

ADMIRE:

Advanced Modeled Iterative Reconstruction

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Introduction: Evolution of Siemens Healthineers CT image reconstruction technologies

Image reconstruction is an essential technology that every computed tomography (CT) scanner requires for operation. The function of CT image reconstruction is to translate all of the acquired X-ray data (raw data) into a meaningful three-dimensional representation of the patient. The most well-known method of image reconstruction is commonly referred to as filtered back projection (FBP), in which measured X-ray projections are directly translated into images. In most modern scanners, it is likely that not all measured data can be used for image reconstruction with FBP,¹ i.e., not all radiation dose applied to the patient is actually used for image reconstruction. To address this, Siemens Healthineers CT scanners offer an improved three-dimensional FBP, called weighted filtered back projection (WFBP).²

A common characteristic of both FBP and WFBP is that they do not consider statistical properties of measured X-ray projections. What this means is that all CT projections collected in the detectors are weighted the same, regardless of their quality. With the increased focus in dose reduction, the lack of inclusion of statistical

properties of conventional FBP or WFBP become an important barrier that prevents further radiation dose reduction. In an attempt to overcome such limitations, state-of-the-art CT scanners have been developed with more advanced technology, known as iterative reconstruction (IR). Not surprisingly, among the key advantages of IR is that the statistical properties of measured CT projection data can be readily incorporated into the CT image reconstruction process. This would allow, for example, low-quality (noisy) projections to carry less weight than high-quality projections.

There has been an expanding utilization of IR in clinical practice in recent years, primarily due to the increased focus on radiation dose optimization. Of note, Siemens Healthineers has been placing emphasis on devising technical solutions that can help to consistently achieve the right dose, for the right diagnostic task, for every patient. This was in line with the ALARA principle, that is to use a dose that is "As Low As Reasonably Achievable" to deliver diagnostic image quality.

Development of IR methods

It is well known that the degradation in image quality, most notably an increase in image noise, is the standard tradeoff for achieving a substantial dose reduction. The first IR technology commercially developed by Siemens Healthineers was Iterative Reconstruction in Image Space (IRIS*). IRIS directly addressed the problem of increased image noise in reduced dose acquisitions.³ IRIS is a scientifically validated technology that is effective in reducing image noise in a variety of clinical applications.^{4,5} However, it is expected that IR technologies not only aid in noise reduction but also in reducing spiral artifacts, which can be exacerbated when using CT acquisitions with reduced dose or fast acquisition techniques. In response to this, the next IR technology developed by Siemens Healthineers was the Sinogram Affirmed Iterative Reconstruction (SAFIRE**), launched in 2010.⁶

SAFIRE was Siemens Healthineers' first IR technology that integrated a correction loop in the raw-data domain (a.k.a. "sinogram") and added a model of the CT system geometry during the data forward projection. This correction loop that operates through to the raw-data domain is particularly helpful for reducing spiral artifacts. A second correction loop in image space is applied iteratively to reduce image noise. SAFIRE has been used extensively since its introduction, and a wealth of scientific literature has consistently supported the capabilities of SAFIRE to reduce dose while maintaining high image quality in applications ranging from routine to specialized body and neuro CT – in both adults and pediatrics.⁷⁻¹⁰

* In clinical practice, the use of IRIS may reduce CT patient dose depending on the clinical task, patient size, anatomical location, and clinical practice. A consultation with a radiologist and a physicist should be made to determine the appropriate dose to obtain diagnostic image quality for the particular clinical task.

** In clinical practice, the use of SAFIRE may reduce CT patient dose depending on the clinical task, patient size, anatomical location, and clinical practice. A consultation with a radiologist and a physicist should be made to determine the appropriate dose to obtain diagnostic image quality for the particular clinical task. The following test method was used to determine a 54 to 60% dose reduction when using the SAFIRE reconstruction software. Noise, CT numbers, homogeneity, low-contrast resolution, and high contrast resolution were assessed in a Gammex 438 phantom. Low dose data reconstructed with SAFIRE showed the same image quality compared to full dose data based on this test. Data on file.

Challenges to routine IR usage

One of the main challenges preventing widespread use and acceptance of IR technology is the distortion in image texture that occurs with aggressive use of IR. Image texture refers to the typical appearance (or distribution) of the image noise in CT images. When IR techniques are applied, they may produce an over-smoothed look, sometimes referred anecdotally as “plastic” or “blotchy” in appearance.

These effects are typically more noticeable in applications where low-contrast detectability is important such as abdominal CT examinations,¹¹ or when dose has been reduced to very low levels. As a result, only a limited number of clinical applications may benefit from the higher noise-reduction strengths, hence reducing the full potential for radiation dose reduction. Another important challenge for the application of IR technology in daily routine is that reconstruction speeds must be similar to conventional methods (e.g., WFBP) so as to not affect clinical workflow. One last major challenge for use of IR in daily routine, is the availability of IR algorithms on an entire fleet of scanners, especially having the technology available on mid-to low-range models.

