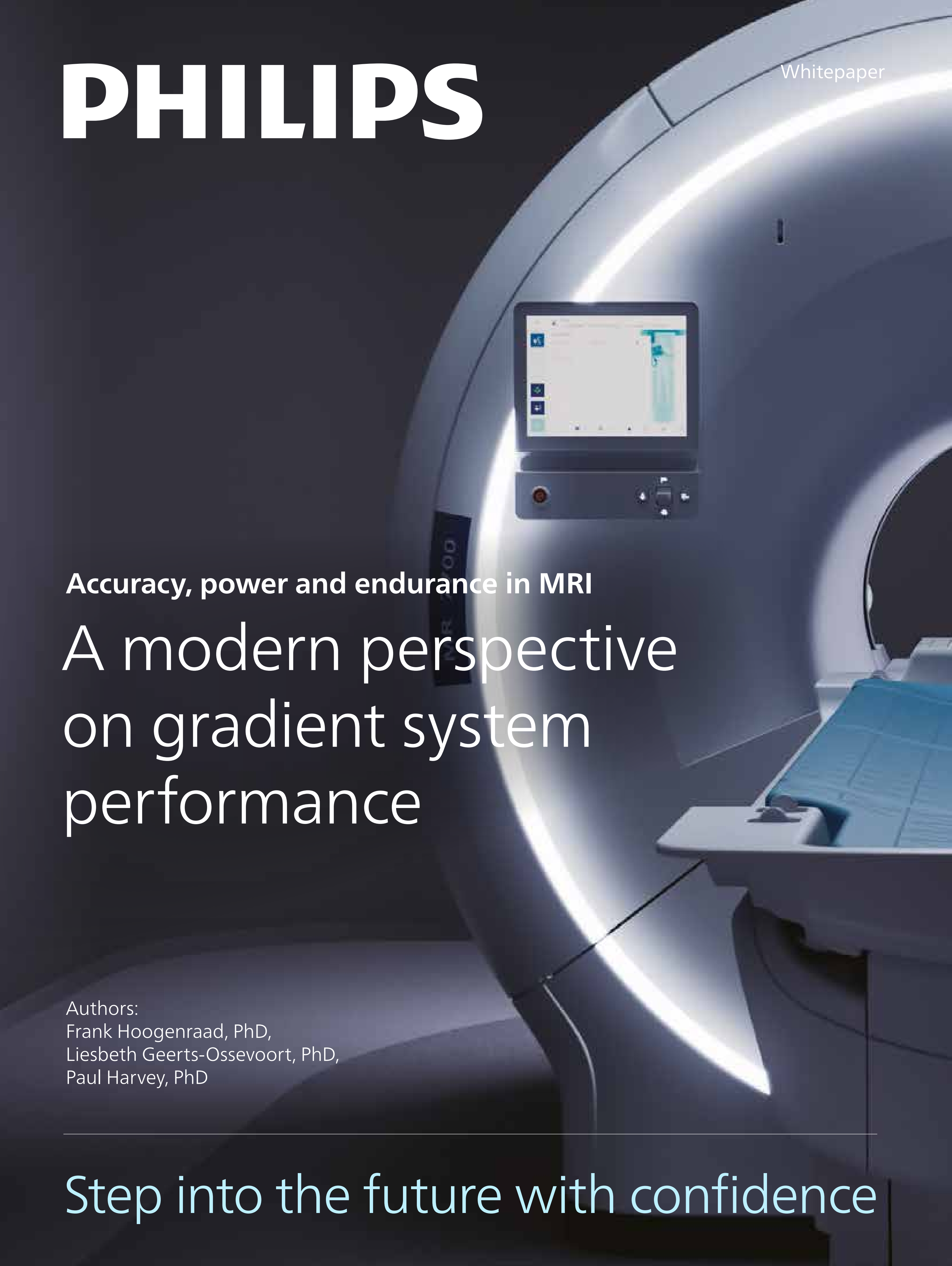

Whitepaper

Accuracy, power and endurance in MRI

A modern perspective on gradient system performance

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Step into the future with confidence

Executive summary

Philips understands the urgency to improve on diagnostic outcomes. MR imaging has, since its introduction, become essential in many diagnostic imaging procedures. The next challenges lie in bringing further diagnostic confidence, e.g. by improving spatial resolution, or improve efficiency by enabling an MRI that can endure more gradient amplitude- and slew-rate activity.

Philips has a history of more than 25 years of innovative gradient designs. This white paper explains how the Philips 3.0T MR portfolio, including Ingenia Elition X with Vega HP gradients and MR 7700 with XP gradients, bring high amplitudes and high simultaneous slew rates, combined with high gradient efficiency, gradient performance in demanding sequences while keeping a high accuracy to optimize image quality and speed.

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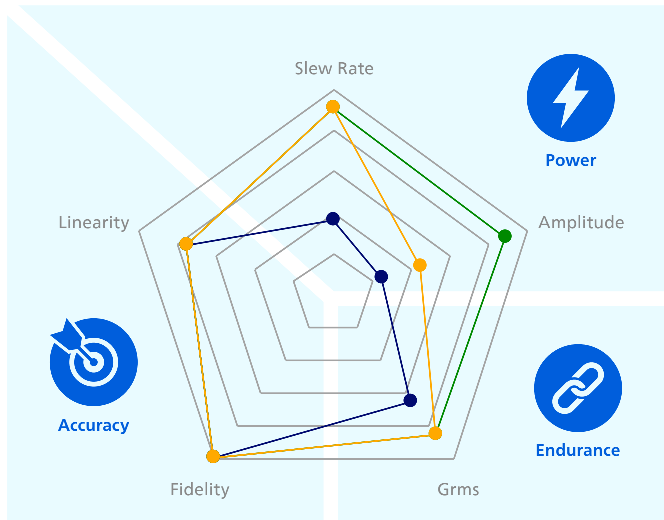
Introduction

Increasing the value of MR imaging by accelerating imaging speed is achievable through optimization of encoding strategies, smarter reconstructions and enabling accelerations by rethinking the architecture of the MR system. While there are many facets of MR systems architecture to consider, this paper focusses on the contribution that a well-designed gradient system can have to this ambition, because this will bring the performance and precision to your MR imaging.

Prominent parameters in the specification of any gradient system include linearity, amplitude, and slew rate. For many people, these represent the full extent of parameters required for MR system comparison. In practice, however other parameters and the underlying design are essential to understand the true gradient performance of a system and it's impact on image quality. The design of both the Vega HP gradient system for the Ingenia Elition X and the XP gradient system for the MR 7700 are an evolution of the Ingenia Omega HP technology [1], and are based on a holistic approach, taking into account the entire system. The design is focusing on high fidelity to achieve spatial and temporal accuracy, high gradient efficiency while keeping exceptional linearity to provide images that are correctly encoded, even at the edges of the FOV.

In a world where bigger is often considered to be better, a larger gradient amplifier (peak) power will only bring a better performance when that power is efficiently used to generate accurate gradient trajectories. None of these gradient characteristics alone can be used to claim outright superiority. It is the interplay between power, endurance and accuracy that defines a high-quality gradient system and the better definition of gradient performance therefore includes five key parameters as given in figure 1.



Elition S
MR 7700
Elition X

	Elition S	Elition X	MR 7700
Slew Rate (T/m/s)	160	220	220
Amplitude (mT/m)	36	45	64
G_{rms} (mT/m)	23	27	27
Fidelity (%)	99,97	99,97	99,97
Linearity (%)	97,6	97,6	97,6

Figure 1: Gradient performance of the Elition 3.0T platforms. For the three different performance levels the fidelity and linearity are identical. The different performance levels can be identified for the combination of gradient amplitude, gradient slew rate, and Grms. As will be explained in the forthcoming paragraphs, the advantage of the high amplitude and high Grms enable (e.g.) short-TR diffusion sequences.

