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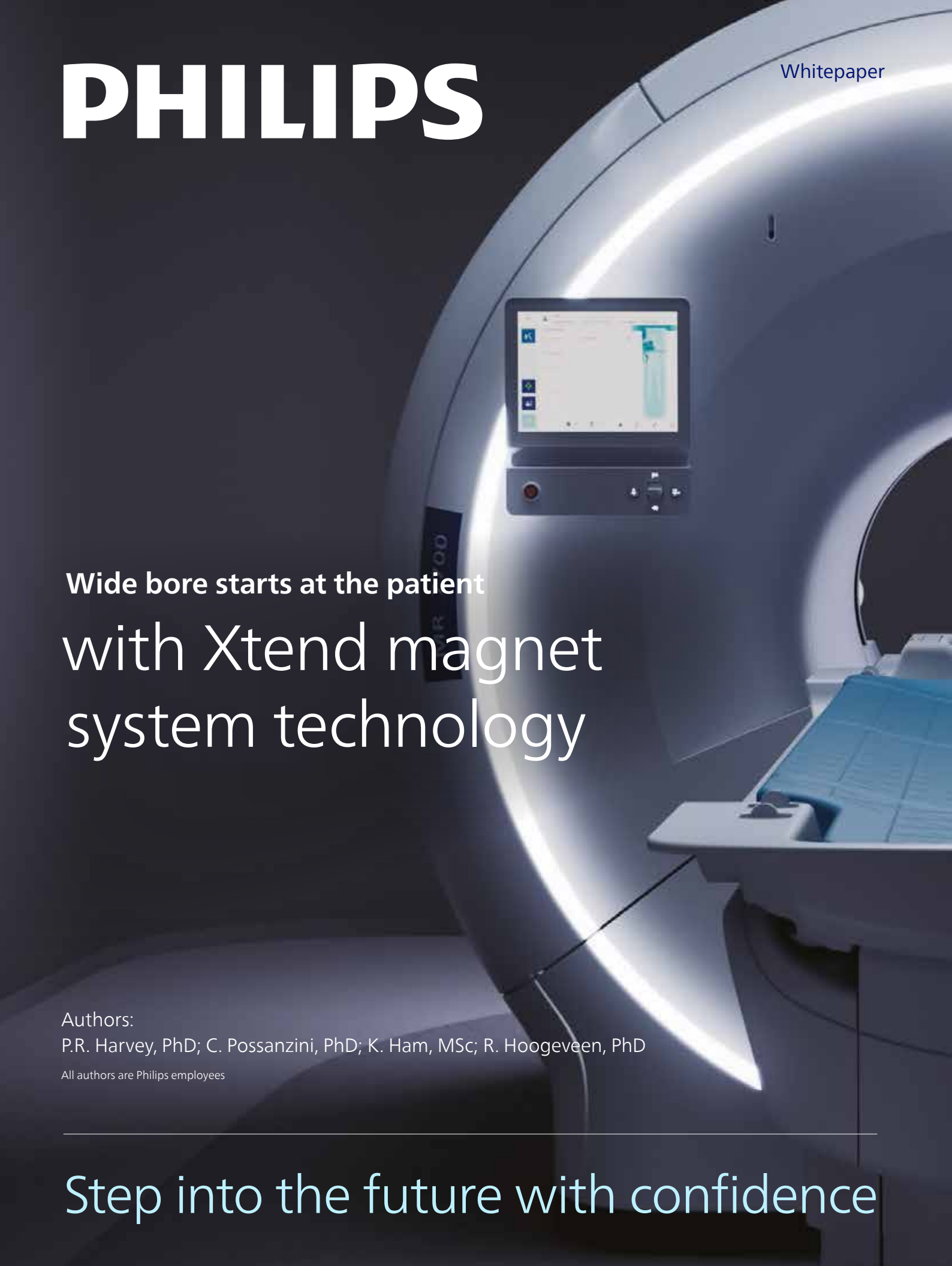
Whitepaper



Wide bore starts at the patient

with Xtend magnet system technology

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Executive summary

Wide bore MRI systems are becoming increasingly popular. Increasing the patient bore diameter from 60 to 70 centimeters has the potential to significantly affect the efficiency of various key components in the system. For example, the sensitivity of a gradient coil scales with its radius to the fifth power! To maintain excellent levels of clinical performance at the larger patient bore diameter, extensive technological innovation and system re-design is required.

The Xtend system design philosophy

What is the fundamental difference between the Xtend system design philosophy and that of other wide bore systems?

In 2004, the first wide bore systems began appearing in the marketplace. Those systems may have provided a wide patient bore, but they were limited by the technology available at that time. As a result, they made significant sacrifices in magnet homogeneity and gradient performance, including an increased specific absorption rate (SAR) and a poorer signal-to-noise ratio (SNR). The consequence of these compromises meant that, while the systems could physically accommodate larger patients, they could not scan a large field-of-view (FOV). When the FOV is compromised, some anatomy simply cannot be accommodated and multiple stations are required, thereby increasing the time the patient stays in the system.

To create a wide bore MRI system with outstanding performance requires attention to various aspects of the system design as well as a number of technological innovations. Philips Ingenia systems with Xtend magnet system technology are designed, not simply to avoid compromises, but to surpass the performance of previous generations of clinical MRI systems. In this paper we shall explain aspects of the design philosophy and technological innovations that allow improved clinical MRI capabilities.
A key aspect here is the wider patient bore. In particular we will answer the following questions:

- What is the fundamental difference between the Xtend design philosophy and that of other wide bore systems?
- Which innovations were made to address the higher power demands and the consequences for SAR and SNR resulting from the wider patient bore?
- Which unique features of the Ingenia design improve clinical performance?

Conclusion

The Xtend system design approach to wide bore begins with the patient and designs the system components outwards. This achieves an efficient balance between FOV, body coil SNR, and gradient system duty cycle, leading to improved clinical performance at low running costs.

How does innovation in the magnet, radio frequency (RF), and gradient system technologies translate into outstanding clinical performance?

There are various approaches to realizing an MRI system with a wide patient bore (Figure 1). One approach is to design from the magnet inwards. That means starting with a conventional magnet design, retain the physical dimensions of the magnet, and squeeze the radial dimensions of the gradient coil and system body coil. The consequence of this approach is demonstrated very clearly in the first wide bore systems. Squeezing the radial thickness of the gradient and system body coil reduces their efficiency. In the case of the gradient coil, maintaining the performance requires a more powerful gradient amplifier. However, driving the higher power into the smaller physical space between the magnet and system body coil requires significant additional cooling capacity. Consequently, the system costs increase dramatically while system duty cycle suffers. This means the previous generation of wide bore systems is potentially limited in terms of the gradient performance that can be used clinically. Squeezing the thickness of the system body coil also has a negative impact on its efficiency which affects both signal-to-noise ratio (SNR) and transmit field amplitude (B1+). While the transmit field amplitude can be restored using more powerful RF amplifiers, the SNR cannot.

