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A close-up, low-angle shot of a Philips MRI machine. The large, circular gantry is illuminated from within, creating a bright, glowing ring. A control console with a screen and buttons is visible on the left side of the gantry. The screen displays a medical image. The overall scene is dark, with the machine's light providing the primary illumination.

Whitepaper

The digital revolution in MRI with dStream architecture

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Step into the future with confidence

Executive summary

The MR world is constantly evolving towards higher levels of performance in terms of better image quality and consistency, faster imaging and processing, and higher patient throughput. To fundamentally and simultaneously address all these needs, Philips introduces the revolutionary Ingenia MRI system with dStream architecture. This white paper looks at what makes dStream architecture revolutionary and how it redefines the possibilities in clinical imaging.

Why is dStream architecture a true paradigm shift in MRI?

Because you can use as many channels as required - without complex logic, data compression, or multiplexing.

A true paradigm shift in clinical imaging

One of the constant challenges in MRI is to improve image quality for each clinical application. That is why with the introduction of parallel imaging techniques in the last two decades^{[2][3]}, the number of receiving channels in the MRI system and elements in the RF coils has increased substantially. This increase in the number of channels has necessitated a subsequent increase in data rates and reconstruction performance. MRI systems have had to support more and more channels which, in turn, has meant adding long receiving cables between coil elements and the MRI data acquisition system. These analog cables, with their bulky connectors and associated electronics, can make the system extra sensitive to noise pickup, which deteriorates image quality.

The Ingenia MR systems with dStream architecture address these issues, and the result is exceptional image quality with major benefits in workflow and throughput time.

The following chapters explain how dStream architecture is designed to deliver innovation that matters to you and why dStream:

- Is a true paradigm shift in MRI
- Produces higher signal-to-noise-ratios (SNR)*
- Enables a truly channel-independent system
- Reduces interface complexity
- Simplifies workflow and improves throughput time
- Is designed to be future proof

Until two to three decades ago, the receiving architecture of MRI systems was limited in acquisition to 1 or 2 channels. Receiving coils were built with 1 or 2 channels, and could eventually be combined in a quad mode. The performance was often not really optimal. For instance, many manufacturers used to place the first amplification stage far away from the receiving coil elements, which negatively affected SNR performance.

The concept of “multi-element phased array receive coils” arrived around 1990. As a result MRI systems typically had up to 4 receive channels; only one manufacturer, Philips, supplied up to 6. Towards the end of the 1990s, with the introduction of parallel imaging, the technology for MRI receiving architecture made enormous progress. Over 10 years, the number of receiving channels increased from the original 2 to 32^{[9][10][11]}. In the last decade, the move towards higher channel counts in coils has been a primary goal of new developments in MRI technology*. However, the technology of the data acquisition system was, and for many manufacturers still is, based on a traditional analog architecture.

Figures 1a-c illustrate the evolution of the MRI channel/element race over the last two decades: from 2 up to 18 elements. These figures show that using traditional analog technology to acquire many elements has required making many changes to multiplexing, complex switching logic, dynamic range compression, and careful manual component adjustments^[4].

In complete contrast to the traditional analog approach (Figure 1a-c), the dStream architecture (Figure 1d) allows the acquisition of as many elements/channels as required by clinical applications without affecting complex logic, data compression, multiplexing, and other aspects of MR systems. This is only possible by replacing the traditional analog RF chain with a digital RF chain and by bringing the analog to digital conversion into the receive coil itself. This digital platform is truly a paradigm shift in the MRI world.