ADMIRE

To address the emerging challenges in CT reconstruction, Siemens Healthineers has more recently released an IR technology called ADMIRE* (Advanced Modeled Iterative Reconstruction) (Figure 1). Similar to SAFIRE, ADMIRE belongs to the category of statistical IR methods, which are also denoted as model-based iterative reconstruction.¹² As with other implementations of statistical IR methods, ADMIRE is characterized by (i) the use of statistical weighting in the raw-data space followed by a back projection (unfiltered or filtered), (ii) the application of a regularization function consisting of a smoothness constraint and a statistical model in the image space, and (iii) the use of forward projection (i.e., data re-projection) with an adequate CT system model. The latter forward-projection step generates “pseudo raw data” that are compared to the measured raw data. The process of repeatedly comparing the measured raw data with pseudo raw data contributes primarily to the cancellation of spiral artifacts and, to a lesser extent, to noise reduction. The latter is mainly reduced by the loop B, which contains the regularization function in the image space.

* Image quality as defined by low contrast detectability using a model observer method for evaluation. Equivalent low contrast detectability can be achieved with 80% to 85% less dose using ADMIRE at highest strength level for thin (0.6 mm) reconstruction slices in measured and simulated body and head phantoms for low contrast objects with different contrasts. See ADMIRE data sheet for further information. In clinical practice, the use of ADMIRE may reduce CT patient dose depending on the clinical task, patient size, anatomical location, and clinical practice. A consultation with a radiologist and a physicist should be made to determine the appropriate dose to obtain diagnostic image quality for the particular clinical task.

It should be noted that repetition of the forward projection operation is often the most demanding computationally, and hence traditional statistical IR methods may require hours of reconstruction time, which noticeably limit their applicability to routine clinical workflow. In order to achieve an efficient reconstruction speed, ADMIRE uses innovative mathematical formulations that allow for reducing the number of computationally heavy forward projections. As a result, ADMIRE only requires a few iterations for the purpose of statistical optimization.¹³ The original comparison of pseudo raw data with measured raw data turns into a comparison of the current image dataset with a master 3D volume.

Although the regularization function becomes more sophisticated, the effective iteration speed is substantially higher, as only a few iterations are needed. Therefore, the ADMIRE reconstruction starts with a limited number of iterations in loop A, which are targeted to remove geometric imperfections by means of the statistical weighting in the raw-data space. As a result, iterations in the image space (loop B) are performed to finalize the statistical optimization. This translates into reaching a target noise-reduction level that depends on the selected ADMIRE strength.

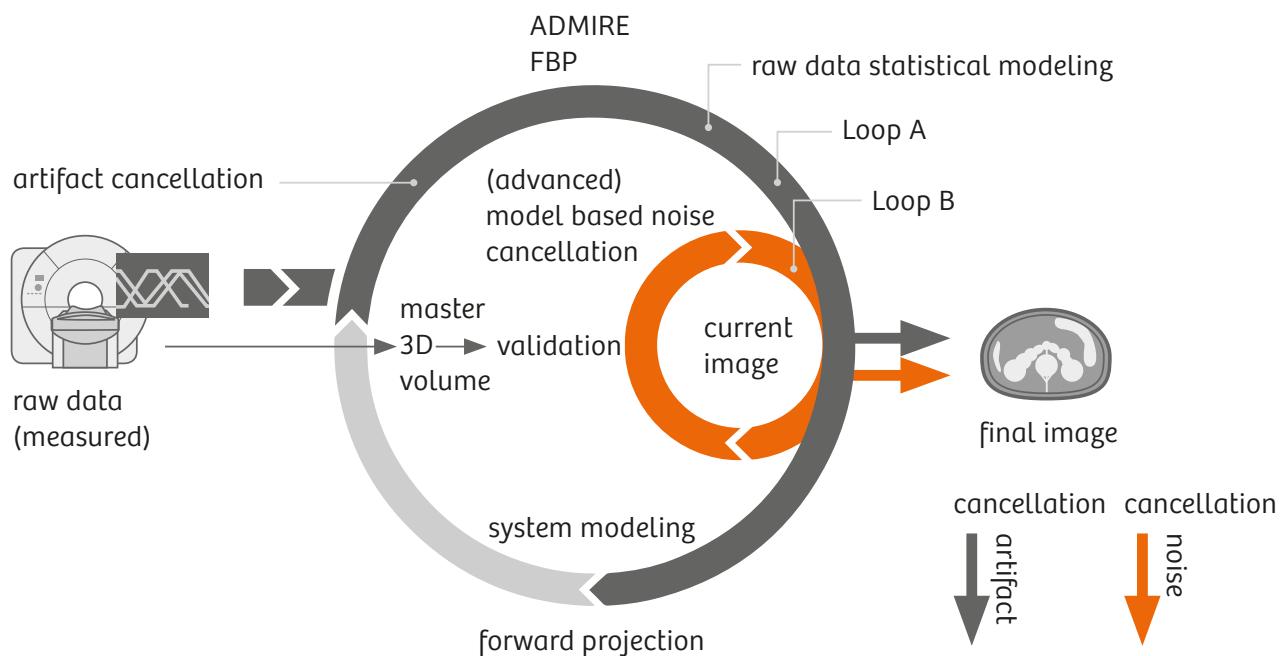
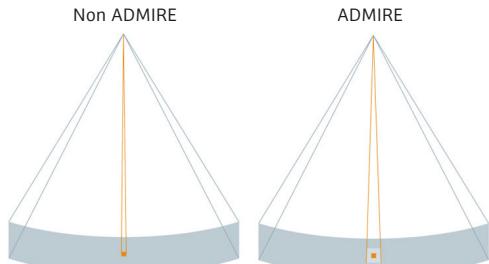