The Ingenia design with Xtend technology is fundamentally different from that of other wide bore systems. It begins with the patient and works outwards. Each component has been designed to match or exceed the equivalent performance of a standard bore MRI system while reducing power and cooling demands. In contrast to other approaches to wide bore system design, the Xtend approach aims to provide higher performance through the favorable balance between FOV, body coil SNR, and gradient system duty cycle. Xtend technology represents one of the innovations required to realize a wide bore system with improved clinical performance at low running costs.

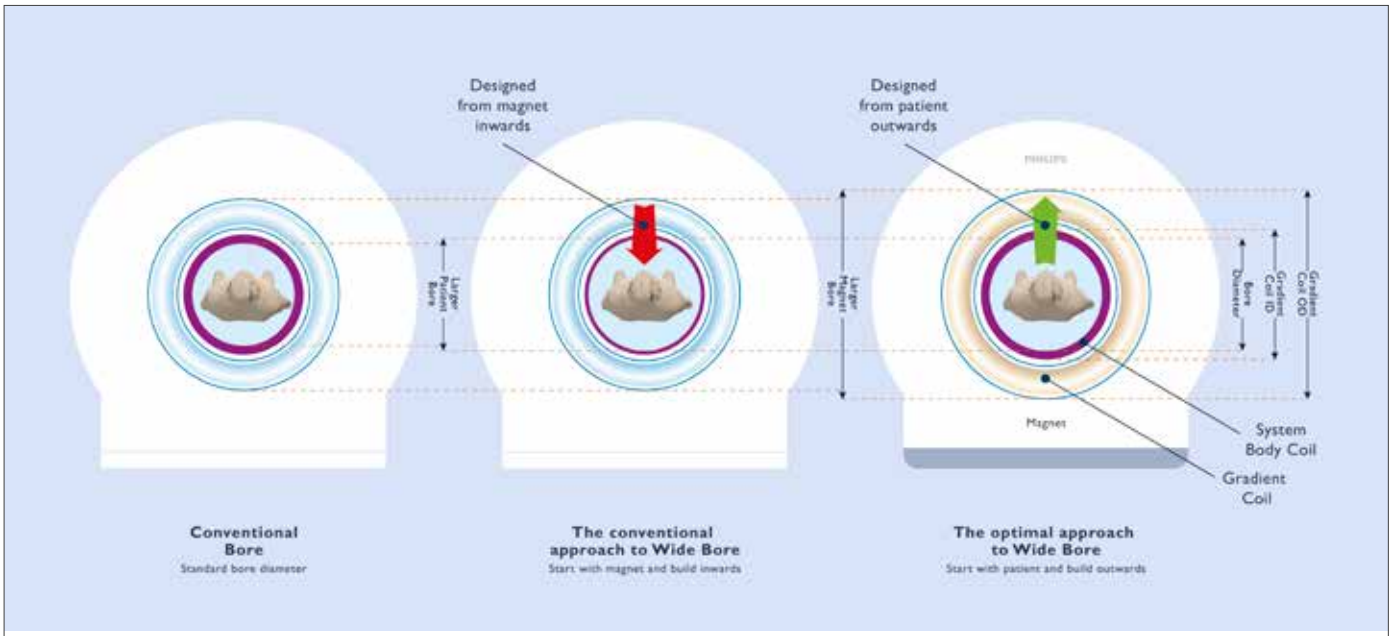


Figure 1: (left) Conventional 60 cm bore. (center) Conventional approach to wide bore design. (right) Xtend wide bore design.

The Xtend RF system: multi-channel dStream body coil

How does Xtend address the higher power demands and the potential adverse effects on SAR and SNR resulting from the wider patient bore?

Efficient and effective performance of the system's integrated body coil depends on several parameters: the inner diameter of the coil, the outer diameter of its associated screen, and the overall length. The inner diameter determines part of the efficiency (in a similar way to a gradient coil) while the radial distance from coil to RF screen has a large influence on coil sensitivity, power efficiency, and SNR. It is clear that the inner diameter will be determined by the patient bore, leaving two parameters which can be technologically innovated to help improve efficiency and performance: the distances between the inner diameter of the gradient coil and between the RF screen and the coil length.

Xtend dStream body coil: balanced design

In a typical MRI system, the system's body coil is permanently fixed between the tube of the patient bore and the inner diameter of the gradient coil. The system's body coil operates at RF frequencies and is not immediately electromagnetically compatible with the environment of the gradient coil. Therefore, it is usual to place a cylindrical RF screen between the body coil antenna and the gradient coil. The choice of radial distance between body coil antenna and RF screen has a significant impact on the sensitivity of the body coil, both in terms of transmit efficiency (RF power demand) and receive sensitivity (SNR).

The ideal situation would be to increase the distance between the antenna and RF screen. This, however, introduces significant additional space which must be taken from either the patient bore diameter, thereby reducing the bore size, or from the gradient coil and magnet diameter. Making the antenna-to-screen distance too small has the impact of reducing coil sensitivity, increasing dissipation (heating), and increasing global and local SAR. Figure 2 illustrates the relative properties of the system body coil as a function of antenna to RF screen separation. The values are derived from electromagnetic field simulations for various antenna and RF screen configurations.
In the theoretical situation where there is no separation between the antenna and the screen, the coil would use infinite power and generate no field (not shown).

Ingenia 3.0T with MultiTransmit and Xtend body coil: allows two station total spine acquisitions without patient positioning or surface coil handling.

The thinner the coil (left hand side of Figure 2) the less sensitive it becomes and, as a consequence, significantly more power input is required to generate a B1 field. The relative inefficiency of such a thin coil drives up the currents in the antenna which leads to higher voltages (E fields) and higher heat dissipation within the coil. When this is the case, it becomes a problem to place the patient close to the bore tube due to increased local SAR and heating. Signal-to-noise is also compromised in such a thin coil. Moving completely to the right hand side of Figure 2 seems to be the answer for most properties. However, it is impractical because, for a desired patient bore diameter, it would drive up the inner diameter of the gradient coil. This would also necessitate the use of a thinner gradient coil design which would be less efficient for the same physical reasons (see below).

Clearly, it is important to make a balanced selection. For the Ingenia system, this is represented in the central area of Figure 2. It was arrived at by considering all of the relevant properties in components of the Xtend chain at the same time: system body coil, RF amplifier, gradient coil, gradient amplifier, magnet, etc.