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

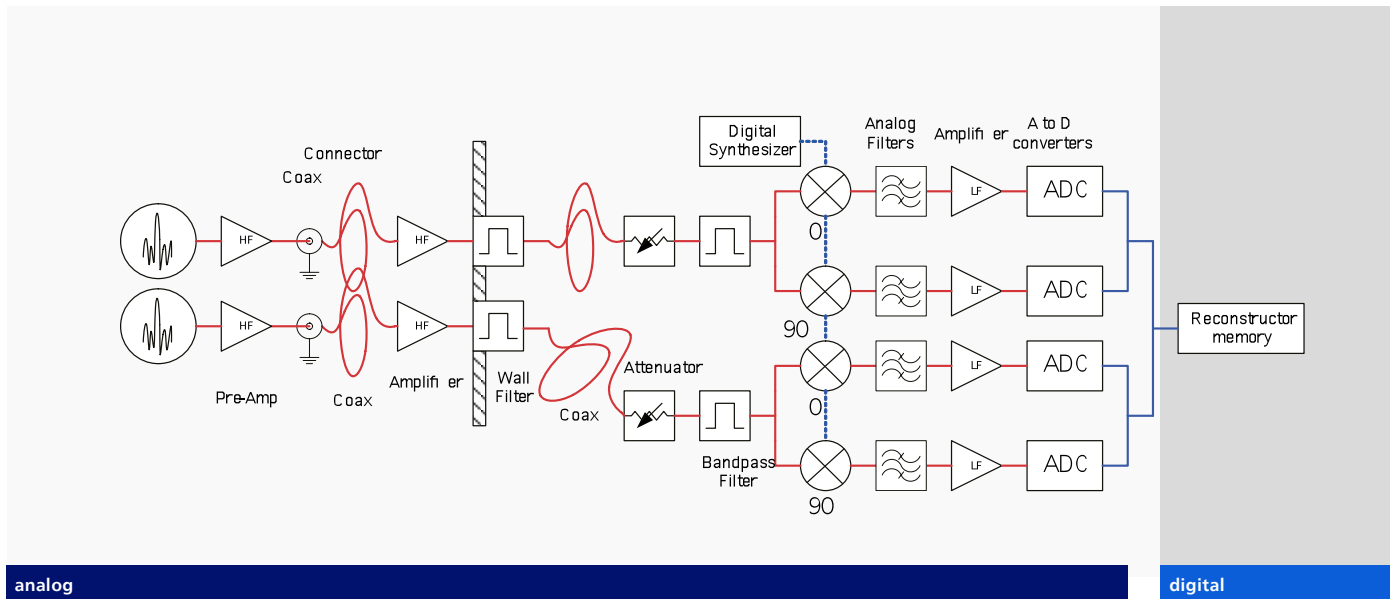


Figure 1a: Basic architecture of an analog system with 2 channels and 2 elements

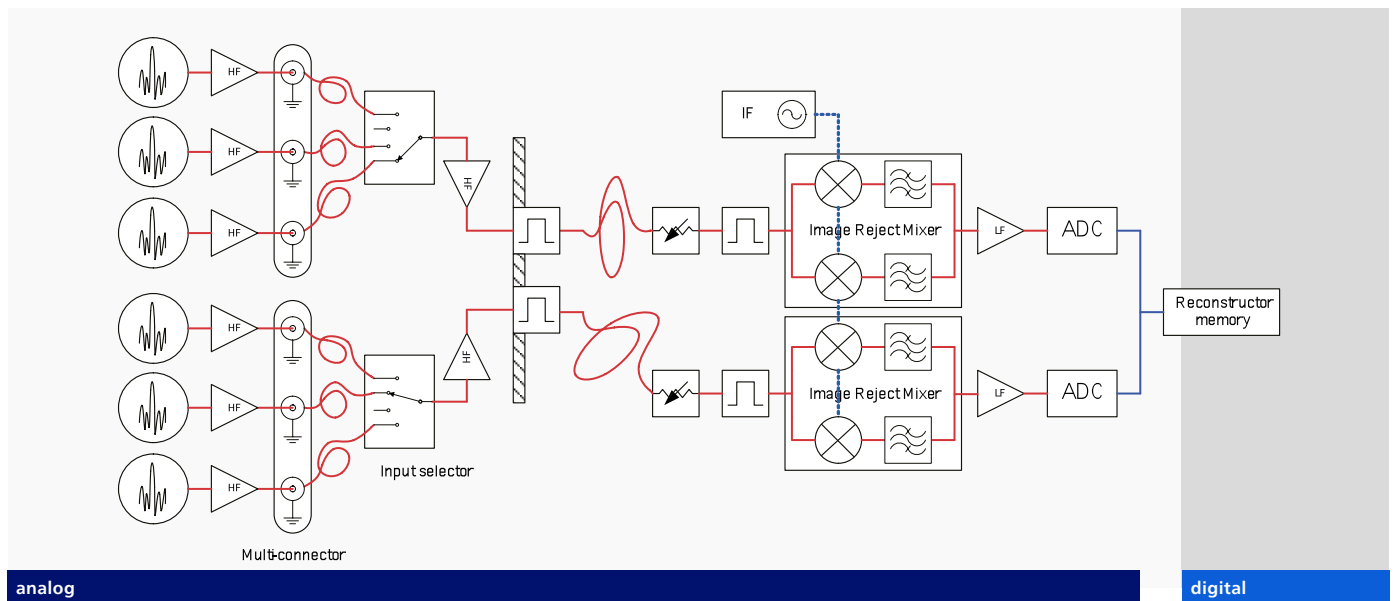


Figure 1b: Reuse of architecture in Figure 1a in order to support more (6) elements