Figure 1: Algorithm scheme of ADMIRE.

ADMIRE in three steps:

1. ADMIRE uses an advanced statistical

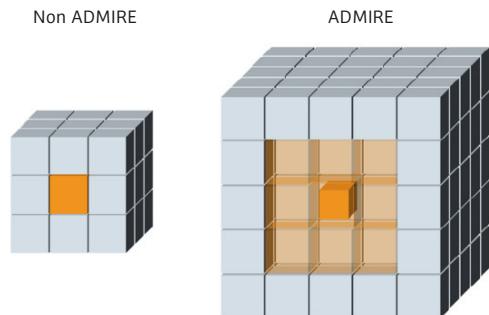
weighting of all projections in the raw-data space. As a result, each projection recorded by individual detector elements is weighted according to its statistical quality (e.g., noisy vs. higher quality signal), and integrates information of neighbor detector elements. This contributes to image noise reduction but more notably to reduce spiral artifacts.



Quality improvement in every projection and measuring points based on information of neighbor detector elements to remove streak artifacts.

2. Advanced regularization intelligently

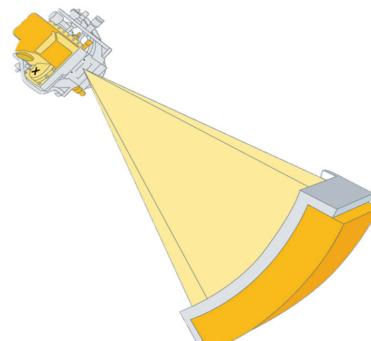
separates noise from actual anatomical structures within the image. The regularization operates within an enlarged 3D voxel neighborhood. These features contribute to an improved capability for dose reduction because they enhance noise reduction potential, but also because the natural “texture appearance” in terms of outliers in the pixel noise structure of the CT images is maintained even at higher ADMIRE strengths and/or thicker image slices.



Analysis on a large scale in all directions to distinguish anatomical structures from noise. This results in a natural image impression and excellent IQ.

3. ADMIRE incorporates a more complete

modeling of the CT geometry and scanner components and characteristics such as detector type and size (e.g., Stellar and StellarInfinity detectors) and flying focal spot. This contributes to improved spatial resolution and reduction of spiral artifacts.



Only about a year after its introduction in December 2013, ADMIRE has been spurring vivid interest as demonstrated by earlier publications in the peer-reviewed scientific literature. Table 1 (on next page) compiles some of the earlier publications covering a variety of clinical applications (chest, abdomen, cardiac and neuro CT) and highlighting technological advances specific to ADMIRE for dose reduction, noise reduction, texture preservation, and improvement of spatial resolution.¹⁴⁻¹⁸