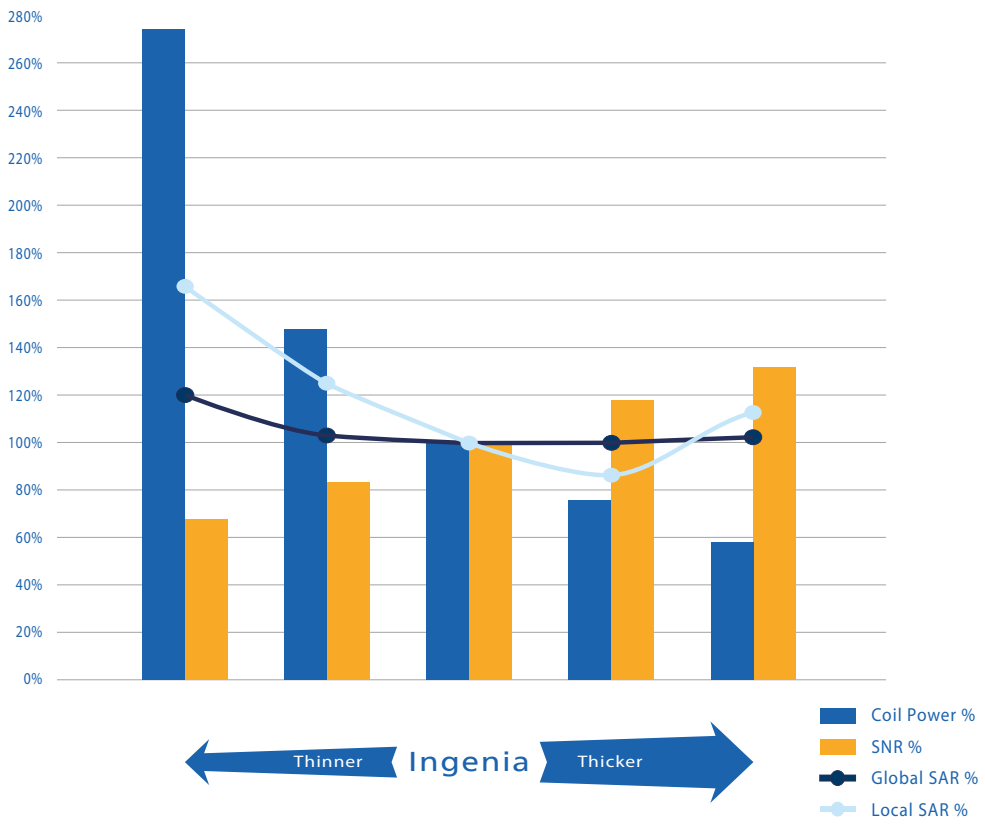


Figure 2: RF coil power, SNR, and SAR behavior as a function of distance between antenna and RF screen.

Xtend dStream body coil: solid-state construction The Xtend multi-channel dStream system body coil is uniquely constructed to increase the available space, enhance efficiency, and reduce the number of discrete electronic components and thereby increase reliability. The typical technology used to manufacture MRI system body coils is PCB conductors with discrete capacitors. For the Xtend dStream body coil, discrete capacitors have been completely eliminated from the design. Using a unique material and design process has made this possible. We refer to this as an integrated solid-state design, meaning no discrete components are used. Capacitance is distributed uniformly throughout the coil structure thereby reducing local electric fields which leads to a 20% lower local SAR than that of a discrete design (see Figure 3).

Figure 3 shows a full wave EM simulation comparison between a discrete component body coil design and the integrated solid-state body coil design. In each case, the body model is placed at an identical position with the arm directly on the patient bore at the closest proximity to the coil conductors. The input power is scaled to realize an identical mean B1+ field within the center slice of the model. The corresponding Whole-Body and Local SAR are computed. In the case of the integrated solid state coil, Figure 3b, both the Local SAR and Whole-body SAR are lower than in the discrete component based design.

The 5% reduction in Whole-Body SAR coupled with up to 20% reduction in local SAR provides additional margin with respect to the industry SAR guideline limits (IEC-60601-2- 33, edition 3.2, 2015-06). This additional margin contributes to enhanced patient comfort. As an additional benefit the reduction in the number of components means that reliability is inherently increased.

