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The New High-Performance MR Gradient System XR 80/200.

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Answers for life.

The New, High-Performance MR Gradient System XR 80/200. Design, Benefits and Safe Operation

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Introduction

At the RSNA 2012, Siemens introduced MAGNETOM Prisma, a new 3 Tesla MR imaging (MRI) scanner. This system is designed to fit the needs of those involved primarily in research activities. The foundation of the system is a new 3T magnet, based on the proven MAGNETOM Trio. It provides the same robust base as Trio did—with high homogeneity, only now with zero helium boil-off. MAGNETOM Prisma combines Siemens' latest technological advancements in MR signal transmit and receive technologies—TimTX TrueShape and Tim 4G technology, with the latter forming the backbone of other Siemens MR scanners 1.5T MAGNETOM Aera and 3T MAGNETOM Skyra. Both technologies have shown an increase in image quality and imaging speed, proving their value in a number of clinical MRI applications [1]. On top of these components, MAGNETOM Prisma includes XR 80/200, a new, high-end gradient system that delivers high gradient amplitudes and fast switching capabilities in a combination that is currently unmatched in the market. This article is to provide insight into the evolution of the new gradient engine: a brief history of gradients in MR, the technical aspects surrounding the XR gradient engine, safety mechanisms, as well as the benefits that MR applications stand to gain from the outstanding performance.

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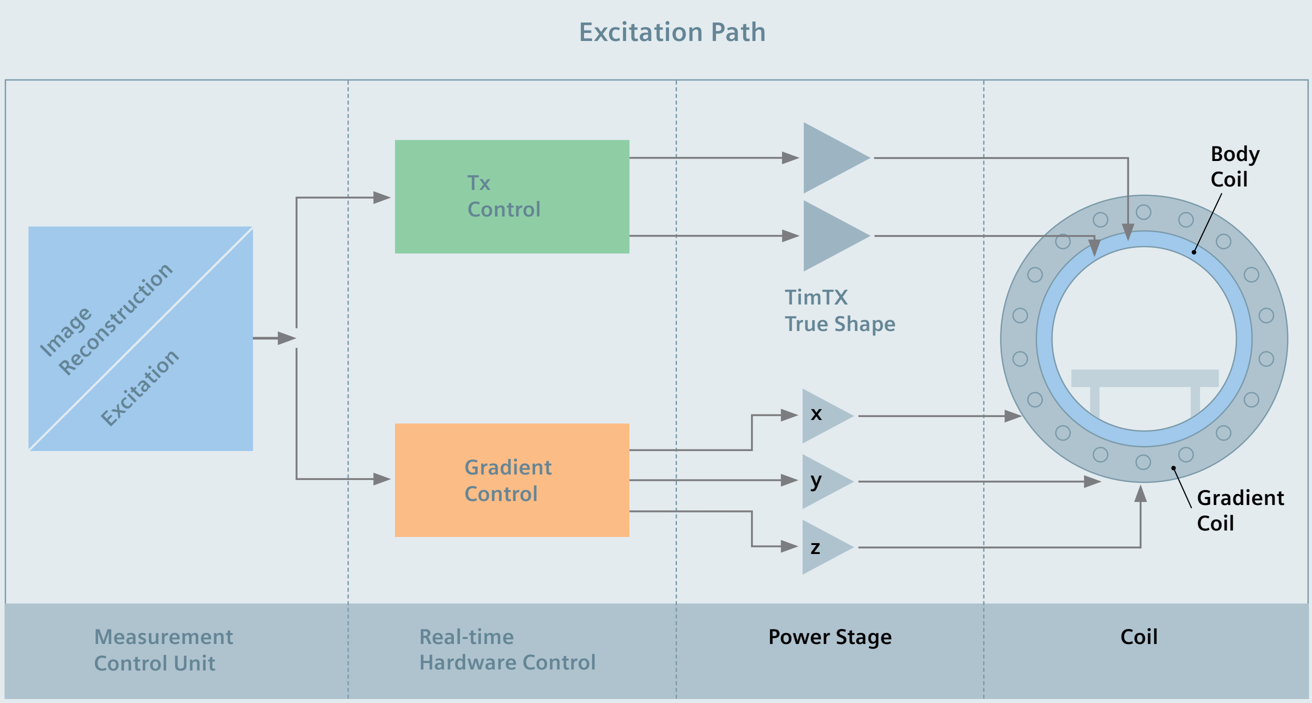


1 Excitation chain of an MR scanner.

A few words on gradients

The gradient system is one of the major sub-systems of any MR scanner. It plays a key role in the creation of the MR image by providing a means to:

1) Spatially select a region that should be imaged and

2) Encode the contents of this region.