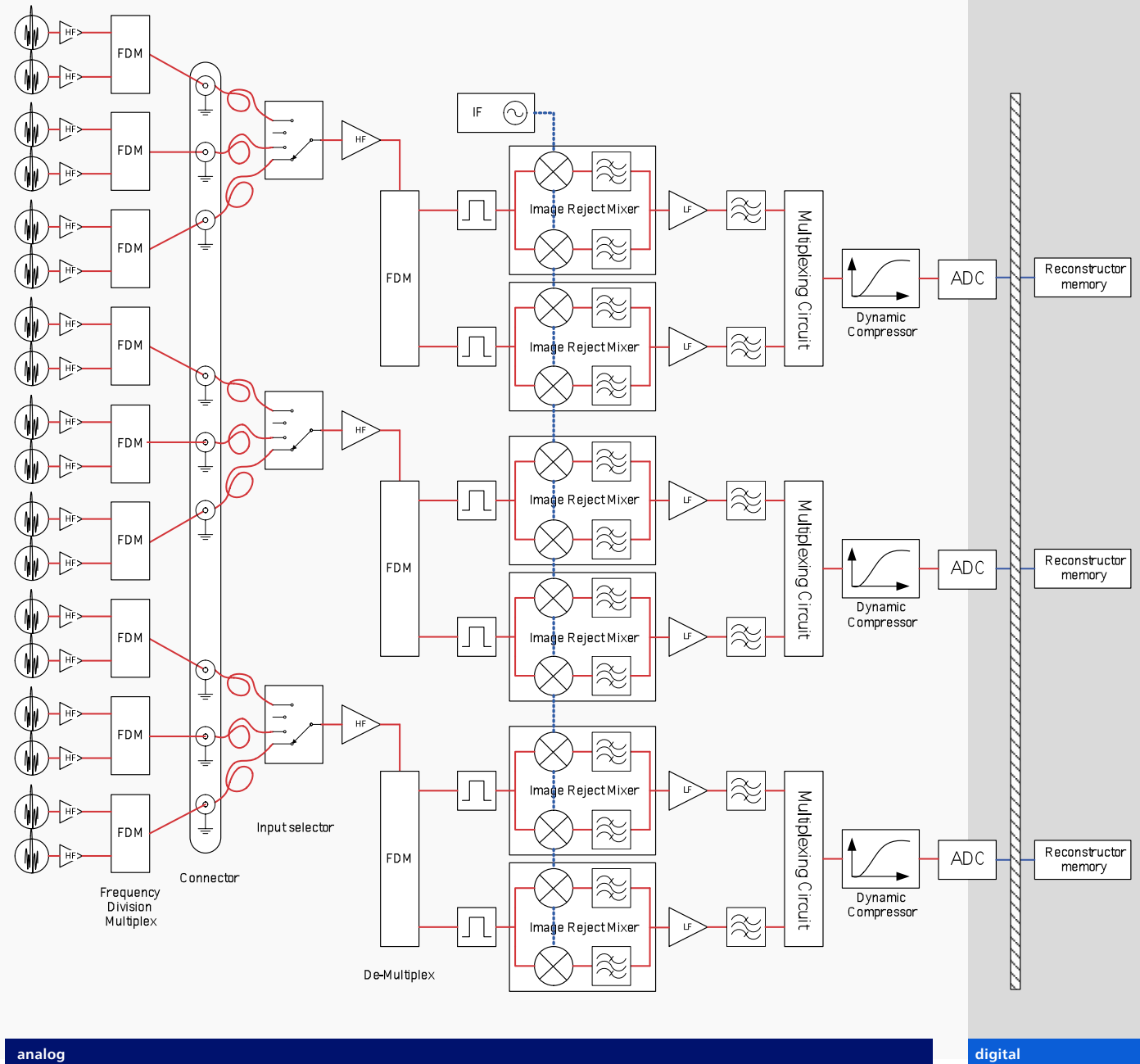


Figure 1c: Evolution of analog architecture in Figure 1a in order to support an increasing number of elements (18)

Our dStream architecture also solves one of the most challenging problems in MR data acquisition: creating MRI receiving channels that have the large dynamic range required for the MRI signal, which can exceed the standard 16-bits of an analog-to-digital converter (ADC) found in an analog MRI system. To exploit the full potential of the MRI signal at any field strength, the dStream architecture acquires the receiving signal in the full dynamic range without pre-distortion or compression of the signal.