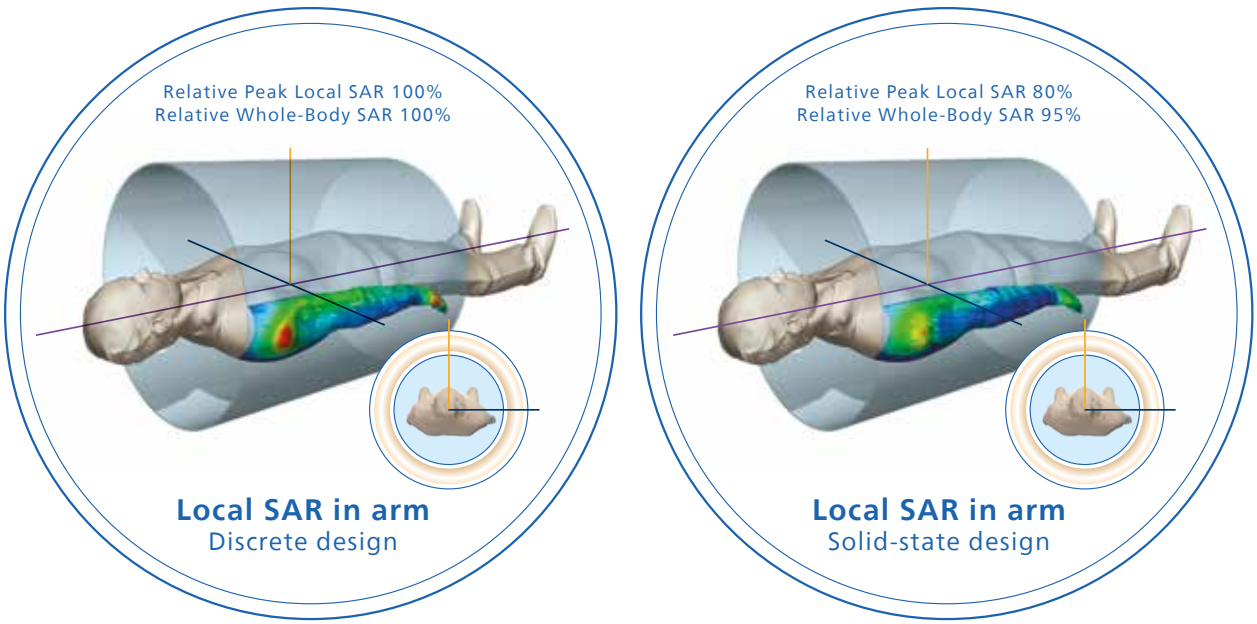


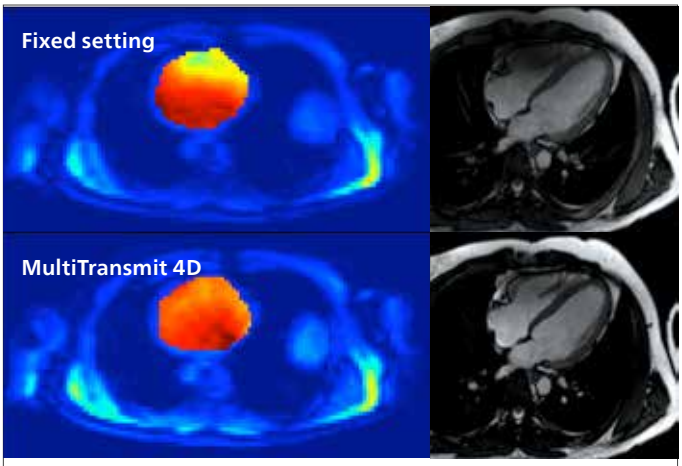
Figure 3: EM simulation comparison between traditional discrete design (top) and Xtend integrated solid-state design (bottom). The solid-state design provides benefits with respect to SAR.

dStream transmit and receive

In a conventional MRI system the system body coil receiver is typically located in the equipment room, as illustrated in Figure 4a. In the 3.0T MultiTransmit configuration multiple independent receivers are used, one for each of the two receive channels of the system's body coil, and two additional receivers for sampling the RF signal of each channel during transmission, making a total of four.

With the development of dStream technology[1] it has become possible to place the miniaturized receivers in close proximity to the system's body coil (Figure 4b), so that all signals in and out of the examination room are digitized and sent over fiber optics. The physical path length of the analog MR signal from the body coil is reduced, thereby increasing SNR.

Each transmit path of the MultiTransmit[2] architecture incorporates an independent solid state RF amplifier utilizing a digital control loop. The control loop directly samples the amplitude and phase of the RF output in each chain. The digital demands of the amplifier are independently adjusted in real-time to compensate for temperature effects and to increase stability and fidelity of each of the multiple RF chains.



Ingenia 3.0T scan acquired with MultiTransmit 4D cardiac. Example of how B1 shimming enhances contrast and image uniformity.

Conclusion

Designing from the patient outward, the Xtend approach to wide bore RF body coil design takes advantage of the increased space available between the patient bore and the inner diameter of the gradient coil. The solid-state body coil design in combination with the dStream digital receiver technology increases SNR while reducing SAR and RF power demand*.

*** Up to 40% more SNR compared to Achieva as non digital/dStream system**

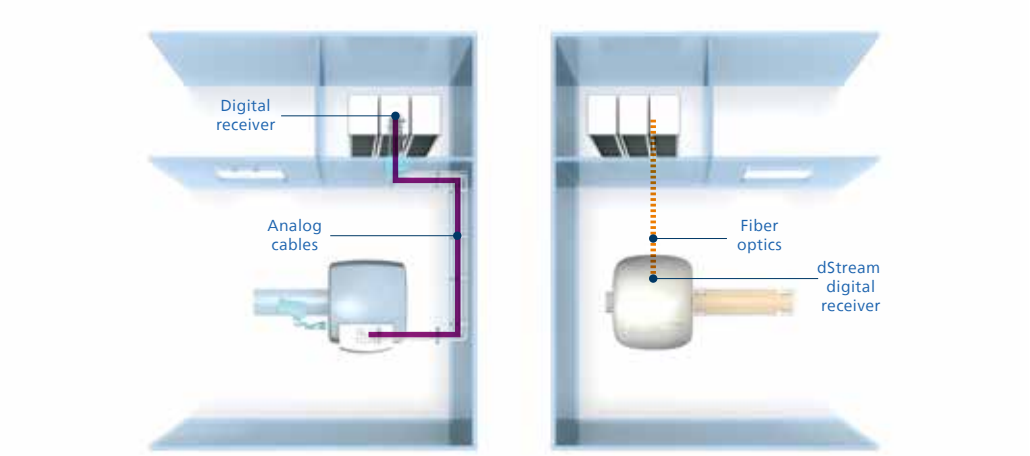


Figure 4: Traditional receiver location for system body coil (left) and dStream digital receiver location with fiber optic data transport and control (right).

The Omega gradient system

What is unique about the design of the Omega gradient system and what is the clinical benefit?

Xtend clinical performance – linearity

Another key element of the Xtend clinical performance is the spatial linearity of the gradient coil. The Xtend magnet system features an Omega gradient system to address this aspect.

The match between the spatial linearity of the gradient coil and the magnetic field homogeneity is important for accurate and efficient clinical performance. The more linear the gradient coil, the more energy is required to achieve a particular amplitude and slew rate. One possible way to address the increasing power demands of a wider bore gradient coil, would be to reduce gradient linearity in favor of amplitude and slew rate. This, in turn, would necessitate a reduction of the magnetic field homogeneity to match the reduced linearity.

In contrast to this approach, the Omega gradient system is designed to match, in linearity, the increased homogeneity required for the larger imaging volume of the Xtend magnet (see below). This combination, together with the Xtend system body coil, realizes an even larger FOV (up to 55 cm in Ingenia than in a typical 60 cm bore system. This larger FOV allows larger patients to be imaged, reduces the number of stations in multi-station exams, and supports off-center fat suppressed shoulder/wrist imaging without patient repositioning.

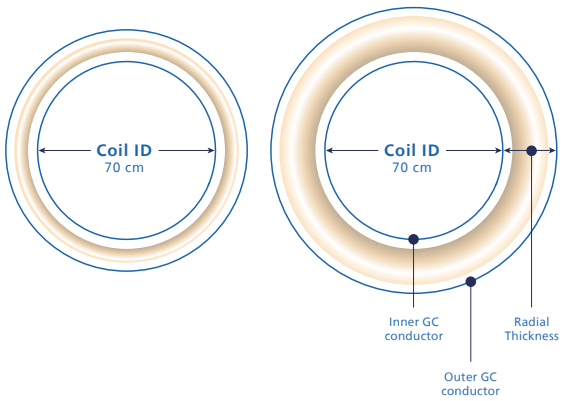


Figure 5: Two approaches to wide bore gradient coil design. Left: Reducing radial thickness and inner diameter of the magnet. Right: Increasing magnet diameter at optimum radial thickness of the gradient coil (Xtend approach).

Xtend power efficiency – leads to lower running costs

The power required to operate a gradient coil scales to the fifth power of its radius. Additional factors which affect the power demand include gradient linearity and radial thickness (the distance between inner and outer gradient coils, see Figure 5).