Gradient system fidelity – **accuracy** first

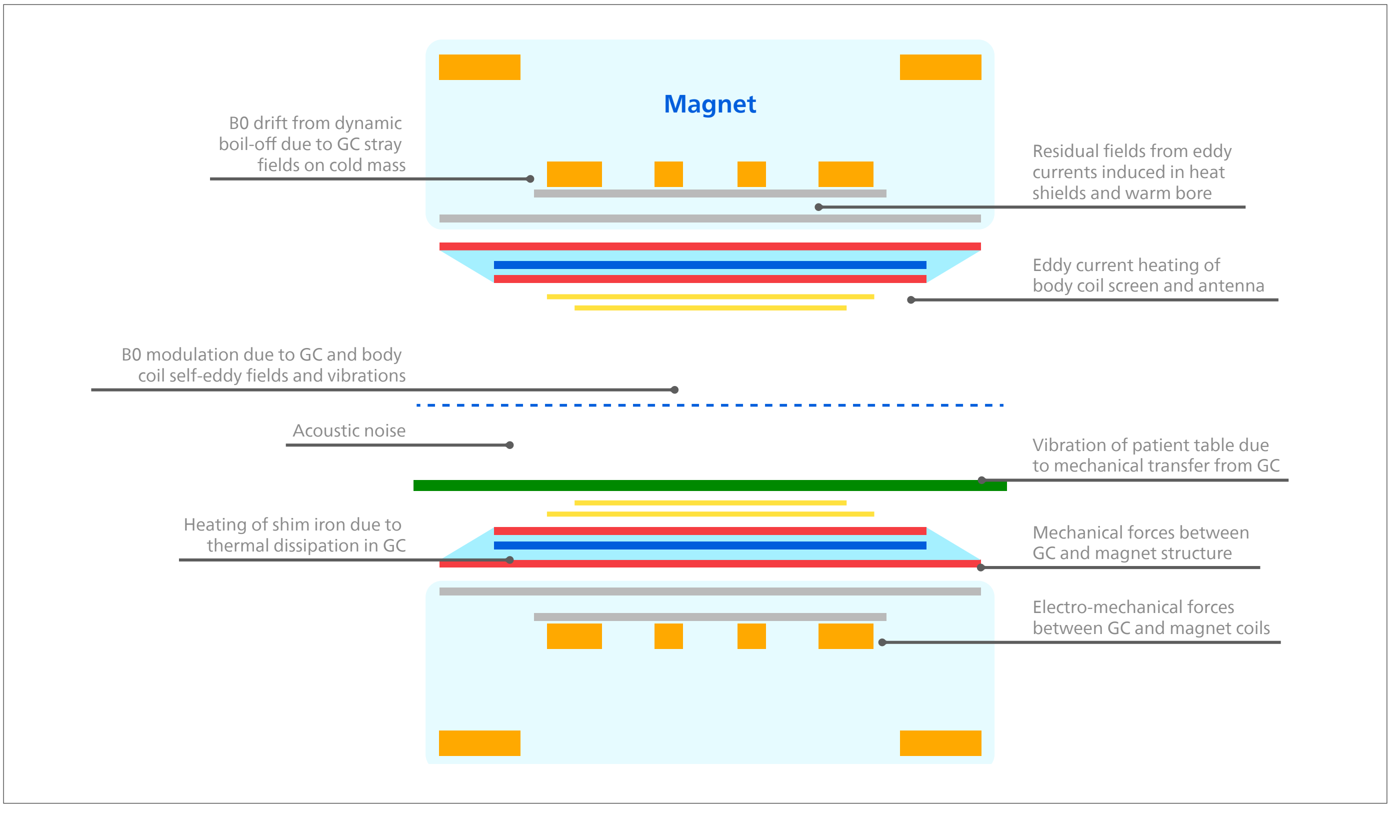
Fidelity refers to the ability to realize the prescribed gradient trajectory as accurately as possible. High levels of amplitude and slew-rate performance become irrelevant when the accuracy of the delivered gradient waveform cannot be guaranteed. Errors in this can introduce image blurring, distortions (see e.g. Figure 5 for an example of diffusion imaging) or ghosting. High fidelity is achieved because accuracy and fidelity requirements are woven into the overall design of the Ingenia Elition X and MR 7700.

Electromagnetic design focused on the FOV

Eddy current fields are time and spatially varying magnetic fields that arise from the many surrounding conductors, for example shown in figure 3, following (gradient-induced) magnetic field changes. These eddy current fields can be short lived (≈ two milliseconds) or much longer (up to 50 milliseconds or longer) depending on the entire electromagnetic configuration of an MR system. Eddy current fields can lead to degraded image quality. Moreover, eddy currents can increase energy dissipation inside the magnet cryostat that results in Helium evaporation and unwanted pressure increase. All modern MR systems have a shielded gradient coil design with two layers, separated by some radial distance (see e.g. figure 8), for each axis separately. The outer coil layer is necessary to minimize the eddy current induction in components of the magnet, such as the magnet warm bore[1] and the thermal shields behind it.

In most gradient coil design approaches, the focus is to minimize the gradient field leakage outside the outer layer. This is done in order to minimize eddy current induction in the magnet container. However, in our design approach, we do not use only this constraint. Instead, we minimize the eddy current field behavior within pre-defined control points, that lie in the FOV [3] (Figure 4). In the optimization, we take into account all MR electromagnetic properties, e.g. including the higher order shim layers, which (in the case of the Ingenia Elition X and MR 7700) lie between the inner- and outer gradient coil layers. With our constraint approach, we have a higher degree of freedom for our electromagnetic design making it possible to reach these new levels of fidelity and G_{rms}.

Figure 3: The physical and electromagnetic environment of the gradient coil (GC).



1 The magnet warm bore is the inner diameter of the 'bare' magnet, in which gradient coil and body transmit coils will be inserted.