Publication	Study Conclusion	Aspects of ADMIRE investigated and clinical application
Gordic S, et al. Ultralow-Dose Chest Computed Tomography for Pulmonary Nodule Detection: First Performance Evaluation of Single Energy Scanning With Spectral Shaping. ¹⁴	Our study suggests that chest CT for the detection of pulmonary nodules can be performed with third-generation dual-source CT producing high image quality, sensitivity, and diagnostic confidence at a very low effective radiation dose of 0.06 mSv when using a single-energy protocol at 100 kVp with spectral shaping and when using advanced iterative reconstruction techniques.	Dose reduction and noise reduction in low-dose chest CT
Newell JD, et al. Very Low-Dose (0.15 mGy) Chest CT Protocols Using the COPDGene 2 Test Object and a Third-Generation Dual-Source CT Scanner With Corresponding Third-Generation Iterative Reconstruction Software. ¹⁵	The third-generation Dual Source CT scanners using third-generation iterative reconstruction methods can acquire accurate quantitative CT images with acceptable image noise at very low-dose levels (0.15 mGy). This opens up new diagnostic and research opportunities in CT phenotyping of the lung for developing new treatments and increased understanding of pulmonary disease.	Dose reduction and noise reduction in low-dose chest CT
Gordic S, et al. Advanced modelled iterative reconstruction for abdominal CT: Qualitative and quantitative evaluation. ¹⁶	Abdominal CT using ADMIRE results in an improved image quality with lower image noise as compared with FBP, while the attenuation of various anatomical regions remains constant among reconstruction algorithms.	Noise reduction and texture preservation in abdominal CT
Meyer M, et al. Initial results of a new generation dual source CT system using only an in-plane comb filter for ultra-high resolution temporal bone imaging. ¹⁷	Temporal bone imaging without z-axis-UHR filter and a novel third-generation IR algorithm allows for significantly higher image quality while lowering effective dose when compared to the first two generations of Dual Source CTs.	Spatial resolution, noise reduction, and dose reduction in neuro CT
Solomon J, et al. Diagnostic Performance of an Advanced Modeled Iterative Reconstruction Algorithm for Low-Contrast Detectability on a Third-Generation Dual-Source MDCT Scanner: Potential for Radiation Dose Reduction in a Multireader Study. ¹⁸	Diagnostic performance for low-contrast detectability increased with increasing object size, object contrast, dose, slice thickness, and ADMIRE strength. Compared to FBP, ADMIRE allows for achieving a substantial radiation dose reduction while preserving low-contrast detectability.	Low-contrast detectability, and dose reduction in body CT

Table 1: Summary of early scientific publications of ADMIRE for various clinical applications.

Practical Aspects and Clinical Use

ADMIRE has five adjustable strength levels which can be optimized according to the clinical application and radiologist preference. The strength level, which can be selected from 1 to 5, controls the amount of noise reduction, with the highest amount of noise reduction achieved with strength 5, and with strength 3 offered as the default value. The strength level does not have an influence on the reconstruction speed, or “loops” through the raw-data space. ADMIRE has the advantage that the user can select the

spatial resolution *a priori*, which is defined by the kernel selected. **Figure 2** shows an example of coronary CT angiography in which the same CT data was reconstructed with conventional WFBP and also with ADMIRE using strength levels 3, 4, and 5. In all cases, the anatomical borders are maintained with excellent delineation of the edges, indicating preservation of spatial resolution. At the same time, the image noise substantially decreases as the ADMIRE strength level increases from 3 to 5.