Increasing the patient bore diameter from 60 cm to 70 cm therefore has an immediate consequence for the power demand of the gradient system. If the radial thickness of the gradient coil is also reduced (thereby making the gradient coil thinner), there are a number of negative consequences, for example both the power demand and cooling requirements of the gradient system increase dramatically. Figure 5 illustrates some of the various physical dimensions of a gradient coil that affect efficiency. Both examples have an equivalent inner diameter. The illustration on the left shows a gradient coil with a smaller radial thickness which has a negative impact on efficiency (typical of the conventional approach to wide bore system design).

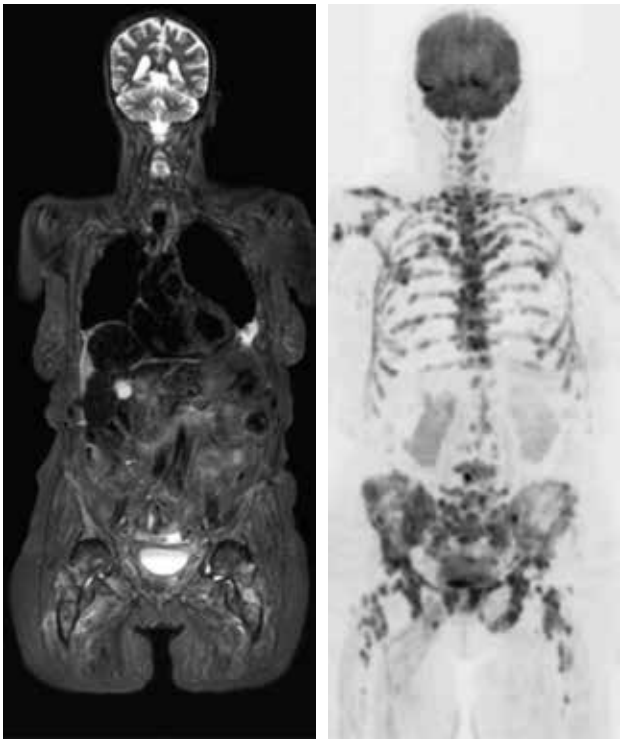
Figure 6 illustrates the relative performance of two different gradient coil designs. The purple line shows the behavior of relative power demand as a function of relative inner diameter for a gradient coil of nominal radial thickness, i.e. 100%. For comparison purposes, the relative coil inner diameter of 100% represents a typical gradient coil designed for a 60 cm patient bore. The power demand for this baseline design is represented by point A. Keeping amplitude and slew rate constant, the orange line represents the relative power demand as a function of relative inner diameter for a gradient coil that is equivalent in linearity, and all other magnetic field requirements, except that the radial thickness is reduced by approximately 22%. The first thing to note is that at an inner diameter (100%) equal to the baseline (purple) design, the thinner gradient coil requires approximately 15% more power (point B)

When moving to a 70 cm bore, it is necessary to increase the inner diameter of the gradient coil. Starting with the thinner gradient coil, point C represents the relative power demand for the wider bore version of this gradient coil. This is approximately 62% higher than the original baseline design. A higher overall power demand means that the system is more expensive to run. Some vendors make a point of emphasizing the power of their gradient amplifiers. While this power can translate to faster slew rates and higher amplitudes, in the context of a 70 cm system it mostly relates to the efficiency of the gradient coil design. A higher power demand can indicate a less efficient gradient coil design which should also be matched with a higher cooling capacity in order to maintain clinical performance. If the cooling capacity matches the increase in power, the system could be even more expensive to run.

Figure 6 further illustrates a more favorable approach. By increasing the radial thickness back to that of the baseline design, a 22% reduction in power demand is achieved (point D). When the magnet bore can be made wide enough to accommodate such a gradient coil, the 22% increase in power efficiency offers benefits in terms of running costs, gradient duty cycle, and clinical performance.

For reference, the dashed line indicates the efficiency dependency proportional to radius to the power 5.

In the Ingenia we have considered the impact on running costs and how they can increase when a less favorable balance of gradient parameters is chosen. Thanks to industry-leading magnet technology we were able to make more space available for the gradient system. The benefit of this increased volume is more efficient translation of amplifier power into clinical gradient performance, leading to lower running costs.



Ingenia 3.0T with Xtend and MultiTransmit leads to robust results due to the enhanced magnet and body coil homogeneity and gradient performance fidelity from the Xtend and Omega combination. (DWIBS: single shot EPI with SPAIR and STIR suppression) * courtesy of Leuven University, Belgium.

Relative power demand versus coil ID and thickness

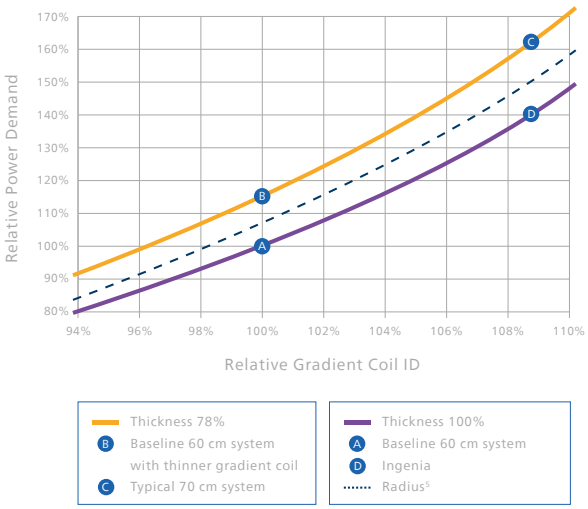


Figure 6: Power efficiency as a function of radial thickness of gradient coil and gradient coil inner diameter (ID).

Xtend direct cooling technology – increasing stability and gradient coil reliability

When a gradient system is operated it dissipates heat due to the finite resistance of the electrical conductors. This heat must be continuously removed from the gradient coil. Today most gradient coils are liquid cooled. The traditional method of cooling is referred to as indirect cooling, in which the cooling pipes are physically separate from the electrical conductors (Figure 7, left). This indirect approach, apart from being less efficient in terms of cooling, uses more material, which is less eco-friendly. It also takes up more space inside the gradient coil leaving less space for conductors.

The approach to liquid cooling the gradient coil for Ingenia builds upon the principle of Direct Cooling introduced by Philips in 1993 and utilized in all Philips MRI products since their introduction to present day. In the Direct Cooling approach, the cooling fluid actually runs inside the hollow conductors of the gradient coil. The copper conductors that perform the electromagnetic function of generating the gradient field also channel the cooling fluid. Due to the larger size of the conductors, this offers the most direct and efficient way to reduce dissipation, and to remove remaining heat from the gradient coil (Figure 7, right). This approach achieves high stability and reliability.

