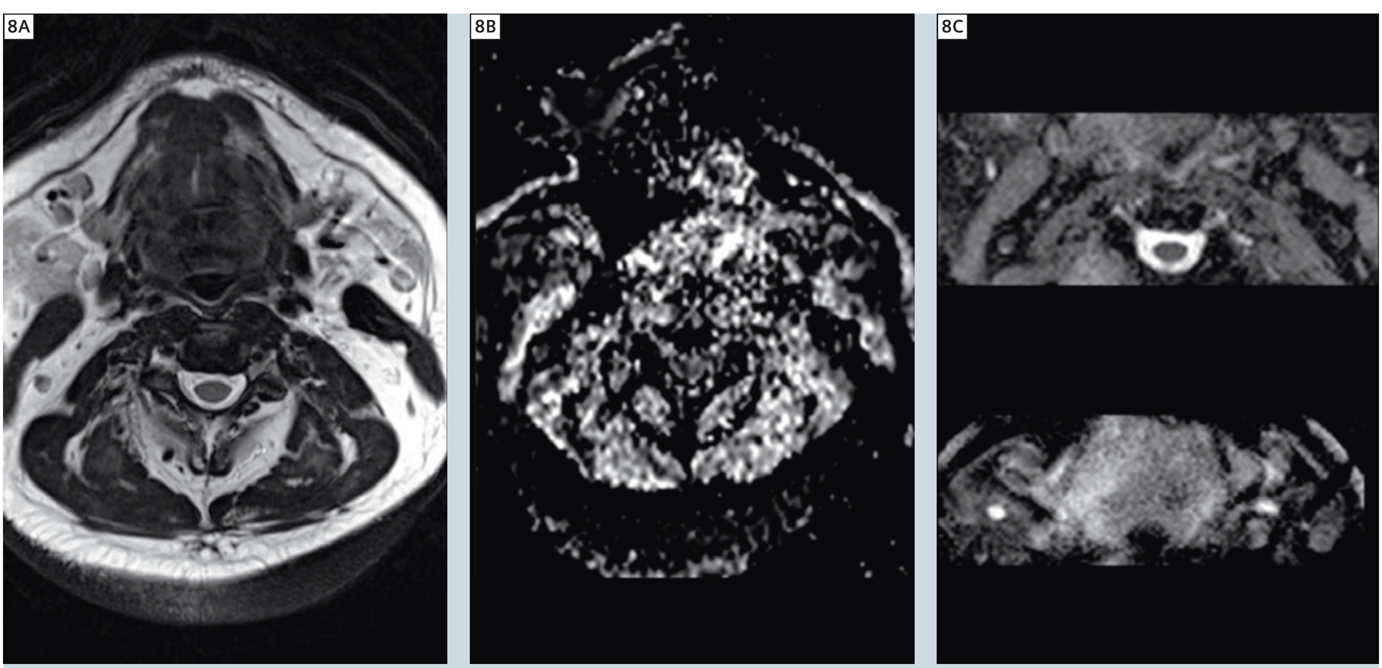
There is some similarity between Transmit SENSE and parallel imaging on the receive side. While the latter results in fewer phase-encoding steps for the same spatial resolution and, consequently, shorter scan times, Transmit SENSE results in a reduction of the length of the excitation pulse to achieve the same 'excitation quality', e.g. the steepness of the excitation profile.

Figure 6 shows the complete transmit diagram for *syngo* ZOOMit, incorporating all the 'treasures' mentioned above: RF amplitude of 2 TX channels (row 1), RF phase of 2 TX channels (row 2), readout gradient (row 3, not active during excitation), phase-encoding gradient with blips in the zoom direction (row 4), slice-select gradient (row 5). Each short RF pulse is a slice-selective sinc pulse. The envelope of all these pulses define the zoomed FOV. The envelope of the RF amplitude (row 1) would again look similar to a 'long sinc', but is modified by the effects of the said 'treasures'.