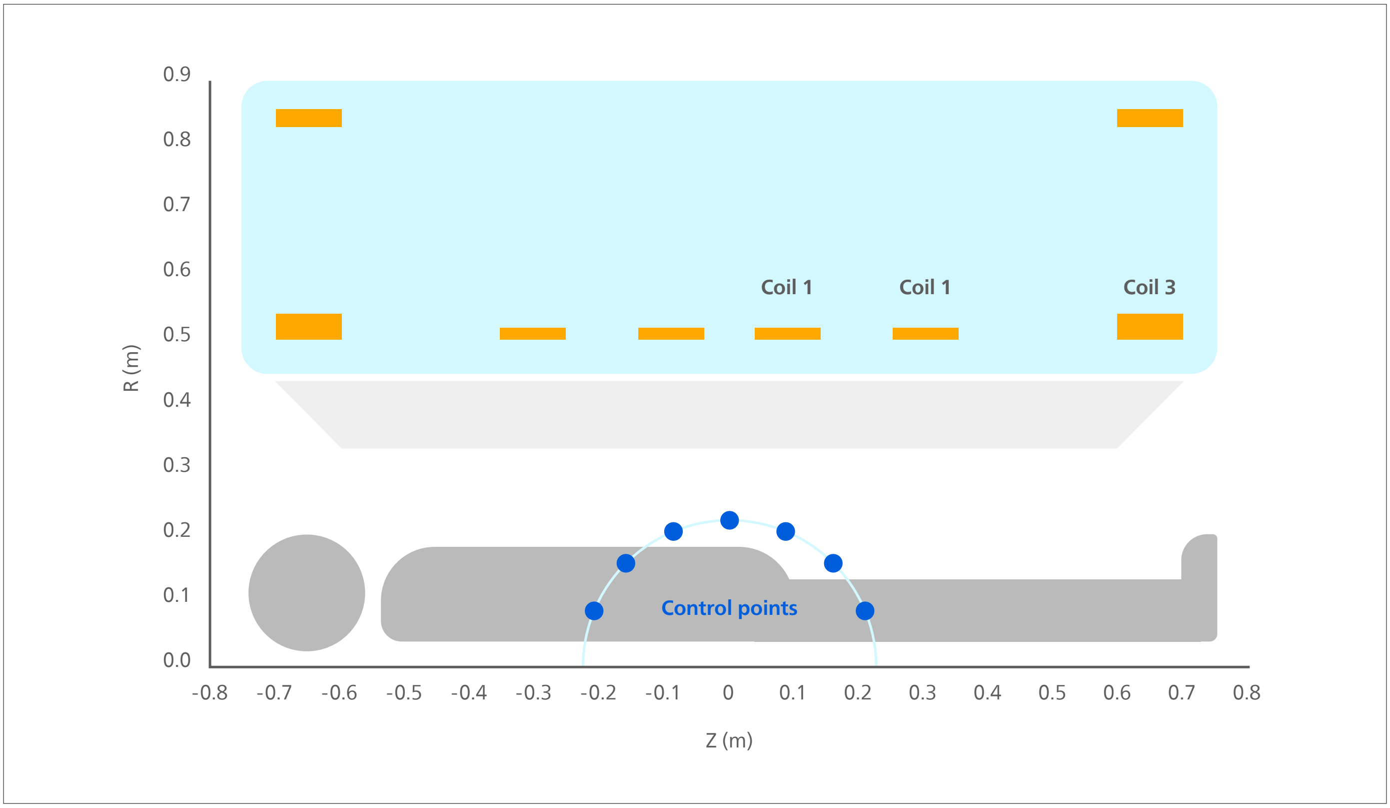


Figure 4: Design of the gradient coil in the context of the magnet. The control points define the key constraints for optimizing the design. The magnet coil elements are part of the optimization model.

Out of the box fidelity using precision manufacturing

In general, a design sets prerequisites to manufacturing accuracy. One approach to gradient coil conductor manufacturing is based on wire winding. However, this approach limits the radius with respect to the electrically conductive pathways. This is due to physical limitations of how copper wire can be bent into shape. The Ingenia Elition X Vega HP gradient coil and MR 7700 XP gradient coil both use a combination of copper sheet layers and hollow conductors that serve also as cooling elements (see Figure 8). The layered copper conductor paths are produced by high pressure water-jet manufacturing process. With this process, high granularity patterns can be realized. This offers superb flexibility with respect to the electromagnetic design.

Finally yet importantly, there is a total of 6 gradient layers, and 5 higher order shim layers, which by themselves need to be aligned properly to – again – ensure low eddy current inductions. These 11 layers are electromagnetically aligned during manufacturing.

As such, all gradient and resistive shim layer conductor sheets are positioned with sub-millimeter accuracy. This highly accurate alignment combined with the high accuracy of the water-jet cutting, enables a high out-of-the-box fidelity for every produced system.

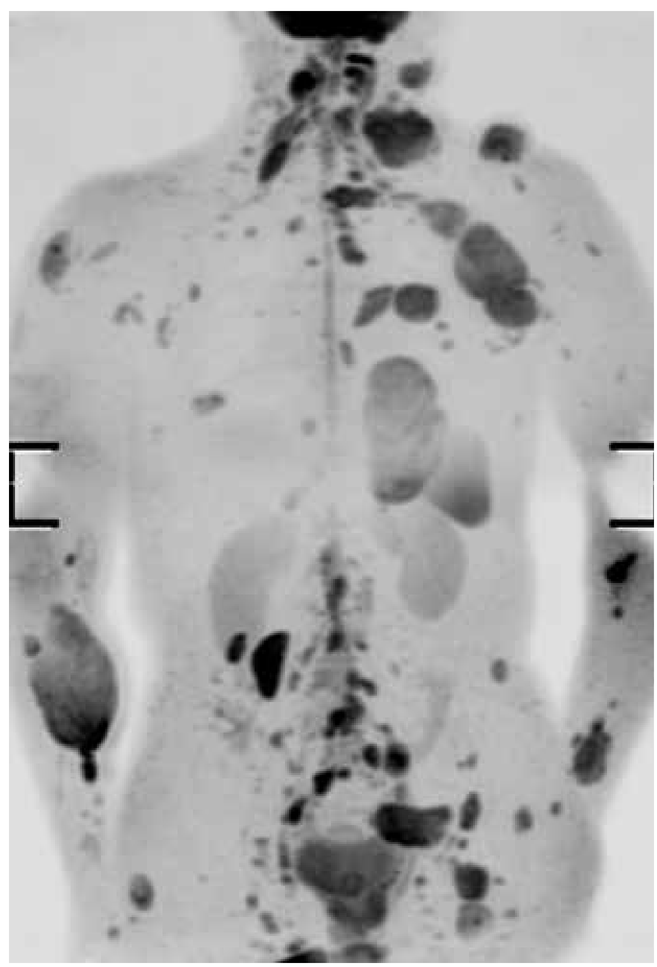
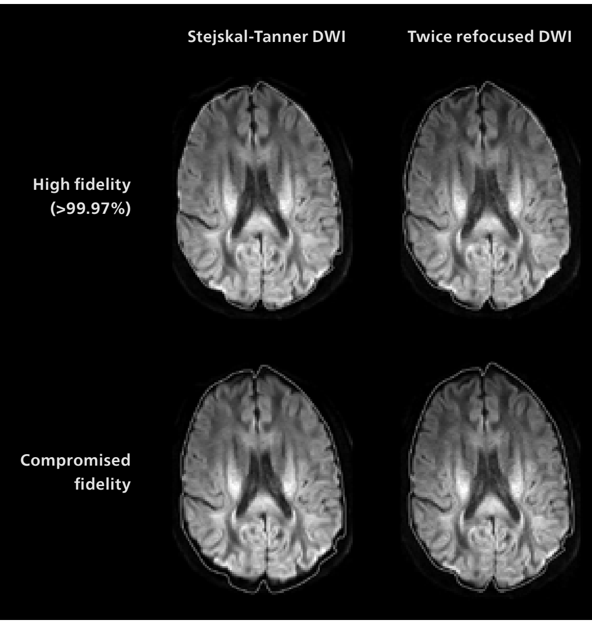


Figure 2: Total body diffusion weighted imaging using DWI XD TSE. Two stations covering a total FOV of 708x484 mm, using Compressed SENSE factor of 6 obtaining a scan-time of 4:49 minutes. The linearity of the gradient enables high conspicuity of all lesions.

Figure 5: Comparison of two different approaches to diffusion imaging at different fidelity situations. The DWI are taken on an Ingenia Elition X with a b1.000 s/mm2. The shown outline is taken from the b=0 image and projected onto the DWI. In the left column the Stjeskal-Tanner approach is shown, using a TE of 80ms.

The upper image shows no distortion while the lower image, suffers from distortions related to poor eddy current control. The column on the right shows the twice refocused DWI [10] approach, which is often run to reduce distortion in case of challenged fidelity at the cost of delayed TE (87 ms).

It can be seen that in both situations (upper-right and lower-right) no/limited distortion can be seen, which is the effect of this imaging approach, at the cost of the longer TE. It can also be seen that Stjeskal-Tanner and twice refocused approaches have similar absence of distortion in case of high fidelity (upper-left versus upper-right), where Stjeskal-Tanner has the additional benefit of lower TE, resulting in higher SNR.



High temporal control of gradient waveforms

The gradient system is not an isolated entity and we must consider the surrounding hardware in the context of the gradient hardware.

For the Ingenia Elition X and MR 7700 the dSync Data Acquisition System (DAS) is the "central nervous system" of the MRI system. It is a distributed digital system that ensures all waveforms are generated as close to the point of use as possible (see figure 6). For example, the gradient waveform timing information is communicated real-time to the gradient amplifier in digital format by optical fiber, with a timing accuracy of 100 nanoseconds. This accurate steering enables improving fidelity by using the knowledge of gradient- and magnet interactions like residual eddy field and cross-channel compensation which are subsequently incorporated into the digital demand signal. We call this digital pre-emphasis [4].