Xtend acoustic comfort

Acoustic noise is a significant factor in patient comfort. Due to the larger dimensions and high linearity of the Omega gradient system, higher Lorentz forces can be generated within the gradient coil. These forces directly affect the acoustic noise level output. Several measures have been taken to reduce the noise level of the Ingenia:

- The Xtend system body coil, located inside the gradient coil, is constructed from a thick glass/epoxy cylinder over the entire length of the gradient coil, serving as an effective noise barrier
- The unique plate construction of the gradient coil provides a higher stiffness compared to traditional winding technology
- The gradient coil assembly is force balanced with respect to the magnet windings, resulting in a lower vibration level
- The gradient coil suspension is flexible to isolate highfrequency vibration towards the magnet
- The magnet feet provide vibration isolation to reduce noise conduction to the floor and surroundings
- Improved cover encasement leads to greater acoustic absorption
- The Xtend magnet system features AutoSoftone.[3] With this unique feature the MRI sequence software automatically adapts to the lowest possible acoustic noise level, while enhancing clinical performance.

Acoustic measurements taken on 30 routine clinical scans, including EPI and steady state techniques, showed average acoustic levels of <105dB for Ingenia 3.0T Omega HP and <99 dB for Ingenia 1.5T Omega HP. These confirm the superb level of acoustic comfort provided with Omega gradients.

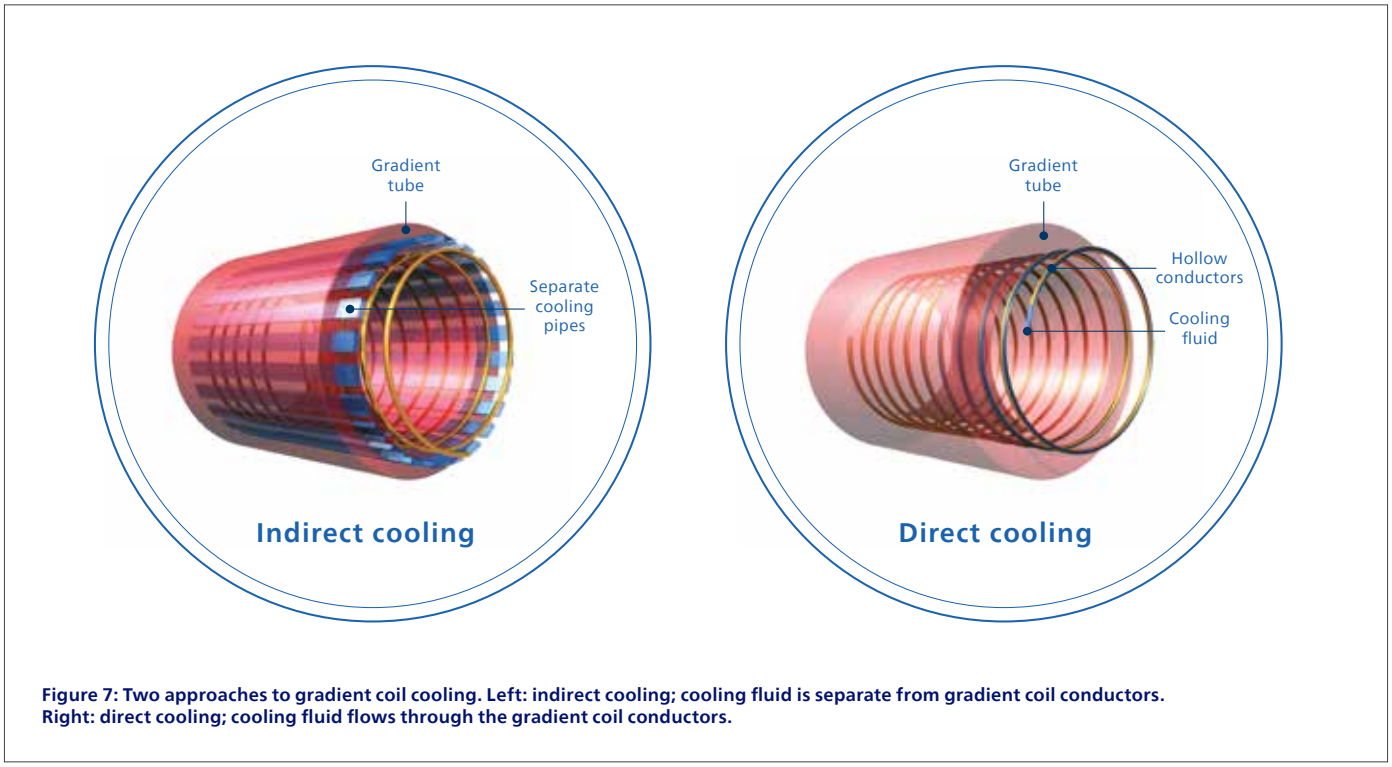
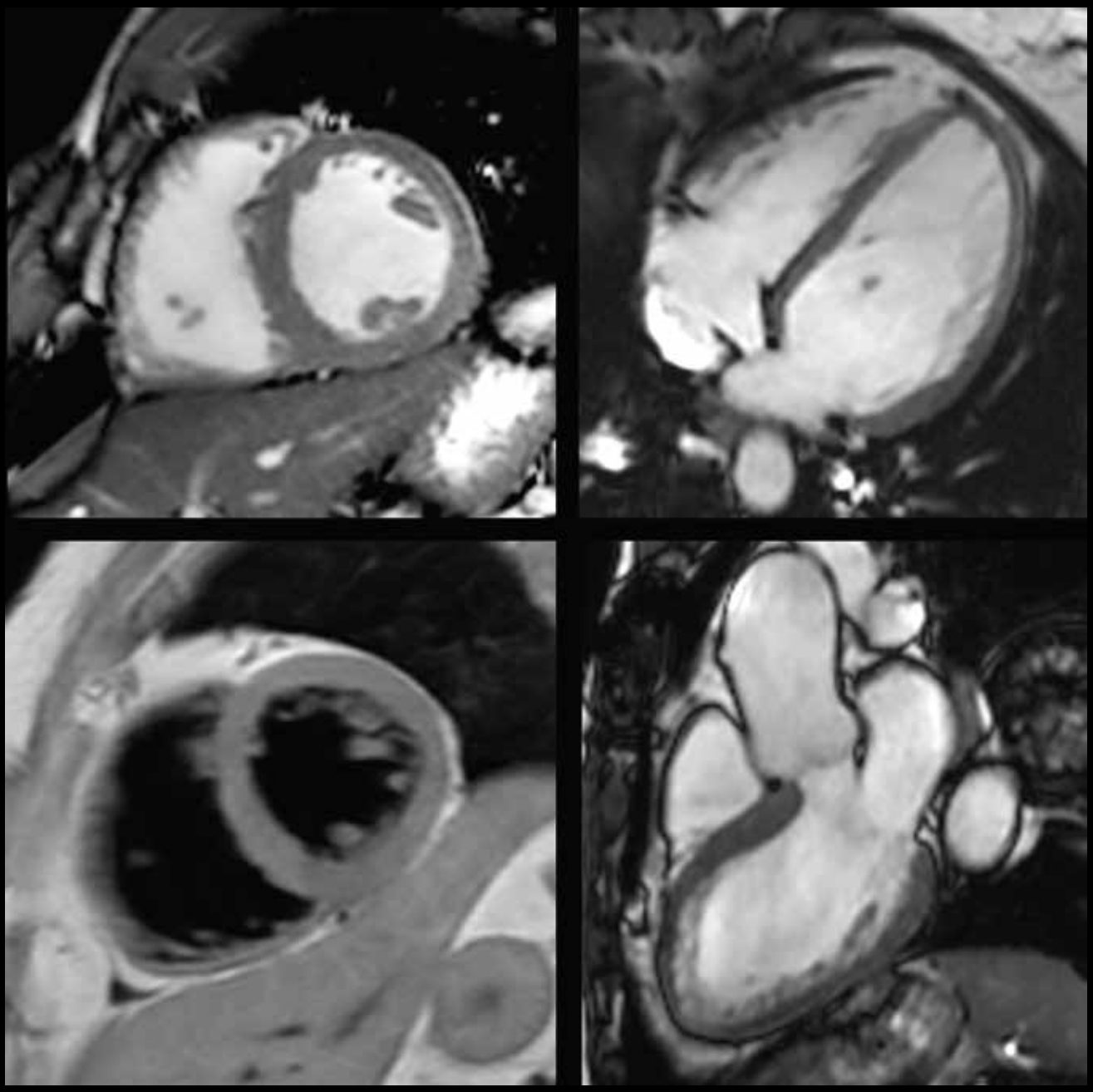