Our dStream architecture uses a direct digital sampling method for digitization: the MRI signal is sampled directly without conversion to DC (zero frequency). This technique avoids all intermediate analog stages for down-conversion of the signal between coil element and the ADC. The overall result is an incredibly simplified receiving architecture, with substantially fewer components, higher SNR* and dynamic range, and improved signal and phase stability.

In addition, the dStream architecture enables acquisition of MRI signals with a dynamic range which scales between 22 and 26 bits (depending on bandwidth), while traditional analog systems typically have a dynamic range of 16 bits. The net result is an improvement of the overall signal fidelity over the whole dynamic range.

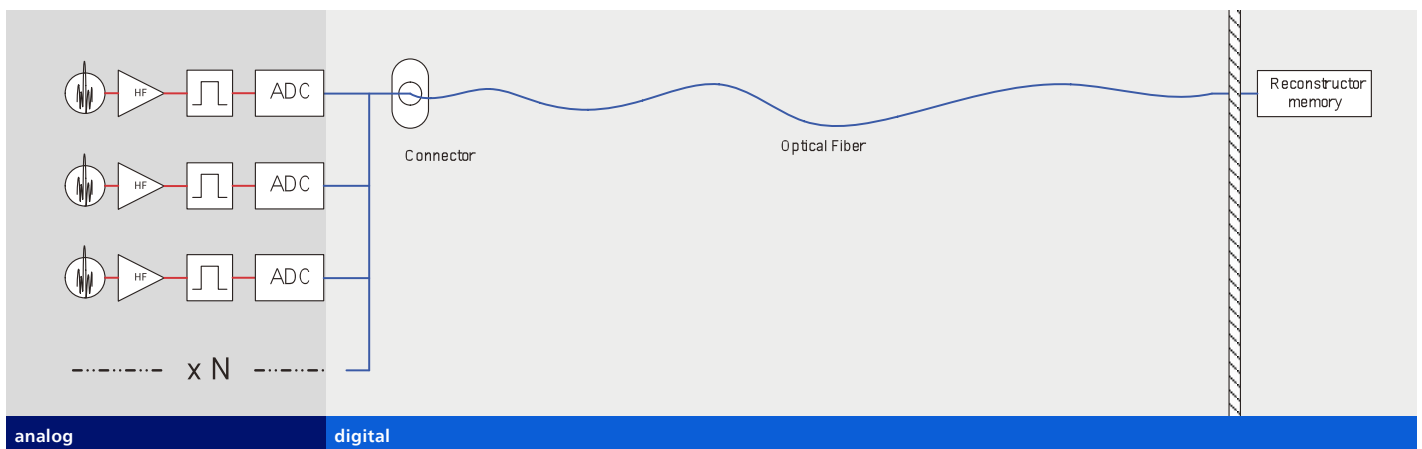


Figure 1d: dStream architecture with dStream digital coil

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

Dynamic range – a little bit of theory

For a digital receiver, the dynamic range (DR) is calculated by^{[5] [8]}:

$$DR = 6.02N \quad (1)$$

where N is the ADC input bit depth.

In order to increase DR, the analog signal is sampled at a much higher rate than the maximum frequency; in this case the DR is given by^{[7], [8], [9]}

$$DR = 6.02N + 10 \log(fs / 2B) \quad (2)$$

where fs is the sampling frequency, which must be at least double the signal frequency (according to Nyquist's theory), and B is the signal bandwidth.

Equation (2) shows that the dynamic range increases linearly with the number of ADC input bit depth and logarithmically with the sampling frequency. Figure 2 indicates the ADC dynamic range as a function of input bit depth, calculated according to equation (2). The values are calculated assuming one ADC for each channel and a bandwidth of 1Hz. The different curves in Figure 2a represent the dynamic range for 1, 4 and 8 interleaved channels. It is clear that multiplexing multiple channels into a single ADC, and/or reducing sample frequency, results in a reduced dynamic range, as required in the architecture reported in Figure 1c, and for this reason it is generally undesirable^{[4] [6]}.

Figure 2b shows that the dStream architecture with digital coils enables an acquisition of the MRI signal with a dynamic range which is equivalent to an effective bit depth at ADC output that varies between 22 and 26 effective bits (depending on the clinical receiving bandwidth).