The digital pre-emphasis, combined with the mentioned electromagnetic design that focuses on low eddy current field contributions within the FOV, and with the high manufacturing accuracy out-of-the-box, reduces eddy current fields as close to zero as possible. The Ingenia Elition X and MR 7700 platforms both realize a gradient fidelity of 99.97% (further detailed on the next page), meaning that the delivered time dependent magnetic field waveform will not deviate more than 0.03% from the intended shape, across the whole performance range of the gradient system.

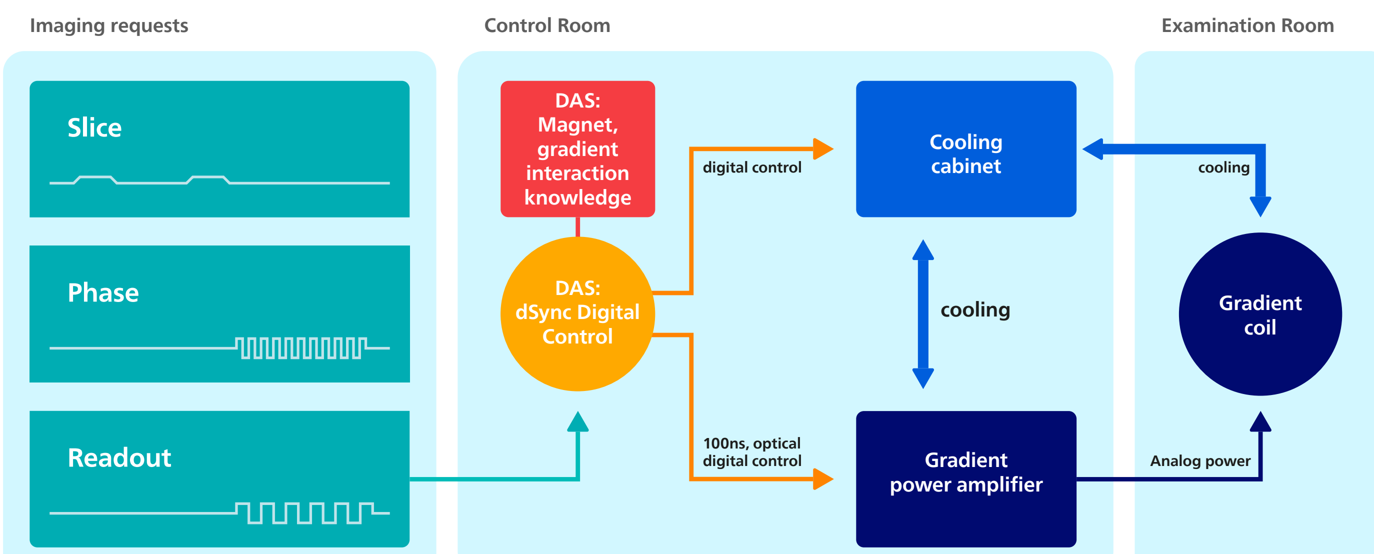


Figure 6: for the Ingenia, Ingenia Elition X and MR 7700 platforms the waveforms required are generated in the dSync DAS (distributed Data Acquisition System) in a digital, real-time system with 100ns clock time resolution. Knowledge about system interactions is used to accurately produce the requested waveforms.

Measuring fidelity and inaccuracy

We can quantify the accuracy of a gradient system by comparing the delivered gradient waveforms to the demand. There exist multiple ways to measure the actual gradient waveform. Some use the MR process itself [6] while others use independent hardware, e.g. a field camera within the MRI bore [7].

One metric of gradient system accuracy is fidelity, a definition of which is provided in references [8] and [9] and which makes use of cross-correlation analysis. In a similar and reciprocal way to an antenna, the fidelity of MR gradients is determined by a measure of similarity of these two waveforms, according the following equation:

$$\text{Fidelity} = 100\% \cdot \int_{-\infty}^{\infty} g^{*}_{nom}(t) \cdot g_{meas}(t+\tau) \cdot dt \qquad (1)$$

where g^{*}_{nom} represents the amplitude normalized complex conjugate of the nominal demand gradient waveform and g_{meas} represents the amplitude normalized measured waveform. Since waveform demand is known and the gradient waveform can be measured, it is possible to establish a value of fidelity for any time dependent gradient waveform.

Another metric of gradient system accuracy is the resulting inaccuracy defined as the standard deviation of the difference between the measured gradient waveform, g_{meas}, and the nominal demand waveform g_{nom} as used in [4]:

$$\text{Inaccuracy} = \sigma(g_{meas}(t) - g_{nom}(t)) \qquad (2)$$

With above we can quantify the fidelity for a real imaging sequence, and we will apply this to spiral imaging. A spiral gradient waveform is a demanding waveform since it uses two gradient axes simultaneously (making it even more difficult to produce an accurate waveform related to potential out-of-sync timing) and invariably involves both maximum gradient amplitude and maximum slew rate in order to achieve short readout times. Deviations from the requested waveform will quickly result in distortion (e.g. shear) and ghosting or blurring (unwanted phase accumulation).

Figure 7 shows the result of the demand- and resulting waveforms, with clear usage of maximum amplitude and slew rates. The zoomed insert shows the size of the deviation of the demand waveform for a small part of the sequence. Table 1 below summarizes the results of the measured fidelity and inaccuracy and the Ingenia Elition X compares favorably against the system used in reference [4] where a less demanding test waveform was used.

	Ingenia Elition X	Ref [4]
Ampl/slew rate of spiral waveform	45/220	20/180
Measured x- and y- fidelity	99.999%	
Measured radial axis fidelity	99.97%	
Measured inaccuracy	0.083 mT/m	0.110 mT/m

Table 1: results of fidelity- and inaccuracy for a spiral waveform, compared to similar studies on other systems.

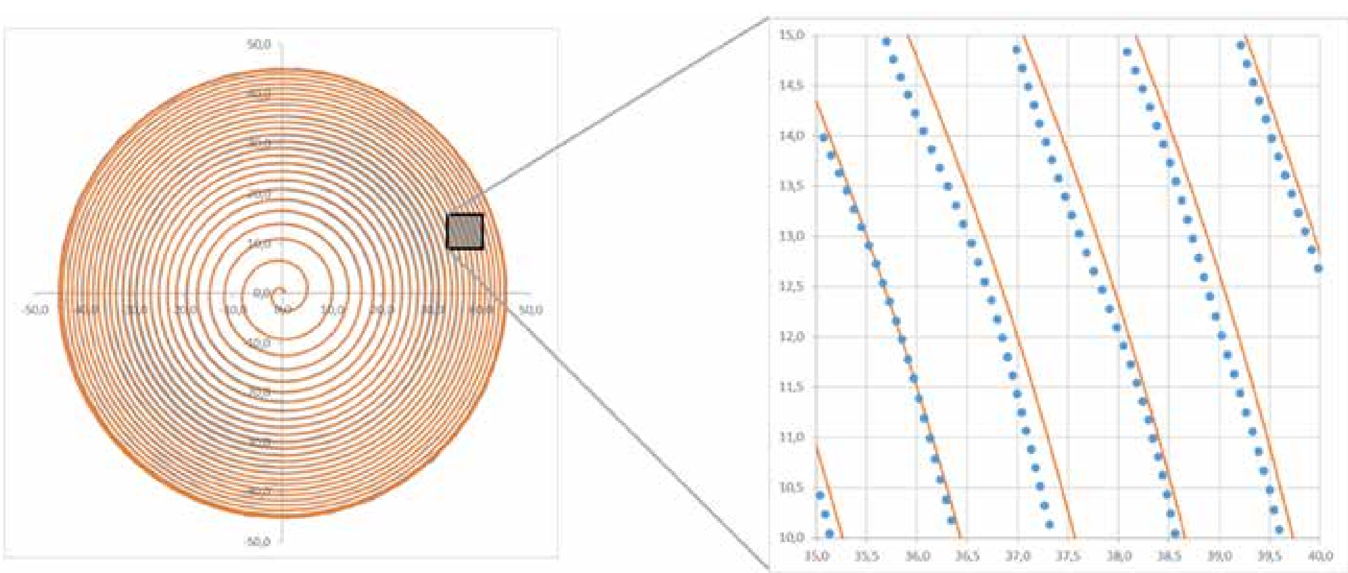


Figure 7: Visualization of the fidelity using the demand (red line) and measured (blue dots) spiral waveforms. The measurements with an independent measurement using a field camera [7]. The inset shows the deviation from demand in more detail.