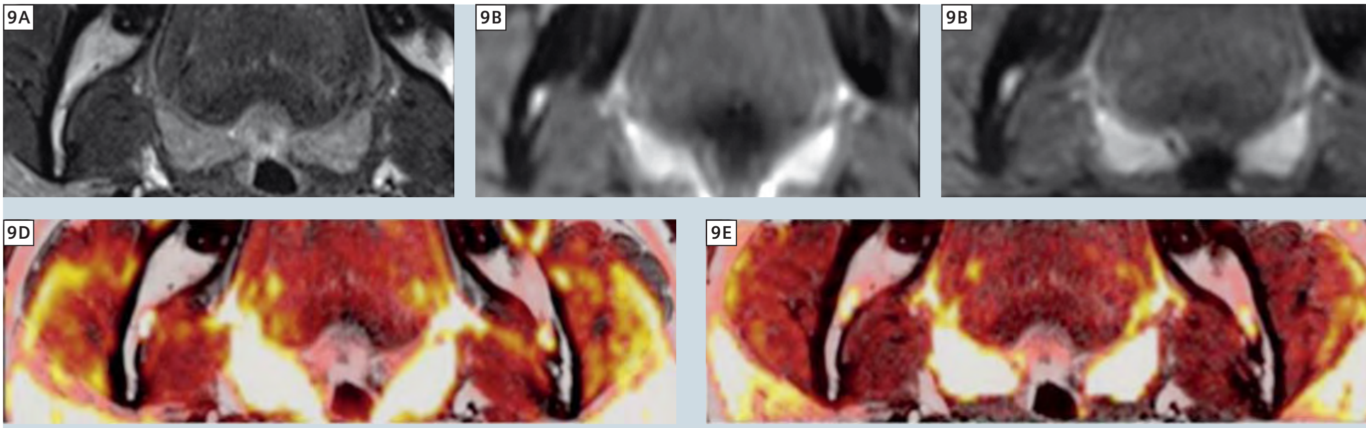
First results with *syngo* ZOOMit

At this time-point, two sequence techniques are available for *syngo* ZOOMit – EPI based imaging for DWI and fMRI, together with SPACE as a 3D TSE imaging technique.