In dStream architecture, the signal of each element is directly digitized without multiplexing different channels. In other words, the ADC is not shared between multiple elements therefore, there is no resulting compromise in the dynamic range. The dStream system with its unique digital conversion and with the ADC located at each coil element guarantees the highest dynamic range in the market (up to 187 dB).

In conclusion, dStream architecture with dStream RF receive channels provides a high purity MR signal with the highest dynamic range in the market. There is no signal pre-distortion, because the signal is directly sampled and digitized on the patient.

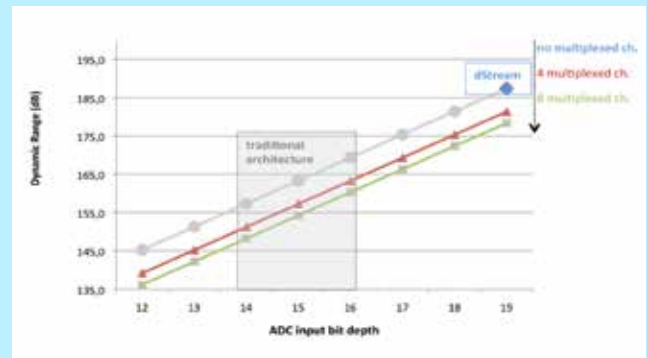


Figure 2a: Dynamic range as a function of input bit depth of ADC (Equation (2)). Values are calculated assuming one ADC for each channel and a bandwidth of 1Hz. The different curves represent the dynamic range for 1 (blue) (i.e. no multiplexing), 4 (red) and 8 (green) multiplexed channels.

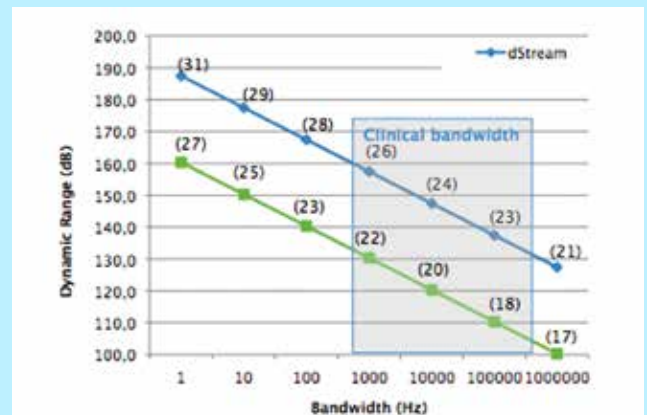


Figure 2b: Dynamic range as a function of receiving bandwidth. The labels between brackets above the curves represent the effective bit depth at the ADC output, calculated according to equation⁽¹⁾. The blue line (dStream) is calculated assuming one ADC for each channel. The green line (traditional, multiplexed architecture) is calculated assuming 8 multiplexed channels.

Why do the dStream architecture and coils produce higher signal-to-noise ratio?*

Because the signal is digitized in the coil and then transported by optical cables. This enables exceptional SNR.

In traditional analog architecture, multi-channel coils are sensitive for crosstalk because analog wires need to be bundled together in thin cables. Moreover, long cables (typically ranging from 10 to 20 m) have to be routed between coil elements and analog/digital conversion boards. This introduces losses and increases crosstalk, which becomes increasingly severe as the number of channels increases.

The dStream architecture with dStream coil solutions delivers high signal fidelity and signal immunity for noise and crosstalk because the signal is digitized in the coil and transported in digital format – via optical fibers– from there on.

In other words, the signal immunity and fidelity is enhanced by transporting a digital signal on optical fibers. Figures 1a-c and 1d show the differences between the dStream architecture (Figure 1d) and a traditional analog/galvanic architecture (Fig 1a-c). Digitization in the coil is made possible by extreme miniaturization of the receiving electronics (Figure 3).

MR signals are characterized by both low-amplitude and high-amplitude signals. In the dStream architecture, the large dynamic range means that the high-amplitude components of the MR signal are neither clipped nor distorted, while the lower-amplitude components -by virtue of digitization- are immune to noise or crosstalk effects. This means the required dynamic range is always available.

Since the introduction of phased-array and parallel imaging ^{[1][2][3]}, the trend in MRI has been to build coils with increasing numbers of elements with the promise of boosting SNR and/or reducing scan time. It is well established that there is an optimal number of elements required in order to achieve the best SNR in the region of interest ^{[13][14][15]}. It has been shown that increasing the number of elements beyond the optimal number improves the SNR at the edge of the volume and significantly less in the middle of the anatomy ^{[13][15]}. In Ingenia, the coils are optimized both for high SNR throughout the whole volume and high acceleration factors. dStream coil design, in combination with dStream architecture, provides exceptional SNR and acquisition speed throughout the whole volume. Figure 4 shows an SNR comparison between dStream digital architecture and our analog architecture with the same scan parameters.