Gradient **endurance** – gradient efficiency first

Gradient endurance may be best defined as the ability to drive high gradient performance for long durations. Endurance is important as it defines the ability of a system to use its maximum amplitude and slew-rate, also for longer duration sequences. For short imaging sequences, an MR system can mostly easily produce the maximum amplitude and/or slew-rate. But often, for longer sequence durations, (e.g. a 10 minute DTI acquisition), there could be limitations to the system endurance forcing it to 'slow down'. The Ingenia Elition X and MR 7700 have a very high endurance enabling it to perform high-spatial resolution imaging sequences (Figure 11), and demanding fMRI and DTI neuro-science acquisitions (Figure 12 -14). The explanation for the high endurance of the Ingenia Elition X and MR 7700 systems is because they exhibit high gradient coil efficiency.

Gradient coil efficiency is defined by the gradient amplitude, multiplied by slew rate, divided by the amount of power (current (*I*) multiplied by voltage (*U*)) needed to get to peak performance values (Eq. 5, page 12). So, the more amplitude and slew rate that can be delivered simultaneously using a given power, the more efficient the gradient subsystem is. Therefore, gradient efficiency will dictate the required power, actual consumed power, and the heat dissipated in the gradient coil.

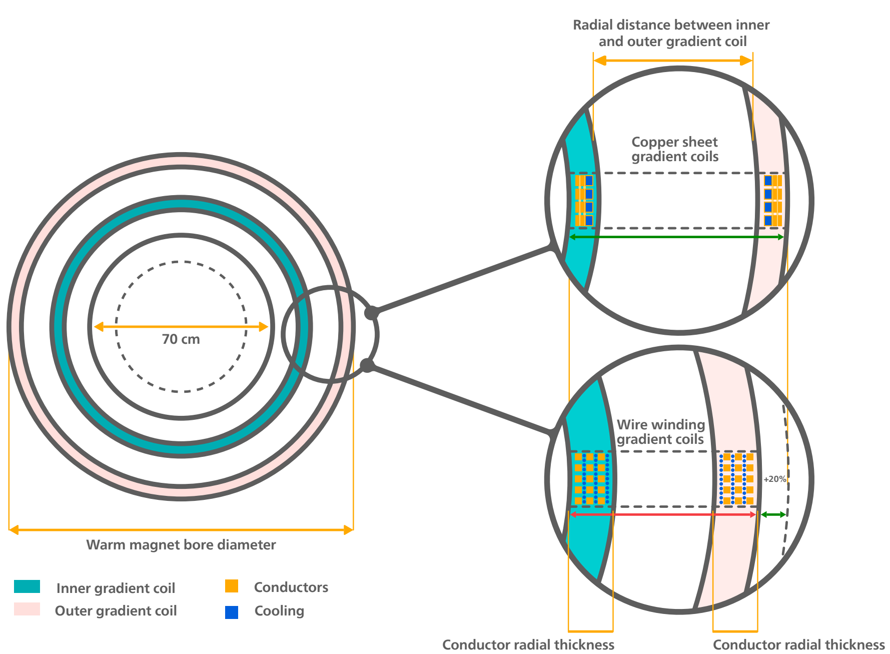
Gradient system efficiency can be achieved by creating high gradient coil sensitivity which is the amount of gradient amplitude per given current. The gradient sensitivity for the Ingenia Elition X and MR 7700 is high because of the design choices made.

High sensitivity: large distance between inner- and outer gradient coils.

The gradient coil sensitivity scales with the separation between inner and outer layers: the larger the distance, the higher the sensitivity. To exemplify, increasing the distance between inner and outer layer diameters by just 2 cm can yield a ~20% increase in gradient coil power efficiency. The inner diameter is constrained by the requested patient bore size (typically 70 cm in 3.0T MR) while the outer diameter is limited by the size of the warm bore magnet (Figure 8).

The Ingenia Elition X and MR 7700 have a large magnet warm bore to extend the distance between the inner and outer gradient coils [1]. While the larger warm magnet bore diameter may add cost to the magnet, the benefits gained through improved gradient coil efficiency lead to lower costs on gradient amplifier power and associated cooling infrastructure.

Figure 8: Shielded gradient coil design showing how the distance between inner- and outer gradient coils is determined by both magnet dimensions and gradient coil radial thickness, which in turn is determined by the gradient coil manufacturing approach.



High sensitivity: thin layer gradient coils using copper sheets
The distance between inner and outer gradient coils is further enlarged, by ensuring the gradient coil layers are thin and take up very little "radial" space. This is achieved by the copper sheet layer design described in the previous section and is visualized in Figure 8.

The described gradient coil structure enables a high gradient sensitivity, which in turn enables the high gradient efficiency. On page 12 a quantified view is given on gradient efficiency.

As high gradient efficiency implies low dissipation this reduces the demand on cooling and improves the ability to endure high average gradient amplitudes. The latter is best quantified with G_{rms}, which is defined as the root-mean-square average of all combined gradient axes in a sequence (Eq. 7, page 12).

Not every imaging sequence requires a high G_{rms} of the gradient coil as a matter of fact, today, on average up to ~90% of all scans do not require a G_{rms} higher than 17 mT/m, while only ~2% of all protocols are applying a G_{rms} higher than 25 mT/m. High gradient endurance is required specifically for sequences like diffusion, eThrive, SWIp, and mDIXON as can be seen in Figure 9.

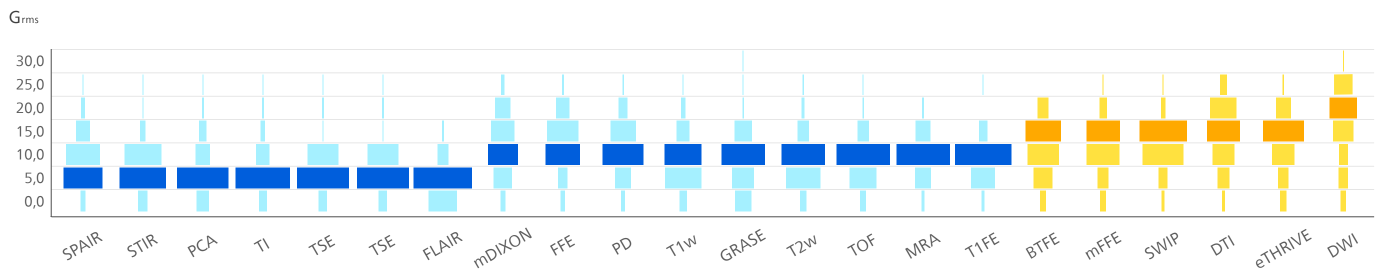


Figure 9: The average G_{rms} across a large number of exams on the Ingenia Elition X platform.

To better explain G_{rms} of an imaging sequence let us take an example from the Ingenia Elition X platform in the case of diffusion which in general puts high demands on gradient systems. In Figure 10a a simplified diffusion sequence is depicted with diffusion gradient amplitudes of 45 mT/m and EPI readout gradient amplitudes of 15 mT/m with a TR of 200 ms. This sequence yields an average gradient amplitude of 18.4 mT/m which is shown as a green dotted line. Since the average gradient amplitude does not exceed the G_{rms} of the Ingenia Elition X system, the sequence will not reach the limits of system cooling. Suppose an MR system is not able to deliver an average gradient amplitude of the given 18.4 mT/m. In this case, there are roughly two approaches by which the sequence can be modified to enable it to run:

1. Lower the applied diffusion gradient amplitude (in the example down to 20 mT/m), ensuring that the average gradient reduces to 12.8 mT/m (figure 10b). The compromise is that – because of the more time consuming bipolar diffusion weighting scheme [5] – the TE will be larger, reducing SNR.
2. Another approach is to add 'dead-time' (Figure 10c) by adding 100 ms to the TR to get to an average gradient of 15 mT/m. However, this lengthens the actual experiment, and in the case of high-end diffusion makes the length of the sequence for the patient intolerable.