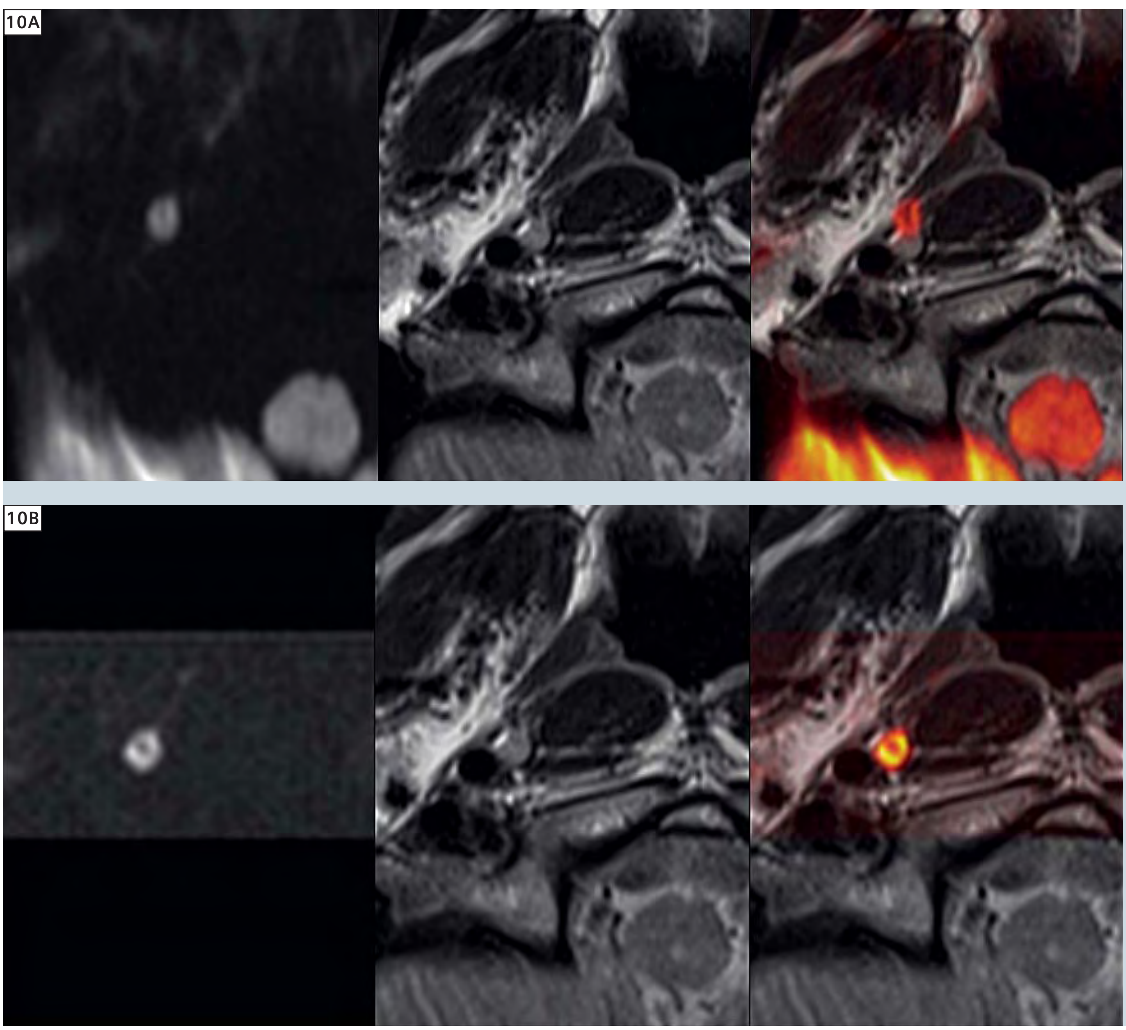
- In clinical routine, the main challenge of 3D imaging is acquisition time because of the large volume which has to be scanned to avoid aliasing. Figure 7 shows a simple comparison between a conventional and a zoomed SPACE scan. In this example the scan time was reduced by 33% from approx. 6 to 4 mins – maintaining the same excellent image quality.
- Quality of DWI is especially crucial when this technique is used for the detection of potentially smallest changes, (e.g. tumor staging in the oral cavity), in areas with high differences of susceptibility, (e.g. the spine or abdomen – bowel, pancreas, stomach), or when quantification of diffusion restriction is required. Figure 8 demonstrates the development of DWI during the past years in one of the most challenging areas – the oral cavity and neck.



8 DWI has seen tremendous evolution during the past years. To visualize this and the potential of zoomed DWI, an ADC map acquired with a standard DWI sequence and conventional parameters, as still often used in clinical routine, is compared with the corresponding ADC maps acquired with *syngo* ZOOMit DWI in the same volunteer. In addition to reduced distortion, the zoomed DWI is characterized by a higher SNR and spatial resolution as a consequence of the TE shortening enabled by parallel transmission. **(8A)** Morphology (T2w TSE) **(8B)** ADC map without optimization **(8C)** ADC maps derived from a zoomed DWI exam with parallel transmission.



9 Even compared to optimized conventional DWI protocols, zoomed imaging can be used to improve SNR and geometrical accuracy as shown in this example of the tongue base. **(9A)** T2w TSE, **(9B)** original b-value image derived from an optimized (magnified image; fusion with morphology shown in **(9D)**) **(9C)** same volunteer and comparable sequence parameters (TE, b-value) examined with zoomed DWI (fusion shown in **(9E)**).



10 High-resolution DWI of a small lymph node in the same volunteer (1.0 x 1.0 mm²in-plane resolution) **Upper row:** conventional DWI, **lower row:** zoomed DWI. Note the precise match between original b-value image (left) and anatomy (middle, right fusion) for the zoomed exam.