The overall result is an increase of SNR of up to 40%* compared to our analog architecture.



Figure 3: A miniaturized digital receiving module used in dStream coils (blue box) compared with the receiver boards implemented in a MR system (red box)

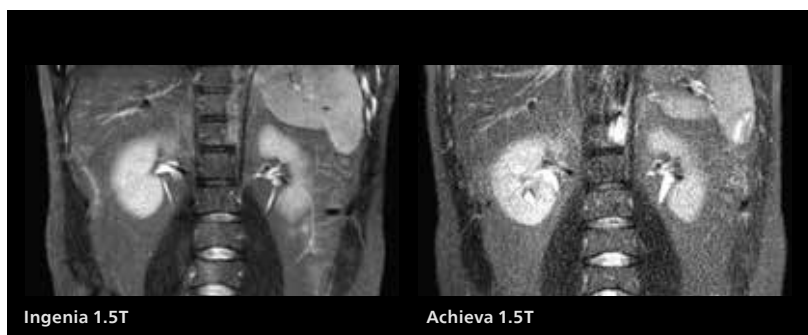


Figure 4: Comparison of body image acquired with identical sequence parameters using dStream architecture (left) and an analog architecture (right). The SNR improvement measured with the dStream architecture is 42%

How does dStream architecture dramatically reduce upgrade complexity?

Because it is truly channel-independent.

The dStream architecture not only substantially improves SNR,* it is a quantum leap in system flexibility, expandability, and scalability. Since the signal of each coil element is processed and digitized directly in the coil, there is now no distinction between the number of coil elements/channels and the number of channels of the MR system.

For example, an 8-channel system can only handle coils up to 8 channels or elements. In order to support a 16-channel coil, an upgrade to a 16-channel system would normally be required. With digitization moved to the coil, as in dStream, a truly channel-independent system is realized, and it is now possible to connect any coil independently of the number of elements/channels of the coil.

In the past decades, the increasing numbers of elements in phased array coils has driven the development of receiver technology to increase the number of available channels. Today's MRI systems are equipped with a fix set of channels. When you want to add more channels, you have to buy costly hardware upgrades for the system. Moreover, connecting a coil that has more elements than the number of system channels has forced manufacturers to build complex logic switches in the coil and/or to multiplex and compress the signal. These approaches increase system complexity and compromise performance.

The Ingenia system with dStream architecture and dStream coils avoids these issues.

Coils with high numbers of independent channels are realized in this architecture by simply acquiring and digitizing the signal of each element independently. The element's signals are not compressed or multiplexed to match the number of coil elements with the number of channels in the MR system⁽¹⁾.

The benefits of dStream architecture over our analog galvanic systems are similar to the benefits of digital TV over analog TV. To continue this analogy, digital TV offers not only a better image quality, but also the capacity to add many more TV channels without any change in infrastructure. Digital TV also provides additional services such as subtitles in many languages, menu structures, interactivity, and programs on demand.

Similarly, the dStream architecture offers excellent image quality, channel independence, as well as additional information, for example DigiDetect diagnostic information on the various digital-based components in the MR system including coil performance.

In conclusion, dStream is a truly channel-independent architecture, and this translates into full expandability of the Ingenia MR system. This architecture is not only a step forward in terms of image quality, but also for the additional services.

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

Why does dStream architecture reduce interface complexity?

Because all coil functions are handled in the digital domain.



Figure 5a: 16-Channel analog connector



Figure 5b: Robust channel-independent digital connector with 2 optical fiber pairs and 4 coaxial power lines

The dStream architecture not only improves SNR,* signal fidelity, and system scalability, but also ease-of-use.

Each dStream coil plugged into the system is immediately recognized. Every coil has its unique IP address which is recognized by the dStream platform, via a plug & play mechanism.

The interface between coil and connector is also simplified for dStream coils. A typical analog connector contains as many pins as the number of channels used by the coil and control lines to interface the coil to the system (Fig. 5a). In the dStream platform, both the MR signal and control functions as well as the coil logic are digitized within the coil and transported through the system via the same optical fiber. This total translation of all coil functions to the digital domain results in an extremely simplified coil connector (Fig. 5b).