Clearly, a constraint on G_{rms} means sequences need to be compromised on acquisition time, SNR or resolution. While the example used was focused on diffusion, similar challenges will occur in other sequences.

Importantly G_{rms} correlates to the heat dissipation in a gradient coil and thus tells us what the gradient system can endure.
The Ingenia Elition X system can endure gradient sequences with a G_{rms} of up to 27 mT/m, also in case of long scans. Note that one can still run imaging sequences where the G_{rms} goes beyond this value, but only for a limited amount of time before the cooling system intervenes and reigns back performance in order to protect the hardware. The sophisticated iterative scan engine of Philips MR products allows real time optimization of all scans such that they avoid exceeding the thermal limits of the hardware thereby avoiding unwanted scan aborts from component overheating.

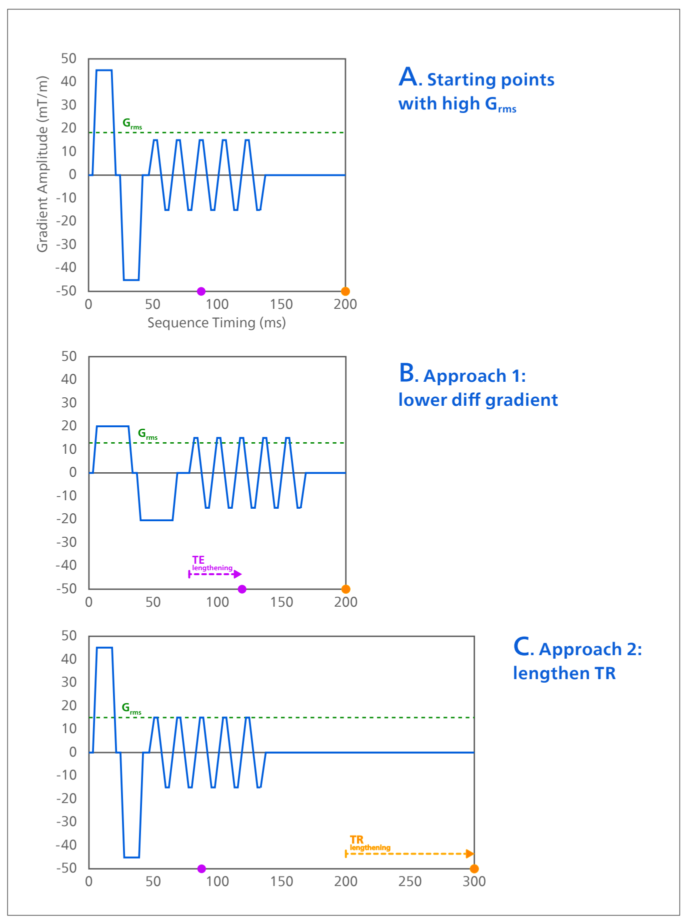
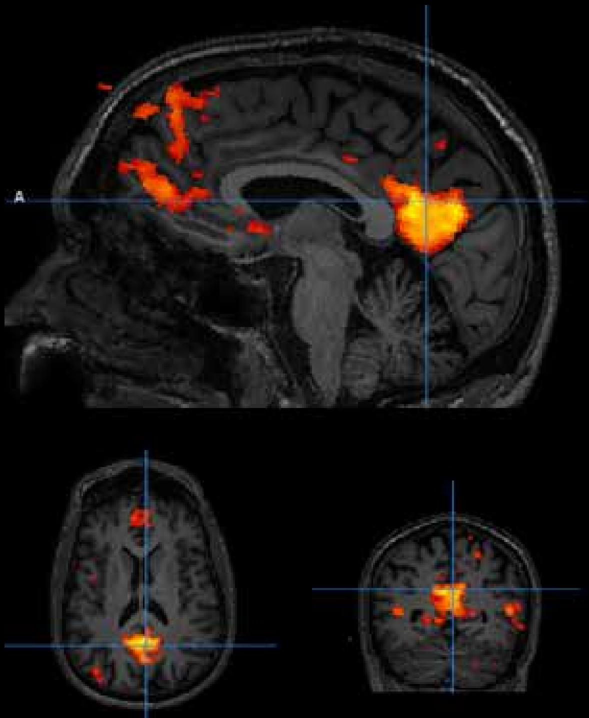


Figure 10: Illustration of the applied average gradient (green dotted line) on the Ingenia Elition X platform in different simplified diffusion sequences. In (a) we have the starting situation: an average gradient of around 18 mT/m is feasible on a system with a G_{rms} of 27 mT/m. A workaround – for a system with lower G_{rms} - is shown in (b), where a lower gradient amplitude is used at the cost of losing SNR. In (c) another workaround is used: extending TR to 300 ms reducing the average applied gradient at the cost of a longer scan duration.

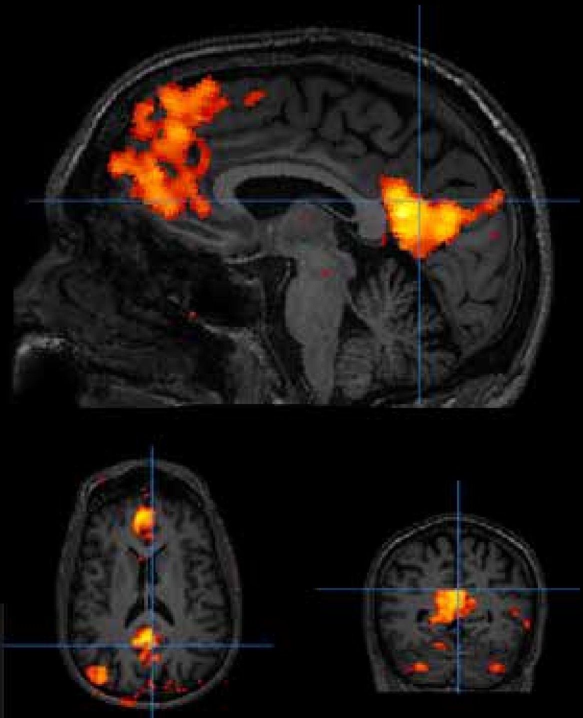
Wrist T2* mFFE, FOV 60 mm, 0.2 x 0.3 x 2.0 mm, 3:07 min, G_{rms} 22.4 mT/m

Knee PDw TSE, FOV 120 mm, 0.2 x 0.2 x 2.0 mm, 4:18 min, G_{rms} 23.2 mT/m

Figure 11: High spatial resolution imaging of the wrist (left) and knee (right) using microscopy coils. In both sequences the endurance of the gradient system is important as can be seen from the high G_{rms} at which the given acquisitions were run.



Ingenia 3.0T, 2.2 x 2.2 x 2.2 mm, 56 slices, MB SENSE 4, SENSE 1.7, TR 1.62 seconds, 5:57 min, 220 volumes



Ingenia Elition X, 2.2 x 2.2 x 2.2 mm, 56 slices, MB SENSE 4, SENSE 1.7, TR 0.88 seconds, 6:05 min, 415 volumes

Figure 12: Resting state fMRI generally requires a short TR to enable characterization of physiological noise (e.g. the heartbeat). In this comparison a much shorter TR is achieved on the Ingenia Elition X compared to the Ingenia 3.0T. Resting state fMRI results are shown, using seed-based correlation using the CONN-toolbox (https://web.conn-toolbox.org/), including re-alignment, co-registration with 3D T1w, smoothing, and denoising. The seed was placed mid-parietal to identify the default mode network. The fMRI data acquisition on the Ingenia Elition X had a much shorter TR 870 ms compared to Ingenia 3.0T 1620 ms enabling a higher temporal sampling and almost double the amount of dynamics in the overall scantime of 6 minutes.