Conventional DWI has seen a lot of improvements and the latest developments include read-out segmented EPI (*syngo* RESOLVE). But also by comparing optimized protocols, further improvements can be achieved with zoomed imaging. Figures 9–11 show some further potential advantages.

Future developments

Zoomed imaging offers a high potential to significantly increase image quality and decrease scan times, as shown in the examples above. However, dynamic parallel transmission (TimTX TrueShape) offers a wide field of additional potential applications. Some examples:

- Creation of curved saturation pulses (e.g. along the spine) for optimal suppression of motion and flow artifacts. Such a saturation pulse would be achieved with a 2D spiral excitation.
- 3D-selective excitation, for example a cuboid or a sphere or even the exact shape of the object. This might be interesting for e.g. 3D CSI of the prostate.
  Figure 7 shows what a 3D-selective excitation with a 3D spiral looks like in excitation k-space. This does not bear much resemblance anymore to the conventional slice excitation from Figure 4.
- Vessel-selective excitation, e.g. for ASL (selective Arterial Spin Labeling).

Besides new applications, also going to a higher number of transmit channels is an interesting option, with the potential to go to higher TX-SENSE factors and shorter excitation pulses. This might be useful for multi-channel B_1 Shimming and B_1 Mitigation, especially at ultra-high field strength. Multiple channels would also facilitate the excitation of complex multi-dimensional excitation shapes.
The 1980s were the decade of the magnets, the 1990s saw a vast increase of gradient performance. While the 2000s can be seen as the decade of RF receive technology with multi-channel array coils and Parallel Imaging, the 2010s might well become the decade of RF transmit. TimTX TrueShape sets the stage for a new act in MRI.

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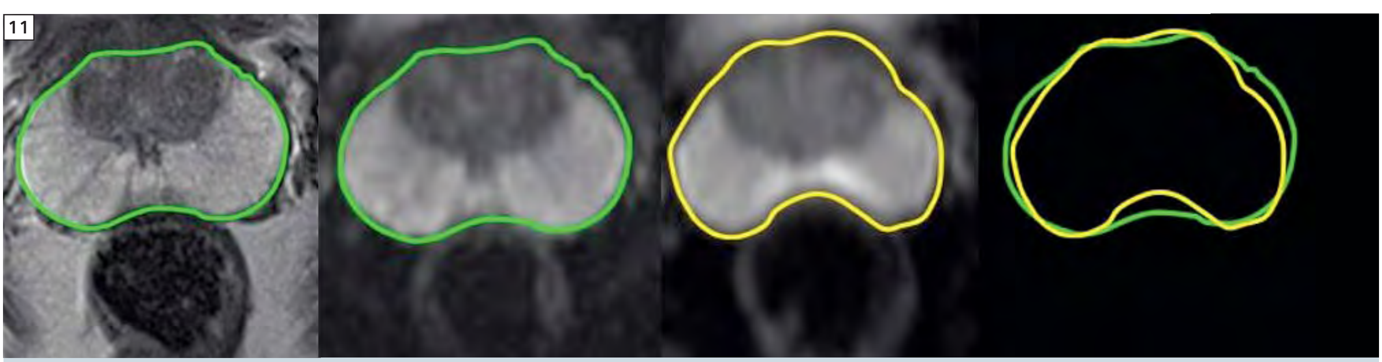

11 Distortion-free imaging with *syngo* ZOOMit of the prostate. Anatomy and high-resolution DWI show an excellent match of the outlined prostate. In contrast, conventional DWI shows distortion especially in the area of the peripheral gland – the main area for prostate cancer.

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Disclaimer:
TimTX TrueShape (with *syngo* ZOOMit) is Works in Progress. The information about this product is preliminary. The product is under development and is not commercially available in the U.S., and its future availability cannot be ensured.