Figure 7: Two approaches to gradient coil cooling. Left: indirect cooling; cooling fluid is separate from gradient coil conductors. Right: direct cooling; cooling fluid flows through the gradient coil conductors.



Ingenia 3.0T with MultiTransmit: Balanced TFE demonstrating the superb gradient performance and duty cycle control.

Conclusion

The performance requirements of the Omega gradient system determine the inner diameter of the magnet. The increased space available for the gradient coil, together with the use of direct cooling, increases the volume available for field generating conductors and reduces the overall power demand in terms of both gradient field generation and cooling capacity. High linearity, high duty cycle, and greater acoustic comfort promote state-of-the-art clinical performance for the Ingenia.

The Xtend magnet system

How does technical leadership in magnet technology translate into improved system performance?

Magnet homogeneity is a key parameter in the capability of an MRI system. A synergistic relationship exists between the size of the magnet homogeneity volume, the spatial linearity of the gradient coil, and the transmit coverage of the system's body coil. Together, the performance of these components defines the available FOV for imaging.

When a wide bore magnet is not fundamentally designed for a larger FOV (for larger patients), there is a mismatch between the homogeneous volume and the size of the patient. When the homogeneous volume is smaller than the size of the patient, the FOV is compromised and various hardware and software countermeasures are required to prevent unwanted signal from folding into the FOV. These countermeasures often increase complexity, cost, and scan time.

Shortening the magnet too much has a direct impact on the maximum FOV. For a specific FOV there is a certain minimum magnet length. Making the magnet shorter than this not only compromises the FOV along the bore, but also in its radial dimensions. The consequence of this approach is that body imaging must often be performed with more than one station and the patient spends more time in the system.

Designing a magnet for wide bore starts with meeting the requirements of the FOV to be imaged. In the Xtend approach to wide bore system design, a key consideration is that the system should not only be able to physically accommodate larger patients, but should also be able to image the extended anatomies of those larger patients in the most efficient manner possible. This requires a large FOV in all dimensions, which also accommodates a large fatsat volume.

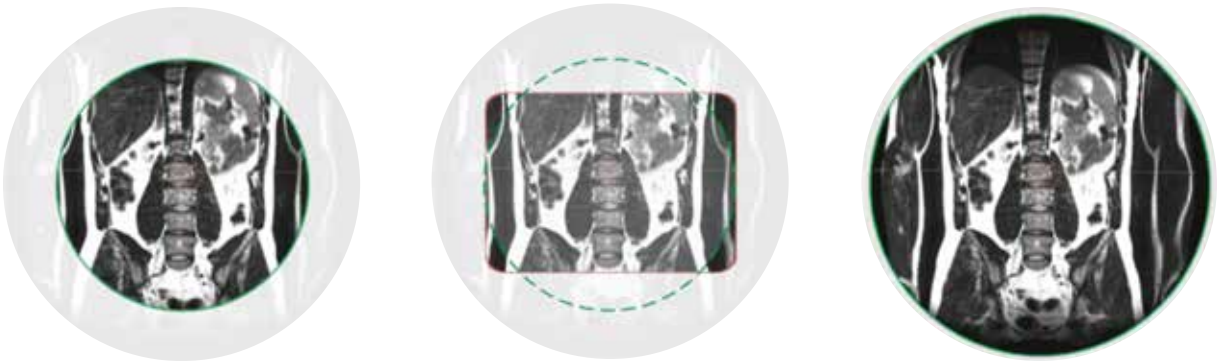
Figure 8a illustrates a reference spherical magnet homogeneity volume of arbitrary size in a standard magnet that is used for a conventional MR system.

Some previous wide bore technology developments[4] advocate changing the shape of the magnet homogeneity volume from a sphere to a cylinder (Figure 8b). The value of this approach, however, depends upon the starting point. The starting point for such an approach is usually less than optimal, namely a spherical homogeneity volume which is too short. Figure 8b shows the negative effects to the FOV along the direction of the bore.

Figure 8c illustrates how a cylindrical homogeneity volume is unnecessary when the magnet is fundamentally designed for a wide bore with a larger FOV.

Designing a magnet for a larger FOV necessitates a magnet with a fundamentally larger inner diameter. Philips has always been at the forefront in magnet technology.[5] Achieving a robust and commercially viable wide bore magnet design with a large FOV required taking a next step innovation to create cutting edge technology.

The magnets for Ingenia 1.5T and 3.0T combine compact design with both a larger patient bore and a larger FOV in all dimensions.



8a. FOV of conventional system.
No wide-bore.

8b. FOV of wide-bore.
With cylindrical homogeneity volume.

8c. Wide-bore FOV.
Optimised for large patients - Ingenia

Figure 8: Homogeneity performance for industry-wide conventional 60 cm (a) vs. cylindrical 70 cm (b) vs. Xtend 70 cm (c). The largest FOV for a 70 cm bore can be obtained using Xtend technology.