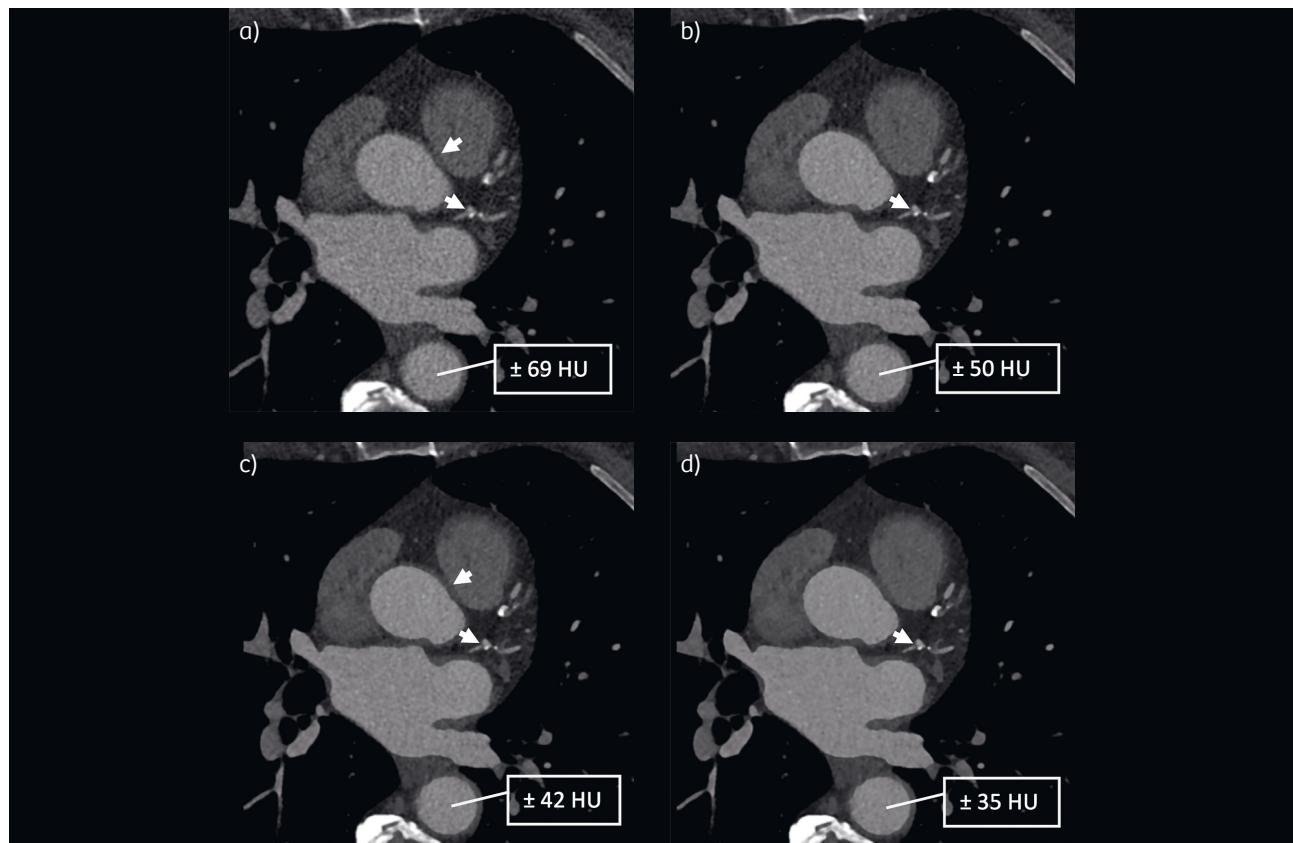


Figure 2: Example of ADMIRE in cardiac CT angiography. The patient was scanned at 70 kVp and 555 mAs, with recorded radiation exposure parameters of $CTDI_{vol} = 1.56$ mGy, $DLP = 26.1$ mGy cm. Images were reconstructed with 0.5 mm thickness using (a) WFBP, (b) ADMIRE strength 3, (c) ADMIRE strength 4, and (d) ADMIRE strength 5. The images illustrate a progressive decrease in image noise as a function of the ADMIRE strength. The two arrows in each image point to a calcification and vessel wall respectively, which are better visualized with ADMIRE. Courtesy of the Medical University of South Carolina, USA.

All the benefits of ADMIRE for noise reduction, spatial resolution improvement and artifact reduction are best achieved with the concurrent use of the Stellar^{infinity} and Stellar detectors. These detectors are available for SOMATOM Force, SOMATOM Drive, and selected CT scanners from the SOMATOM Definition family, such as the SOMATOM Definition Edge, SOMATOM Definition Flash and SOMATOM Definition AS+ scanners. A recent multireader study found that with the use of ADMIRE, they were able to significantly improve their detection rate with increasing radiation dose, slice

thickness, and ADMIRE strength over standard reconstruction.¹⁸ At the same time, the study found that compared to the standard reconstruction, ADMIRE yielded a potential for substantial dose reduction while maintaining similar detectability performance compared to higher dose acquisitions. The study authors used a 3D-printed low-contrast detail phantom, which was scanned with $CTDI_{vol}$ levels ranging from 0.7 to 5.8 mGy (Figure 3). The phantom contained cylindrical- and spherical-shaped objects, with diameter sizes of 4, 6, and 30 mm; and low-contrast levels from 5 to 20 HU.

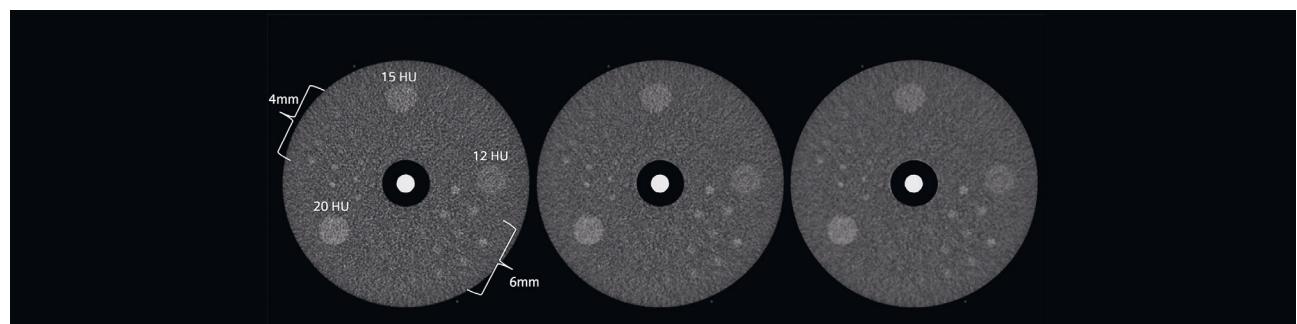


Figure 3: Low-contrast detail phantom scanned with 120 kV, $CTDI_{vol}$ = 2.97 mGy and reconstructed with standard WFBP and ADMIRE (strengths 3 and 5). Contrast levels ranged from 5 to 20 HU, with larger targets having 12, 15, and 20 HU, respectively. Indicated targets had diameters of 4 and 6 mm, respectively. A study performed with this phantom found that compared to standard reconstruction (WFBP), ADMIRE has a potential to reduce dose and maintain performance.¹⁸

Courtesy of Duke University Medical Center, USA.