Both selection and encoding are done by applying electric current to the gradient coil, thus creating a field slope on any one of the physical axes x, y, or z. Through precise timing of these additional fields, or gradients, a specific section of an object can be selected and then encoded. By altering the physical characteristics of the selected image region, it can be seen that the gradients have a tremendous influence on the overall quality of the acquired image.

In order to create a gradient pulse in the context of an MR measurement, a lot has to happen, and it all has to happen very fast. The gradient sub-system can be generalized as a chain of several individual units that receive data from their previous neighbor on the chain, process it, and then pass it down the chain to their next neighbor. First in this chain is the measurement control unit, which controls the entire MR pulse sequence and image reconstruction task. This unit has the task of 'ordering' not only gradient pulses, but also the necessary RF pulses and performing the reconstruction algorithms on the received MR data. The 'ordered' gradient pulse information is passed onto the next unit, the gradient control module, which works digitally and in sub-millisecond intervals, executing the desired gradient pulse forms in real-time and performing algorithms on these wave forms in order to compensate for effects such as eddy currents, delays, and other gradient-field-induced abnormalities. Next, the small-signal unit processes the digital signal further and converts it into an analog signal, to be fed into the power stage. Here, the signal is amplified and finally fed to the last member of the chain, the gradient coil, in which the rapidly flowing current creates a gradient field in the region of interest.The two main performance characteristics of any gradient sub-system are the maximum attainable amplitude (Gmax), which is measured in millitesla per meter (mT/m), and the slew rate (SR), which describes how fast a gradient can attain a desired amplitude and is measured in Tesla per meter per second (T/m/s). Ideally, the gradient sub-system is designed in a way to allow the highest amount of performance (Gmax and SR) without having to compromise one measure for the other. It is not uncommon to find clinical scanners with a Gmax anywhere from 33 mT/m to 45 mT/m, while slew rates can vary from 100 T/m/s to 200 T/m/s. To get an idea as to how gradient performance has evolved over the past 30 years: In 1983 the first super-conducting 0.35T clinical Siemens MAGNETOM system, was commissioned in St. Louis, USA and could deliver a maximum gradient amplitude of 3 mT/m and a slew rate of 3 T/m/s. Ten years later in 1993, the MAGNETOM Vision was introduced and set a new standard in gradient performance for clinical systems with a maximum amplitude of 25 mT/m and a slew rate of 42 T/m/s. Shifting to the new century, MAGNETOM Avanto, the first Tim system, was introduced in 2003 and boasted gradients with a 45 mT/m maximum amplitude and a 200 slew rate. MAGNETOM Prisma raises the gradient performance bar again, delivering maximum gradient amplitude of 80 mT/m and a slew rate of 200. In very few industries has there been such a dramatic enhancement in performance in such a short period of time. So what are the benefits of maximum amplitude and slew rate? The gradient sub-system has a direct influence on the spatial resolution and acquisition time of the MR image [4]. By increasing the performance of the gradient sub-system, you can increase the spatial resolution and decrease the acquisition time. In terms of MR images, increased gradient performance translates into more signal-to-noise (SNR), fewer distortions, higher in-plane resolution and thinner slices.