Magnet weight has become an important property as MRI technology has matured over the years. For many practical reasons it is important that the magnet weight remains as low as possible.[5] The Xtend magnets used in both the Ingenia 1.5T and 3.0T are the lightest magnets in their class. The relative weight compared with other vendors is illustrated in Figure 9. Contrary to popular belief, a superconducting magnet that weighs less is indicative of a more efficient design using more advanced technology.

An important indicator for advanced magnet technology is the ratio of homogeneous volume divided by the mass of the magnet. The higher the value, the more efficient and advanced the magnet design. We refer to this as the Compactness Performance Index (CPI).

The CPI determines the ratio of the spherical volume in which Vrms homogeneity is higher than 0.5 ppm divided by the mass of the bare magnet. Figure 10 shows the CPI for Ingenia versus other vendors.

Conclusion

Xtend delivers a truly exceptional clinical wide bore system. This is due to the flexibility in magnet design starting with the patient and working outward, which allows all components to be fine-tuned for the best possible performance. We have drawn upon our long expertise in developing leading magnet technology to increase the bore space without compromising homogeneity.

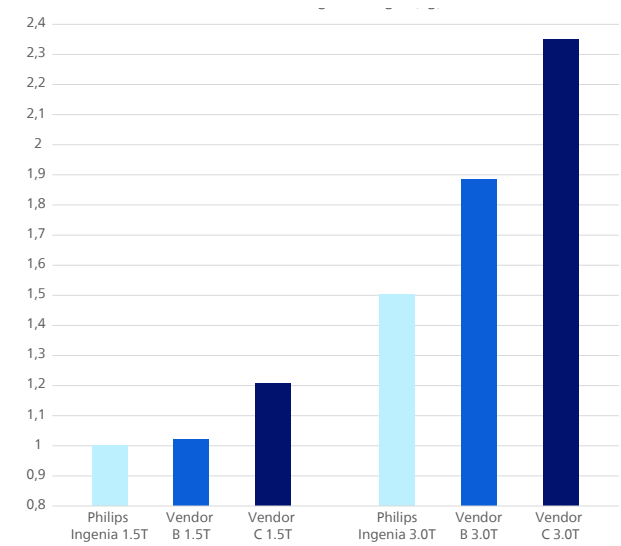


Figure 9: Comparison of bare magnet weight between Ingenia, vendor B and vendor C. Lower weight is a known characteristic of advancing technology in many industries.

$$\text{CPI} = \frac{\text{DSV (cm}^3\text{) at 0.5 ppm Vrms}}{\text{Magnet Mass (kg)}}$$

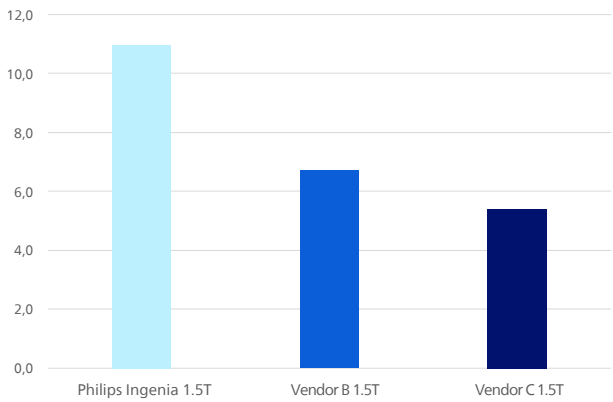
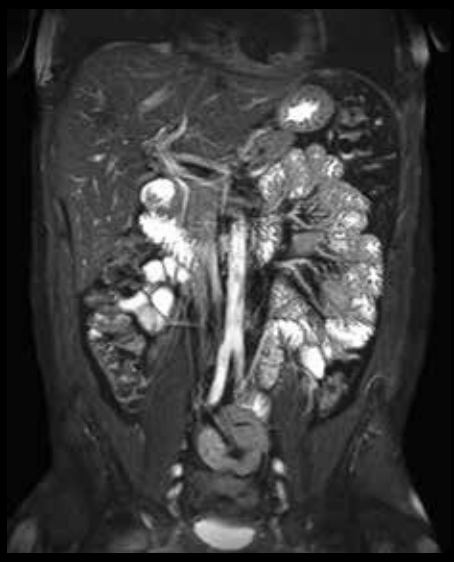
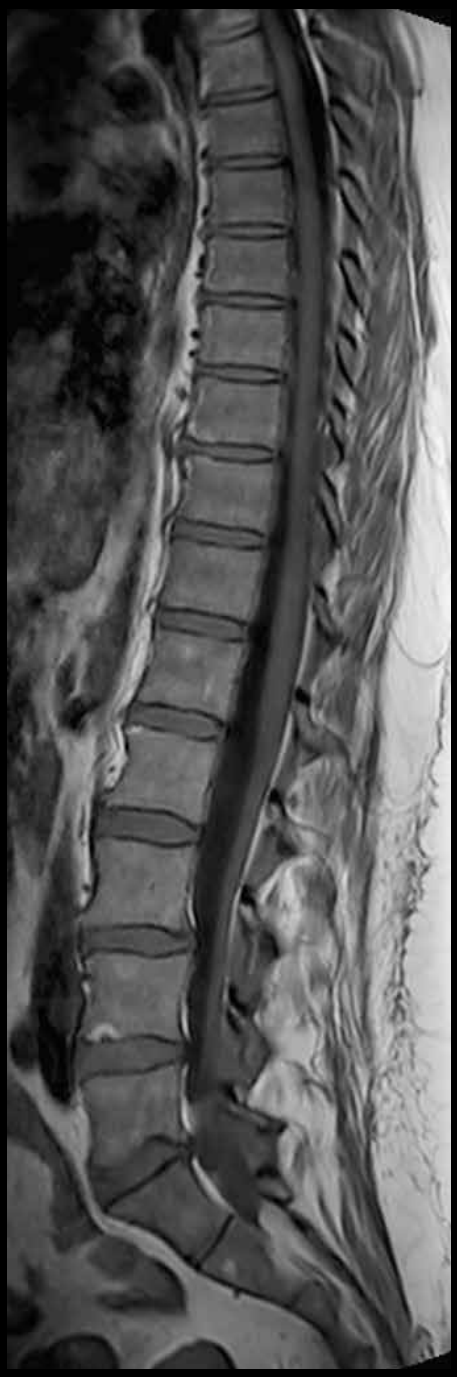


Figure 10: Compactness Performance Index (CPI), a measure of how large the useful homogeneity volume is compared to the mass of the magnet. Currently, the 0.5 ppm Vrms Diametric Spherical Volume (DSV) for Ingenia is the largest in its class while the magnet is also the lightest in its class.



Ingenia 1.5T showing single station large field of view with robust spectral fat suppression technique.

Ingenia 1.5T T2 TSE lower leg with single station 500 mm field of view.



Ingenia 3.0T T1W and T2W TSE with single station 450 mm field of view.

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