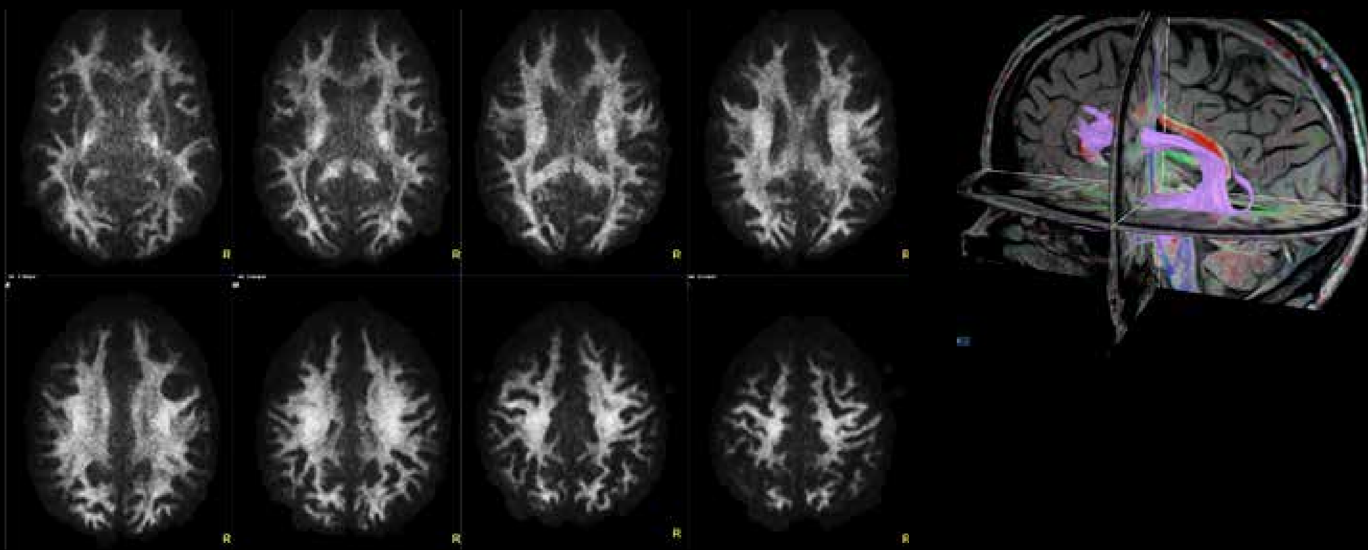


Figure 13: On the left FA maps are shown of a b10.000 DTI with a resolution of 1.2 x1.2 x 4.0 mm, 23 slices, 10 diffusion directions, and 3 averages, with a TR of 5.7 seconds, resulting in a total scan-time of 3:00 minutes. The image on the right displays the arcuate fasciculus which was analyzed using a scan with a resolution of 1.75 x 1.75 x 2.0 mm, 69 slices, 48 diffusion directions, three b-value setup: b0, b1.000, b2.000, MultiBand SENSE 3, and SENSE 1.3, TR of 3.98 seconds, resulting in a total scan time of 6:36 minutes.

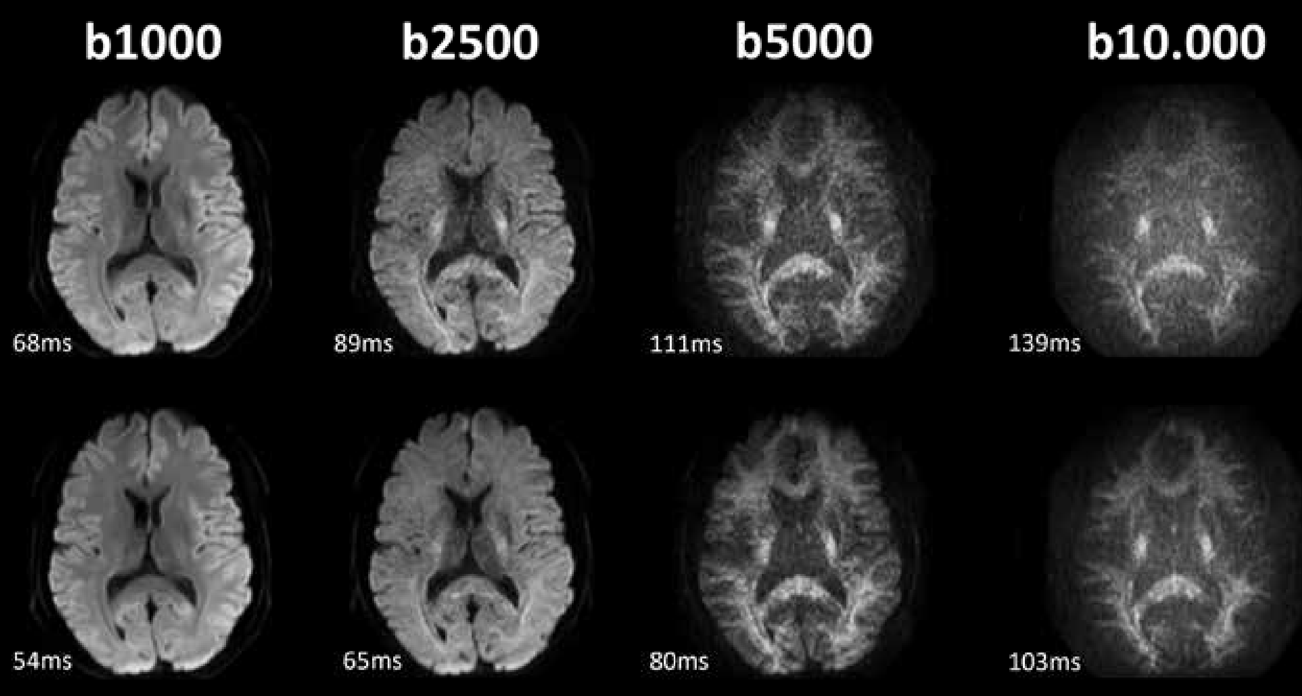


Figure 14: Examples of improved SNR in diffusion imaging for the MR 7700 compared to the Elition X as a result of the shorter echo-times. Comparison of diffusion results are shown for an image acquisition of 1.5 x 1.8 x 4.0 mm³ with 24 slices, SENSE 2 and TR of 4 seconds. Diffusion weighting from 1.000 up to 10.000 are applied for both the Elition X (upper row) as well as the MR 7700 (lower part). TE is shown in the lower-left corner for each image and a reduction in TE of 26% can be observed for the b10.000 example, improving the SNR.

Comparing gradient coil efficiencies

As described in the main text, the Ingenia Elition X Vega HP gradient coil has a very high sensitivity η, which is defined as:

$$\eta = \frac{G}{I} \tag{3}$$

The high sensitivity is achieved by a large warm bore magnet and a large radial distance between the inner- and outer gradient coils. Without providing the full derivation, we can identify the gradient coil efficiency at peak power:

$$\frac{\eta^2}{L} = \frac{G_{max} \cdot SR_{max}}{I_{max} \cdot U_{max} - I_{max}^2 \cdot R} \tag{4}$$

Where L is the gradient coil inductance, G_{max} the maximum gradient amplitude, SR_{max} the maximum slew rate, I_{max} the maximum current, U_{max} the maximum voltage and R the ohmic resistance of the gradient coil. The denominator represents the portion of the amplifier power required to drive the current against the inductance of the gradient coil while the $I^2_{max} \cdot R$ term represents the portion of the amplifier power required to overcome the electrical resistance of the gradient coil. The latter is dissipated as heat, which needs to be cooled away.