Figures 4 and 5 show examples of the excellent performance of ADMIRE regarding low-contrast detectability and spatial resolution for neuro CT applications such as routine non-enhanced head CT and temporal bone imaging, respectively. Figure 6 shows an example of artifact

reduction with ADMIRE for a CT scan using a fast acquisition technique (Turbo Flash) and a tube potential of only 70 kV ($CTDI_{vol}$ = 1.67 mGy, DLP = 82 mGy cm). Artifact reduction in this example can be mainly attributed to ADMIRE's statistical weighting in the raw-data space.

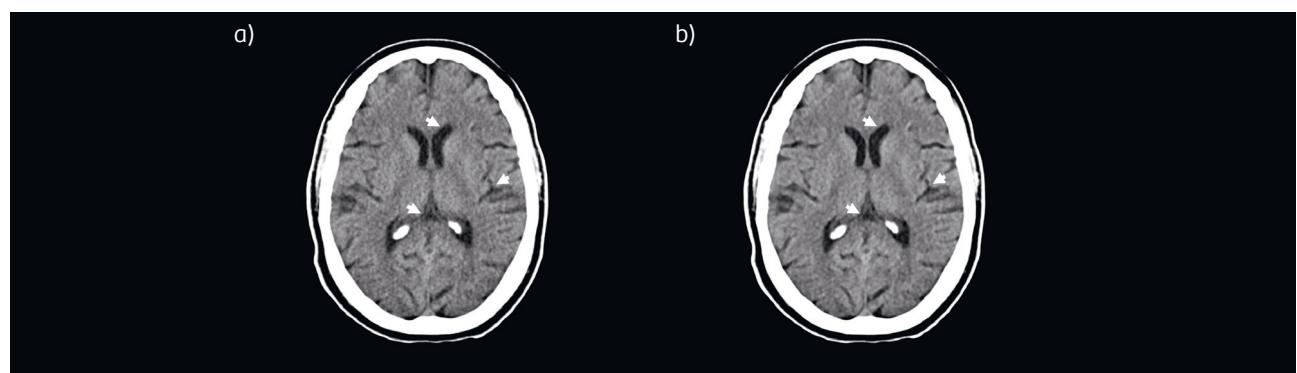


Figure 4: Example of routine non-enhanced head CT using a 5-mm slice reconstruction. (a) Routine WFBP, and (b) ADMIRE with strength 5. In the example, the calculation of the mean and standard deviation of CT numbers in selected locations (Hounsfield Units HU) showed that ADMIRE led to reduced image noise and improved CNR (2.9 vs 1.9) relative to standard WFBP reconstruction. Images reconstructed with ADMIRE also exhibited anatomical edges and borders, which were better defined (arrows) when compared with WFBP. The patient was scanned with 120 kV and 340 mAs, with recorded radiation exposure parameters of $CTDI_{vol}$ = 59.8 mGy and DLP = 1,039 mGy cm.

Courtesy of Duke University Medical Center, USA.

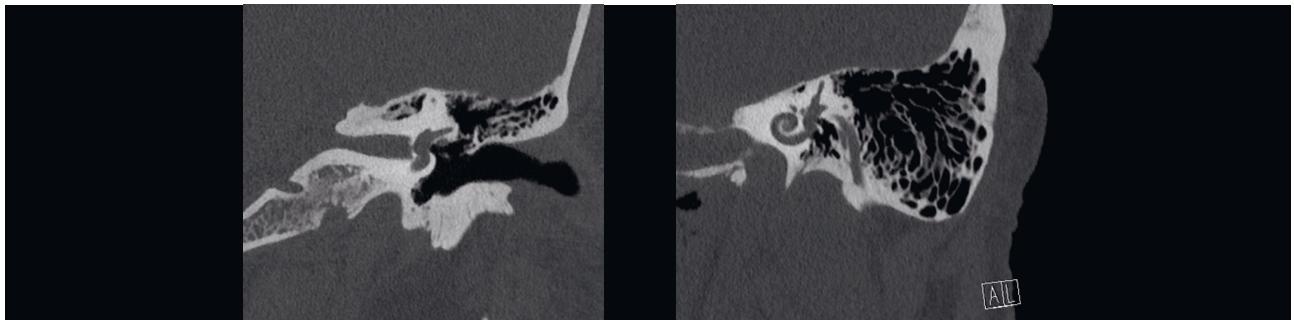


Figure 5: ADMIRE used with an ultra-high resolution temporal bone protocol for imaging of the inner ear, with an effective slice thickness of 0.4 mm. (a) Coronal and (a) oblique plane reconstructions. Data acquisition used 120 kV, CTD_{vol} = 55 mGy and DLP = 545 mGy cm. Courtesy of the Medical University of South Carolina, USA.