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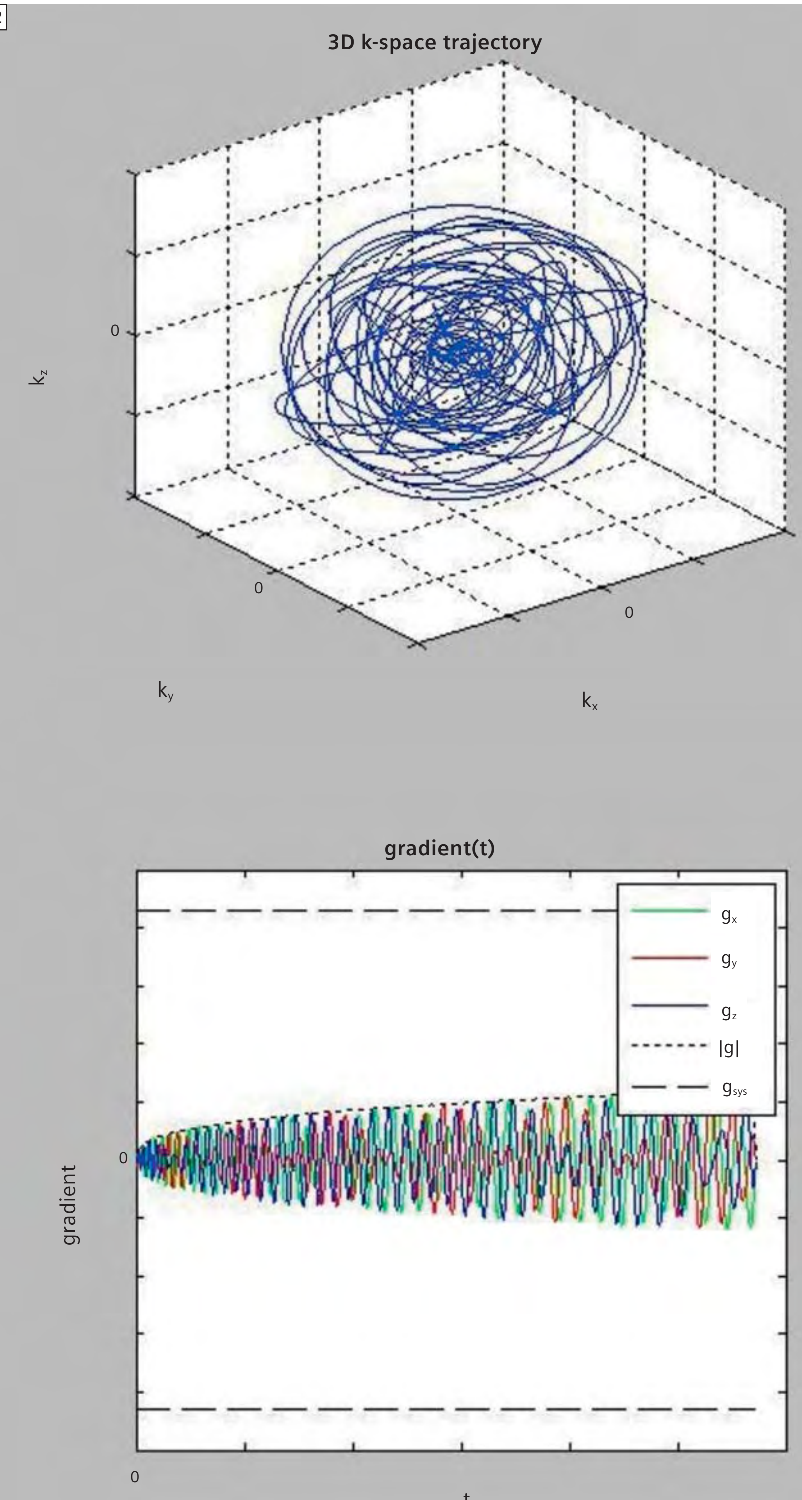

12 Example of a sequence diagram for 3D-selective excitation with a 3-dimensional spiral with simultaneous use of 2 TX channels and all 3 gradient channels.