syngo TimCT – Continuous Table Move, Powered by Tim

Mathias Blasche

Siemens Medical Solutions, Erlangen, Germany

Scanning with Continuous Table Move (CTM) is a very new and exciting technology for all applications that require large anatomical coverage, beyond the scanners intrinsic field-of-view (FoV). As publications show [1–30], CTM has so far been possible only on prototype scanners, with significant modifications to the MR system.
Siemens is proud to introduce *syngo* TimCT – Continuous Table move, powered by Tim (Total imaging matrix) for the new T-class generation of Tim systems. The following chapters will discuss the physical principles of Continuous Table Move, the benefits, the scanner requirements and the Siemens implementation of Continuous Table Move: *syngo* TimCT.

TimCT – Physical Principles

There are many possible methods for Continuous Table Move, the main differentiators being the readout direction (parallel or orthogonal to the direction of table movement) and the imaging method (2D or 3D). In the literature, we find examples of a large variety of methods, e.g.

1. 2D transversal sequential scans [19, 22, 26]
2. 2D transversal multi-slice scans [13, 15, 20, 21]
3. 3D transversal scans [16, 18, 23, 24, 27]
4. 2D and 3D radial transversal scans [3, 28]
5. 3D coronal scans [1, 2, 4–6, 8–12, 14, 17, 25, 29, 30]

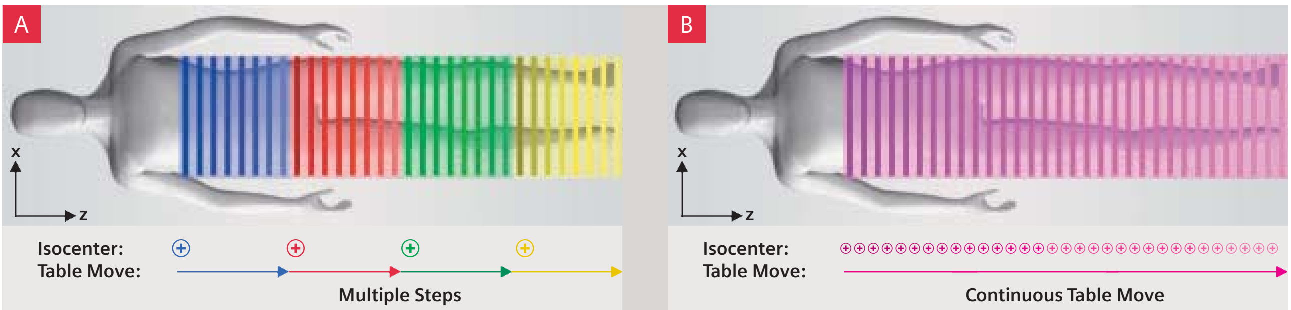
In the following, we will concentrate on the methods 1 and 5 of this list since these are the first implementations of the new Siemens product, *syngo* TimCT.

Transversal 2D Sequential

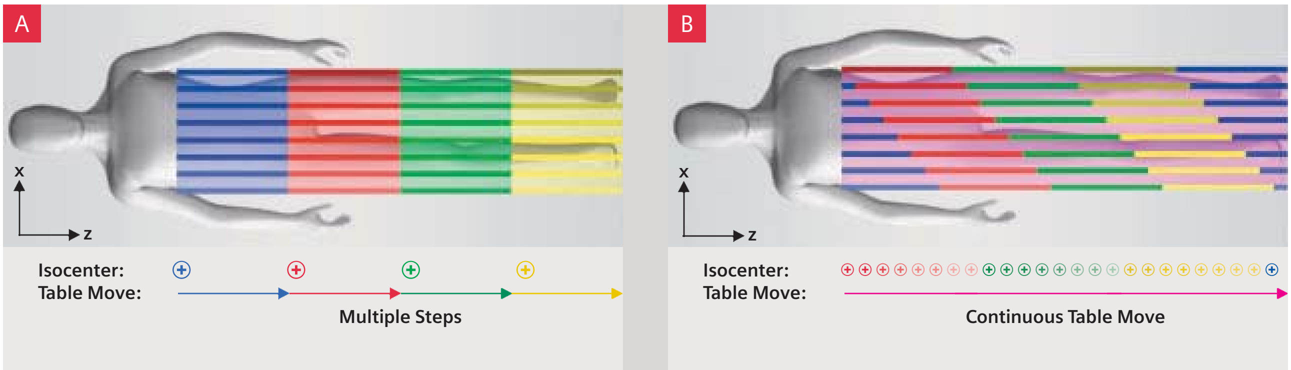
The transversal orientation is useful when one is interested in the whole extension of anatomy in both the left-right direction (x) and the anterior-posterior direction (y). The sequential mode makes sense with fast sequences (e.g., TurboFLASH, HASTE, single shot EPI) where the complete phase-encoding of the single slice can be applied without pauses.
With "Transversal 2D Sequential", each slice, in axial orientation, is measured completely before proceeding to the next slice. The sequential method is different from conventional multi-slice scans (e.g., with Spin Scho) where a stack of slices is excited in an interleaved fashion.