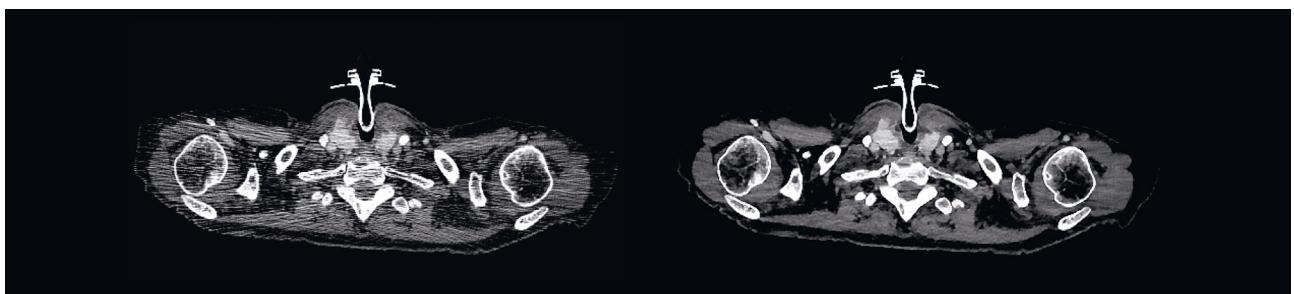


Figure 6: Artifact reduction with ADMIRE in highly attenuating anatomy such as the shoulders for an examination using 70 kV (a) WFBP, and (b) ADMIRE. Courtesy of the Medical University of South Carolina, USA.

ADMIRE also works synergistically with the Tin Filter (selective photon shield II – SPS II), a state-of-the-art technology available in the SOMATOM Force that enables further reductions in radiation dose for non-enhanced CT examinations such as chest CT.

This technology is now also available on the Dual Source CT scanner SOMATOM Drive, featuring Tin Filter on both tubes.

Figure 7 shows an example of a patient undergoing two consecutive unenhanced CT scans of the chest on SOMATOM Force. The first scan used a routine chest protocol with 120 kV, while the second scan used a reduced dose acquisition with 100 kV and Tin Filter.¹⁹ Images reconstructed with ADMIRE demonstrate the range of applicability of ADMIRE in applications that are guided by the diagnostic task. Remarkably, with Tin Filter and ADMIRE the images were acquired with a scanner radiation output of only 0.34 mGy which was significantly less than the routine acquisition of 4.27 mGy.