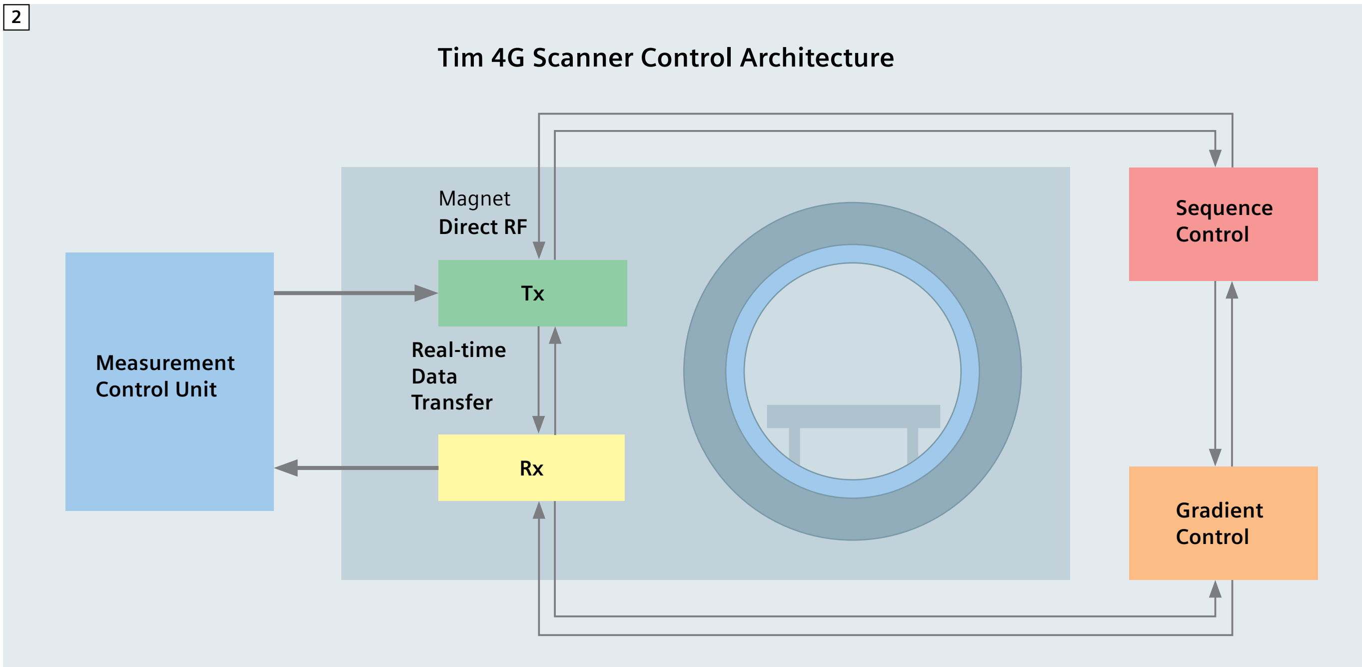
In short, better image quality. Fast imaging techniques such as echo planar imaging (EPI) and turbo spin echo (TSE) have evolved and thrived in part because of the higher performance that gradient sub-systems have been able to offer. Diffusion-weighted imaging (DWI) benefits greatly as well because there is a direct relation of the measured ADC data to the square of the diffusion gradient amplitudes. By utilizing higher gradient amplitudes, higher levels of SNR can be achieved, improving DWI and making it even more relevant in the clinical and research environments.

The technical challenge in designing a gradient system is two-fold. On one hand, the desire exists to deliver outstanding performance, which allows the user to realize the previously mentioned imaging benefits. On the other hand, guaranteeing safe operation is paramount. Striking the right balance of performance and safety is the key guiding principle in this process. The characteristics of high gradient performance and safety are largely dependent on the design of the analog components in the gradient sub-system, namely the power amplifier and gradient coil, and play a major role in achieving the desired image quality results. However, the surrounding digital infrastructure also contributes significantly. The following sections give an overview of the XR gradient system in the MAGNETOM Prisma.

The XR gradient system

The XR gradient is a key component of the technological foundation upon which the MAGNETOM Prisma is built. This gradient is capable of driving maximum amplitudes of up to 80 mT/m with a slew rate of 200 T/m/s, on each axis, simultaneously. Let's take a deeper look at these aspects as they relate to designing the XR gradient system.