In conventional imaging, one would plan a stack of slices at isocenter, scan all these slices sequentially, move the table by a distance equaling the thickness of the slice stack, and repeat this process until the entire scan range is covered (Fig. 1A). This approach has some disadvantages:

a) The "outer" slices of the stack (indicated in Fig. 1 by the darker and brighter shades) are out of isocenter in a region of lower magnet homogeneity and lower gradient linearity, possibly degrading image quality.
b) Scan efficiency is compromised since it is interrupted by table moves without scanning.
c) Planning of the slice stacks is more cumbersome and time-consuming since each slice stack has to be planned exactly adjacent to its neighbors.



[Figure 1] *Transversal 2D sequential scanning with (A) conventional multi-step approach and with (B) Continuous Table Move. Each colored line represents a transversal image.*



[Figure 2] *Coronal 3D acquisition with (A) conventional multi-step approach and with (B) Continuous Table Move in hybrid k-space (z-k_x). k_x is the in-plane phase-encoding direction (left-right), while k_y (anterior-posterior, not shown) is the through-plane partition-encoding direction. Each colored line represents one partition-encoding loop, Fourier-transformed in the readout direction, z. Each color represents a complete in-plane plus through-plane encoding-cycle of one slab (in case of CTM, "virtual slab").*

"Transversal 2D Sequential" is the most intuitive method when thinking about Continuous Table Move. Each slice is exactly scanned at isocenter (indicated by identical shades of purple of lines and isocenter symbols in Fig. 1B), while the table is constantly moving.

The table velocity for "Transversal 2D Sequential" with gapless axial slices is the slice thickness divided by the scan time per slice:

$$V_{Table} = \frac{Thk_{Slice}}{N_{Phase} \cdot TR} = \frac{Thk_{Slice}}{TA}$$

Continuous Table Move with the "Transversal 2D Sequential" approach is advantageous in the following aspects:

a) Each slice is scanned at isocenter, in a region of optimal magnet homogeneity and gradient linearity, optimizing image quality.

b) Since no time is required for table movements while scanning is suspended, Continuous Table Move offers higher scan time efficiency.

c) Workflow is also facilitated by the fact that the whole slice stack can be planned in one seamless block.

The method "Transversal 2D Sequential" is implemented in TimCT FastView, used for easy extended-FoV localizer imaging. It is based on a fast TurboFLASH sequence (refer to chapter "TimCT Product Implementation" for more details).

Coronal 3D

The coronal orientation is beneficial if the region of interest has a large extension in the cranio-caudal direction (z) and the left-right direction (x), but when it is not necessary to cover the whole anatomy in the anterior-posterior direction (y). These conditions are exactly met by peripheral angiography, explaining the fact that most CTM publications about the "Coronal 3D" method cover this application.

The conventional approach to cover the entire peripheral vasculature is to acquire multiple coronal 3D slabs with overlapping regions (overlaps omitted in Fig. 2 for simplicity). Although this multi-step approach is well-established and yields very good results in clinical routine, there are a couple of intrinsic disadvantages:

a) Scan efficiency is compromised since it is interrupted by table movements without scanning.

b) Planning of the coronal slabs is more cumbersome and time-consuming since typically all slabs are aligned individually in order to seamlessly cover the whole peripheral vasculature with defined overlaps.

c) The individual slabs have to be composed to get the complete vasculature in one resulting image (although this can be done automatically with the Inline Composer).

d) The resulting composed image may suffer from "boundary artifacts", i.e. shading or signal differences at the edges of the (previously) independent 3D slabs.