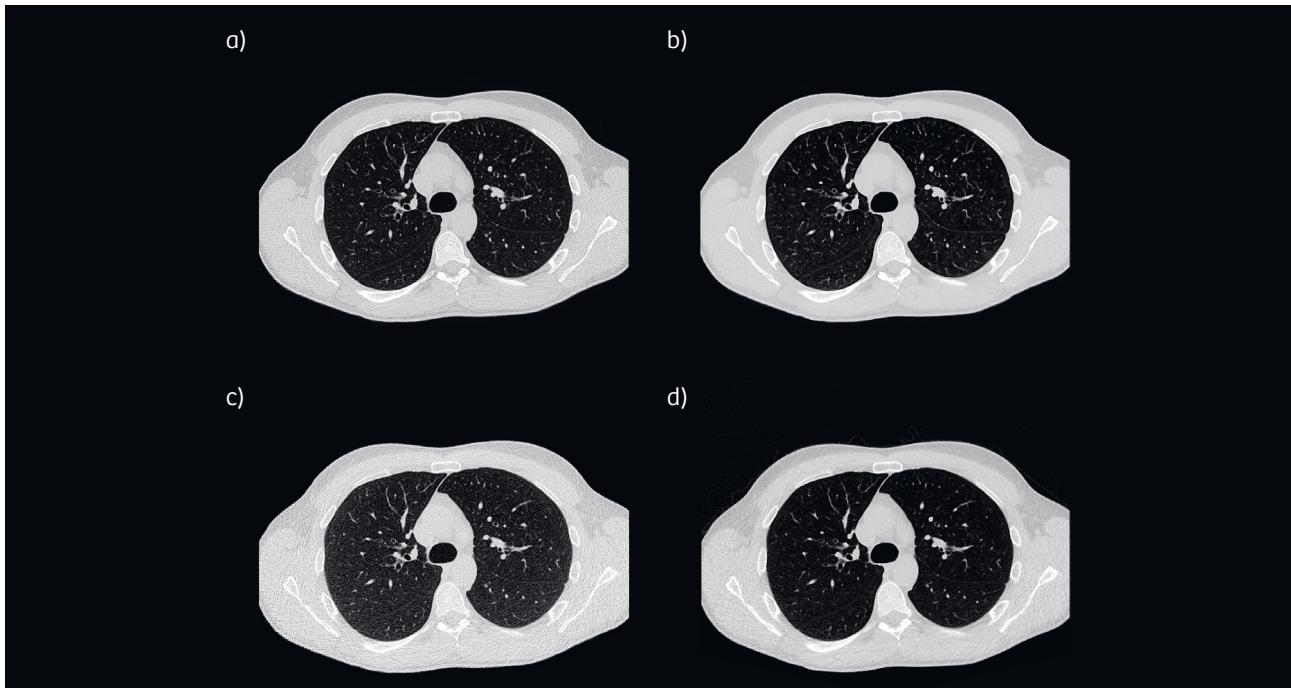


Figure 7: This example shows images of a patient who underwent two different CT scans: a routine chest CT protocol with 120 kV, $CTDI_{vol} = 4.27 \text{ mGy}$, $DLP = 171 \text{ mGy cm}$ (a, b); followed by a reduced dose chest CT protocol with 100 kV and Tin Filter (SPS II), $CTDI_{vol} = 0.34 \text{ mGy}$, $DLP = 13.6 \text{ mGy cm}$ (c, d). Images were reconstructed with conventional WFPB reconstruction (a, c) and with ADMIRE strength 4 (b, d). Courtesy of Mayo Foundation for Medical Education and Research, Rochester MN, USA.

It is also important to note that ADMIRE is compatible with dual-energy CT, a technique that continues to gain importance in clinical practice. **Figure 8** provides an example of contrast-enhanced Dual Energy CT acquisition of the abdomen using a tube potential pair

of 100 kV / $Sn^*150 \text{ kV}$. Excellent image quality is achieved for both the conventional mixed image as well as with the virtual non-contrast image, which used ADMIRE.

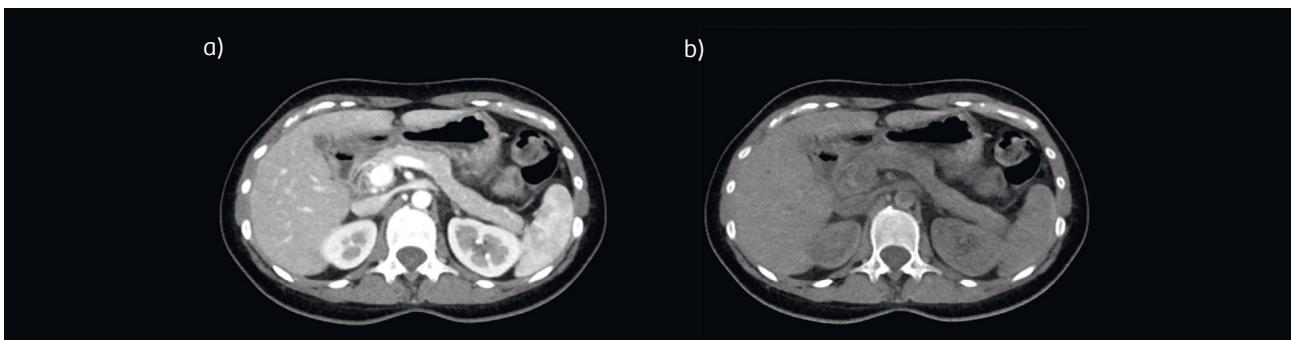


Figure 8: Application of ADMIRE in Dual Energy imaging. Data was acquired in dual source scan mode (tube A 100 kV/tube B $Sn^*150 \text{ kV}$). Images were reconstructed using ADMIRE strength 3 and were used to generate (a) mixed image and (b) virtual non-contrast image series. Courtesy of the Medical University of South Carolina, USA.

* *Sn denotes use of the Selective Photon Shield II, a Tin Filter that enables the filtration of unnecessary radiation and increases the spectral separation in Dual Energy.*

Conclusion

With the introduction of ADMIRE, Siemens Healthineers demonstrates its commitment to the continual innovation and improvement of CT technology. Importantly, this commitment extends to the goal of making IR technology available on the entire fleet of CT systems (Table 2). In this manner, IR technology is available from the most advanced systems to systems aimed for routine clinical work.

CT scanner	IR technologies available		
	ADMIRE	SAFIRE	IRIS
SOMATOM Force	X	X	
SOMATOM Drive	X		
SOMATOM Edge Plus	X	X	
SOMATOM Definition Edge	X	X	
SOMATOM Definition AS+	X*	X	
SOMATOM Definition AS 20, 40, 64		X	
SOMATOM Perspective 16, 32, 64, 128		X	
SOMATOM go.Top		X	
SOMATOM go.All		X	
SOMATOM go.Up		X	
SOMATOM go.Now		X	
SOMATOM Scope, SOMATOM Scope Power	X	X	

Table 2: IR technologies available in Siemens Healthineers fleet of CT scanners.

* Requires Stellar detector.

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