In the approximation where the ohmic resistance plays a negligible role ($I^2_{max} \cdot R \ll I_{max} \cdot U_{max}$) we can write

$$\frac{\eta^2}{L} \approx \frac{G_{max} \cdot SR_{max}}{I_{max} \cdot U_{max}} \tag{5}$$

Which can be recognized as the equation for gradient coil efficiency ε as also shown in a recent publication [2]:

$$\varepsilon = \frac{\eta^2}{L} \tag{6}$$

By doing a comparison between the Ingenia Elition X configuration and a different configuration, referred to as Configuration B, we can quickly calculate the relative efficiency based on their known performance parameters as given in the table below.

	Ingenia Elition X	Configuration B
Required power per axis	1.5MVA	2.03MVA
Gmax	45 mT/m	45 mT/m
SRmax	220 T/m/s	200 T/m/s
gradient coil efficiency ε	0.0066	0.0044

Table 2: comparison of gradient efficiency of 70cm 3.0T configurations using equation (5).

We can also use the full equation for sensitivity ε by incorporating coil resistance, but this will effect the final result by around 5% only. We find the Ingenia Elition X configuration to be around 50% more efficient. This minimizes the power that the gradient amplifier needs to supply as well as the power consumed and dissipated by the Ingenia Elition X gradient coil.

With the knowledge above, we can identify how the Ingenia Elition X Vega HP gradient system would benefit from a 2.0MVA gradient amplifier: to around 60 mT/m @ 220 T/m/s, consistent with the 50% efficiency power advantage.

	Peak power	Ampl. (mT/m) / Slew rate (T/m/s)
Elition S	0.9 MVA	36 / 160
Elition X	1.5 MVA	45 / 220
Configuration B	2.0 MVA	45 / 200
MR 7700	2.4 MVA	65 / 220

Table 3: comparison of delivered peak amplitude for the Elition platforms and Configuration B.

Time averaged gradient amplitude (Grms) and the effect towards sequence timing

The time averaged gradient amplitude, G_{rms}, throughout a sequence will determine the average power consumption as well as the heat dissipation within the gradient coil. The RMS subscript stands for "Root Mean Square" used to represent the average value of a time varying function. Typically, the peak gradient amplitude is utilized for only a limited period whereas the ability for the system to perform prolonged and continuous scanning is better characterized by its G_{rms} capability. The G_{rms} is defined as:

$$G_{rms} = \sqrt{\frac{1}{TR}\int_{t=0}^{TR}\left(G_x^2(t) + G_y^2(t) + G_z^2(t)\right) \cdot dt} \tag{7}$$

From equation 10 it can be seen that there are multiple ways to change the overall G_{rms} (and thus effects of heating) which is also visualized in Figure 10.

Gradient coil **power** – consumption

As mentioned gradient efficiency will highly influence final gradient coil power consumption. Power consumption is not only dependent on gradient coil characteristics, like the coil-inductance *L*, but depends on the waveforms in the sequence.

In order to estimate gradient coil power consumption a gradient coil can be viewed as an inductor with series resistance. When supplied with a DC current, only the resistance of the coil contributes to power dissipation. A pure inductor (i.e. no resistance) does not consume or dissipate any real power. However, gradient waveforms are generated using AC-like current and voltage waveforms. When driven with changing voltages, a back Electromagnetic Field (back-EMF) is produced by the coil due to its self-inductance. This opposes changes to the current flowing in the coil with the effect that the current waveform *I* reaches its peak some time after that of the voltage *V*. The total power consumed by a gradient coil with an AC waveform must include the real power, as characterized by the resistance, and the reactive power (accounting for the phase delay between peak voltage and peak current).

The average power consumed in an inductor carrying an AC current is given by:

$$P^{Cons} = V_{rms} \cdot I_{rms} \cdot Cos(\theta) \qquad (8)$$

Where $Cos(\theta)$ is the power factor determined by the ratio of the resistance and the impedance of the coil.

$$Cos(\theta) = \frac{R}{\sqrt{R^2 + X_L^2}} \qquad (9)$$

Where X_L is known as the reactance and is given by

$$X_L = 2 \cdot \pi \cdot f \cdot L \qquad (10)$$

The parameter *f* represents the frequency of the supplied current and, for any configuration, the inductance, *L*, can be calculated via equations (3) and (5).

To compare the actual power consumption for the two configurations identified earlier, we take a sinusoidal time varying waveform with a peak gradient amplitude of 45 mT/m. It can be shown that such a waveform has a maximum slew rate of 200 T/m/s when the sinusoidal frequency is around 707 Hz. In Table 4 below it can be seen that around 40% additional peak power is required to drive the gradient system of configuration B for such a sinusoidal waveform.

	Ingenia Elition X	Configuration B
L	440µH	540µH
XL - equation (10)	1.97Ω	2.40Ω
R	90mΩ	100mΩ, reference [2]
P^{cons}	30.6 kW[3]	42.2 Kw

Table 4: Calculation of the relative power consumption for two 3.0T configurations, for a sinusoidal waveform of 707 Hz, maximum amplitude of 45 mT/m, and maximum slew rate of 200 T/m/s.

3 Note that we use 1670 for Ingenia Elition X for this comparison A because this corresponds with a slew rate of 200 T/m/s.

Performance summary

A deeper understanding of the gradient system reveals the relationship of constraints that exist between the gradient coil, the gradient amplifier and interactions with the rest of the MR components. As a concrete example, the power consumed by a gradient system is determined mostly by the gradient coil design, and not so much by the amplifier, while peak gradient amplitude relies on both.

Amplitude and slew rate are essential in key sequences like diffusion, and some high spatial resolution imaging. However, in many other sequences other performance characteristics are equally- or more important.

Accuracy, and fidelity, determine the ability of the system to deliver gradient waveforms that are minimally affected by eddy current fields or other system imperfections. The ability to achieve high fidelity gradient waveforms strongly depends on many details of the gradient system design, manufacturing process and integration.

The gradient system efficiency, which is largely determined by gradient coil sensitivity, determines how much power is required to simultaneously achieve a specific gradient amplitude and slew rate. A high efficiency lowers the demands on the gradient amplifier power and also reduces the heat dissipation within the gradient coil. The latter in turn enables shorter TR's in gradient intense sequences (expressed by the G_{rms}) like diffusion. From a design perspective, high efficiency is typically achieved by maximizing the warm bore diameter of the magnet which allows to increase the radial distance between inner and outer gradient coil layers. The above dependencies are visualized in figure 8.

The Ingenia Elition X and MR 7700 are built to deliver on demanding imaging requirements with high amplitude and slew-rate, but also with high power efficiency. However, the most important starting point for these platforms was to ensure a high accuracy of the gradient waveform at the full FOV of 55 cm, to ensure the high image quality required at this field strength. As in any endeavor where high performance is important, accuracy should come first. High efficiency then enables best use of the available power to deliver speed and endurance.

	Influence from: **Gradient coil**	**Gradient amplifier**
Peak gradient amplitude	Determined by gradient coil efficiency, which in turn is highly dependent on gradient coil sensitivity. Gradient sensitivity in turn is defined by the design of the coil. For a given patient bore diameter mainly the radial distance between inner- and outer (shielding) gradient layers, and in turn dependent on the warm magnet bore diameter.	Constrained by peak current
Peak gradient slew rate	Determined by coil inductance	Constrained by peak voltage
Consumed power and dissipated heat	Determined by resistance and reactive power (related to coil inductance), but also dependent on the gradient efficiency as this latter ratio determines the current for a required gradient amplitude.	Constrained by peak and average power
Gradient endurance (G_{rms})	Gradient endurance is mainly determined by heat dissipation in the coil. Gradient endurance can be improved by adding cooling capacity.	
Gradient fidelity	Coil design taking into account the full environment, including internal magnet interaction. Manufacturing of a precisely defined gradient current pattern with high flexibility (small radius) of conductive pathways.	Real-time dynamic control at 100ns accuracy (e.g. ability of pre-emphasis).

Table 5: summary of relevance of gradient characteristics versus technical gradient performance parameters.

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