The gradient coil can truly be considered a masterpiece of engineering as it brings a number of separate topics together: physics, electro-magnetics, thermodynamics, mechanics, and manufacturing. As the gradient coil is responsible for precisely encoding the physical characteristics within the measurement volume, it is imperative that particular attention be paid to its design. The XR gradient coil itself is constructed of numerous individual



2 Tim 4G control architecture.

layers of different materials, making the coil substantially thicker and, as a result, much heavier than conventional gradient coils. These layers all have a specific function—whether the conductors to create and adjust the gradient fields, the isolation layers to aid in protection from RF disturbances as well as those potentially induced by the coil itself, or the fill layers to ensure a stable and rigid coil. Additionally, a number of these layers are dedicated water-cooling. High gradient performance delivers a strong, stable and linear gradient field. A byproduct of all of this current is induced mechanical vibration [3] and thermal noise as well as heat as a result of simple electrical resistance. Through an efficient force compensation design on all axes, these vibrations can be reduced to a minimum. The sheer size of the gradient coil plays to its advantage, whilst the mass of the coil helps reduce vibrations, acoustic noise, and eddy currents further. Heat must still be dealt with as efficiently as possible. Failure to do so can result in a decrease in contrast and an increase in susceptibility artifacts due to a thermally induced drift of the B_0 frequency, a common effect with fast imaging techniques such as EPI. With this in mind, the designers of the XR gradient coil utilized a special conductive material that allows thermal energy to be transferred easily to the coolant flowing through these layers in the coil. Each cooling layer is then placed next to a coil conductor, effectively giving each axis its own individual cooling source. In total, the MAGNETOM Prisma has the ability to cool up to 60 kW, thus ensuring that any thermal energy created by the system is also removed from the system, guaranteeing stability and performance at the same time. Driving the gradient coil is a power amplifier system designed specifically to handle the needs of such a high-performance gradient system. Modular in design and small in footprint, the solid-state amplifier provides 2250 V at maximum voltage for fast switching gradients and up to 900A of peak current for high-amplitude pulses, which this amplifier can achieve simultaneously. It has the total specified power available to it at all times—there is no need to switch to a special hardware mode which would create some compromise with respect to maximum amplitude or slew rate.
It is these specific capabilities that made this amplifier so attractive for the renowned high-performance gradient system supplied by Siemens for the Human Connectome* Project (HCP). For this project, two unique MR systems were built, using this amplifier specifically for neurological research. One such system is able to deliver up to 300 mT/m of peak gradient amplitude with a slew rate of 200 T/m/s! While power is important to drive performance, it is just as important to have the ability to accurately reproduce the pulses from scan to scan. Unless the unit controlling the amplifier and thus the gradient coil is deterministic and precise in its functionality, then stable performance of the entire system cannot be guaranteed. The gradient control unit of the XR gradient system consists of a real-time digital signal-processing unit working in sub-millisecond intervals to control the entire operation of the gradient system as requested by the MR sequence. Like many other control units critical to the MR system functionality, the gradient control unit contains a vast amount of intelligence. It has the ability to influence the state of the entire MR system through an intelligent real-time data transfer,

realized via a fiber-optic communication network. Through this real-time data transfer, which is common on all Tim 4G MR scanners and made possible by DirectRF, all components that rely on data produced by the gradient system—be it for fine-tuning of the RF transmit/receive systems, patient safety data collection, or supplying algorithms with data, can receive it in real-time and integrate it into their data processing chain. The gradient control unit is part of an intelligent network and plays an integral part not only in the operation of the XR gradients, but also the entire MAGNETOM Prisma.