Moreover, the optical connector improves the reliability of the coil by eliminating the RF pin connections.

In conclusion, every dStream receive coil has a single cable with a simple and robust connector, independent of the number of channels/elements in the coil.

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Why does dStream architecture simplify workflow and improve throughput time?

Because a complete set of multi-channel coils, requiring little or no handling, together with smart technology, enable fast and easy imaging from head to toe.

In addition to its many other benefits, dStream architecture enhances ease-of-use throughout the MRI system. The system provides a complete set of dStream coils for head to toe solutions. All applications can be performed using not more than 3 connectors on the patient table top. The connectors are very easy to plug-in with a single-handed movement.

The coils have the optimal number of elements to provide excellent image quality for both small and large fields of view (Figures 6-8), while the overall complexity in handling them is significantly reduced.

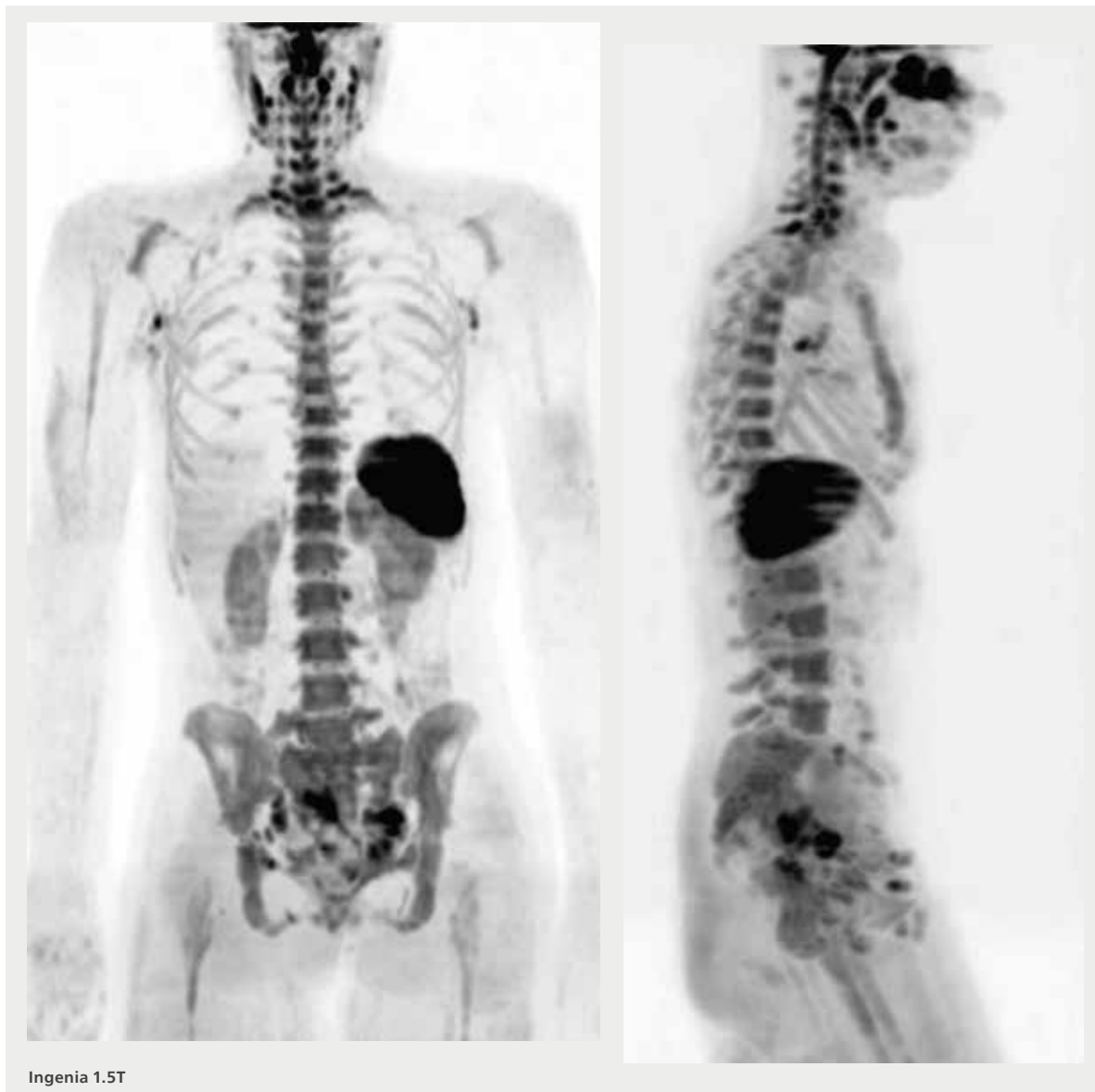
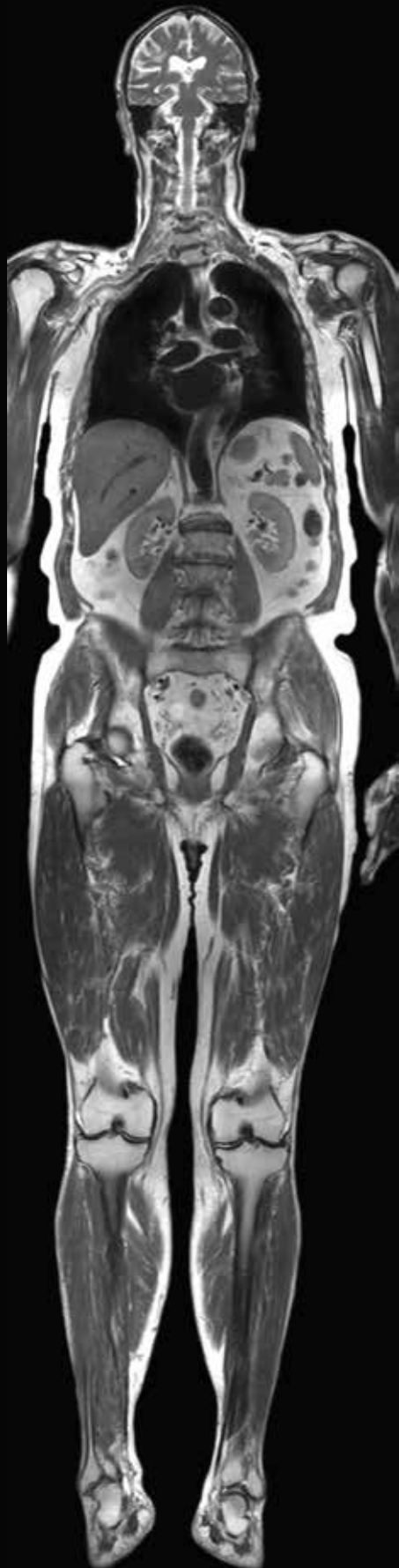