Safe operation

Unfortunately we cannot continuously increase the amplitudes and slew rates of our gradient pulses and reap their benefits. A rapidly changing magnetic field, which is essentially what MR gradients are meant to produce, have been shown to produce physiological effects such as peripheral nerve stimulation (PNS) in humans [2]. These effects can be uncomfortable. All MR systems with agradient system that has the potential to stimulate must provide measures in order to ensure that this does not occur. How is it possible to maximize performance of the gradient system while maintaining safe operation under these conditions? The XR gradient system, like all other Tim 4G scanners, employs several safety measures (or layers) in order to allow the user to not only maximize the performance of the gradient system, but also to ensure that the patient is in no way harmed and safe at all times. Feeding off the vast knowledge that has been accumulated through projects such as the Human Connectome* Project, the MAGNETOM Prisma employs three main layers of safety. First—the prediction. A so-called 'look-ahead', or prediction monitor examines the critical pulses in a measurement protocol and determines whether or not it will be possible to run the protocol without exceeding the stimulation limit. If it is deemed that the protocol will exceed stimulation limits, then the user is presented with a set of possibilities as to how to adjust the protocol, allowing it to run. If the MR protocol checks out OK, then it is allowed to run. Prior to the actual execution of the sequence, the look-ahead monitor sends measurement parameters to the second safety layer – the online monitor. The online monitor has the task of calculating the current stimulation level and checking this against that calculated by the prediction model. Each calculation occurs at regular sub-millisecond intervals during a running sequence. Should at any time during a running sequence the measured levels exceed the predicted levels, the measurement is stopped. Upon completion of a measurement, the prediction model obtains the final stimulation results from the online monitor and does a comparison: does the calculated prediction model stimulation correlate with the actual measured stimulation? By checking the prediction model with the online calculation, there is the added security that the hardware is performing as intended and the user is receiving the maximum performance available. If there were a discrepancy, the user would be notified of this. The third and final safety layer involves Tim 4G technology. We are not referring to the high-density coils that Tim 4G is known for, but rather the infrastructure that makes it possible to integrate them flawlessly into a complex system. Through the intense use of fiber optics that enable the DirectRF real-time data transfer, the scanner can digitally transmit large amounts of raw data over dedicated channels from the receivers located directly at the magnet, to the measurement control unit located in the equipment room in a fast and efficient manner. At the same time, other MR components, such as the transmitter or gradient controller, utilize the same fiber optic technology to communicate with each other, at all times, and in real-time. By doing so, the free exchange of information between MR-critical components is possible. Information such as measurement results, calibration data, status updates, and safety information is broadcast over this 'network' at all times to all components. Should one component in this network exhibit abnormal behavior, this is registered and the scanner is immediately brought into a safe state. Fiber optics is just part of the digital backbone that makes Tim 4G possible—not just for excellent image quality, but also for robust communication and safe operation of all components at the scanner.

Outlook

The XR 80/200 gradient system of the MAGNETOM Prisma sets a new standard in gradient performance. The design of a unique gradient coil that is easily able to handle the stresses demanded by MR researchers, coupled with a powerful amplifier and an intelligent control system make this the gradient system the perfect centerpiece for a 3T MR research platform. Ensuring safe operation is of the utmost importance, and multiple, redundant layers of safety make this possible. Many MR applications will surely benefit from the gradient power that the XR 80/200 gradient system provides. Adding the technologies TimTX TrueShape, Tim 4G, and a solid 3T magnet to the XR gradients and you get MAGNETOM Prisma—a powerful and flexible tool that will offer MR researchers innumerable possibilities.

* MAGNETOM Connectom is ongoing research. All data shown was aquired using a non-commercial system under institutional review board permission. Siemens does not intend to commercialize the system.

References

1 Boada, Shepherd, Rosenkrantz, Sigmund, Fütterer, Chandarana, Hagiwara, Rusinek, Mikheev, Bruno, Geppert, Glielmi, Pfeuffer, Parallel Transmission and its Clinical Implementation: Enabling new Clinical Imaging Paradigms, MAGNETOM Flash 2/2013, Vol. 52, pp 104ff.

2 Reily, J.P., Medical and Biological Engineering and Computing March 1989, Volume 27, Issue 2, pp 101-110.

3 Mansfield, Haywood, Coxon – Active Acoustic Control in Gradient Coils for MRI Magnetic Resonance in Medicine 46:807–818 (2001).

4 Cohen, Echo Planer Imaginer and functional MRI. Appeared in Bandetti and Moonen: Functional MRI 2000, 137-149.

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Notes

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