Figure 6: Coronal and Sagittal MIP DWIBS in 3 stations



Ingenia 1.5T

Figure 7: Thanks to the optimal coverage of Anterior and Posterior coils, spine images and abdominal images can be taken without repositioning the coils or the patient



The Posterior coil, used routinely in about 60% of all applications, is integrated under the patient table and covers from neck to toe for either feet-first or head-first imaging. The Posterior coil is not physically visible to the operator or patient and is deployed automatically according to the demands of the application. As a result of this innovative design, the Posterior coil does not need to be carried, positioned, connected, or exchanged, thereby greatly simplifying the workflow. It is always there when needed without taking up additional space within the bore. The Anterior coils are lightweight and flexibly conform to the patient shape which allows the coil to be as close as possible to the target anatomy (Figure 9). This facilitates ease of handling, patient comfort, and outstanding performance.

Moreover, during the examination, the system automatically selects those coils and elements which contribute to the highest SNR* within the selected field-of-view (SmartSelect). SmartSelect also increases the reproducibility and consistency across scans.

In conclusion, Ingenia with dStream offers a superb solution in terms of ease-of-use, coil handling, and patient comfort. This contributes to significant improvements in throughput.

Figure 8: From head-to-toe: Total Body with only 3 coils connected

* Data on file

How does dStream architecture extend your system lifespan?

Because it is completely digital all the way from the patient

The dStream architecture enables digital communication and data transfer from the individual coil element to image creation. The coil elements are a central part of a digital network. Each sub-unit of this network has its own IP address. This is comparable with a network of computers connected to the internet. The advantages of this dStream architecture with respect to previous-generation systems are numerous:

Since the dStream architecture takes advantage of the latest electronic components, which are constantly being made faster and smaller, the user can easily benefit from the availability of advanced hardware components.

Coils are plug & play with their own network ID and perform self-diagnostics upon connection, without special attention from the operator. In other words, the coil behaves like a USB-device when connected to a computer.

The digital platform of dStream is the only technology which is able to support coils with an increasing number of elements/channels without a major impact on the complete receiver system.

dStream is the way forward for next generation MRI systems.

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