As with multi-step conventional imaging, there are also "subsets" of the total scan range with Continuous Table Move. Each subset represents one complete cycle of in-plane and through-plane phase-encoding, N_x x N_y. We will call the extension of each subset in z-direction the "intrinsic FoV", or FoV_z. FoV_z is analogous to the FoV in the multi-step approach. Due to the continuous table movement, these subsets are "sheared" in hybrid k-space (z-k_x), see Fig. 2B. The echoes in z-direction are Fourier-transformed and combined. Fourier

transformations in the two remaining directions, x and y, will result in one single large FoV of the total scan range. This method, with the echo readout in z-direction, was first proposed by Kruger et al. in a publication from 2002 [1].
The maximum table velocity can be calculated by setting into relation (a) the time it takes to perform a complete encoding cycle N_x x N_y x TR to (b) the time it takes to move the table by one FoV_z. This yields:

$$V_{Table} = \frac{FoV_z}{N_x \cdot N_y \cdot TR}$$

A table velocity smaller than this maximum value is analogous to an overlap of slabs in the conventional multi-step approach. It becomes clear from this formula that the intrinsic FoV in z-direction has an effect on the achievable table velocity V_{Table} and/or spatial resolution N_x x N_y.
"Coronal 3D" with Continuous Table Move offers some significant advantages compared to the multi-step approach:

a) There are no scanning pauses for table moves, scan time efficiency is maximized.
b) Planning is straight-forward, no more difficult than planning of a single stationary FoV: The total scan range can be flexibly increased or decreased in a continuous manner, not only in multiples of the intrinsic z-FoV.
c) The total scan range is one single entity – it is "intrinsically composed".
d) The smooth scanning process will result in less boundary artifacts.

The method "Coronal 3D" is implemented in TimCT Angiography, based on a fast 3D FLASH sequence (refer to chapter "TimCT Product Implementation" for more details).

Benefits of *syngo* TimCT

When scanning a large scan range, Continuous Table Move (CTM) has many advantages compared to multi-step approaches:

Workflow

Fast workflow is probably the biggest advantage of CTM:
Easier and faster examination prescription: The setup of the examination is extremely easy. With an integrated implementation like TimCT, it is no more complicated than, for example, a conventional stationary head scan.
Reduced post-processing: Multi-step approaches can require extensive post-processing [30]. With CTM, the anatomy of the whole scan range – or any part of it in detail – can be viewed directly, without the need of any composing processing.
TimCT also supports Inline multiplanar reconstruction (MPR), Inline Subtraction and Inline maximum intensity projection (MIP): Processing is done automatically at the end of the scan, without any user interaction.

Speed

CTM has higher scan time efficiency than multi-step approaches because there are no scanning pauses during table motion. [1, 2, 17] The higher scan time efficiency is especially beneficial for contrast-enhanced MR angiography where short scan times are dictated by physiology, i.e. blood velocity.
Certain sequence techniques require dummy RF pulses in the beginning to achieve a steady state. With multi-step approaches, these need to be repeated at every level [1, 2] – which is not necessary with CTM.

Image Quality

With CTM, scans are always done exactly at isocenter, i.e. in the region of maximum homogeneity. This directly translates into improved image quality.
Especially ultrashort magnets with lower homogeneity can benefit from CTM. Continuous Table Move can significantly facilitate large-coverage scans with ultrashort magnets. [21, 22, 27]
Being intrinsically continuous, CTM provides seamless images, without the boundary artifacts that are sometimes visible in composed multi-step images. [1, 2]

Patient Comfort

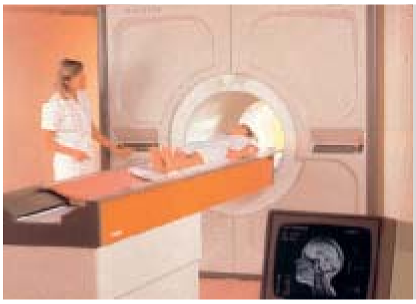
A CTM scan is a smooth process without repeated scan-move-stop procedures. The less frequent "table jerking" increases patient comfort. [9]

Be Ready for the Future

syngo TimCT – Continuous Table move, powered by Tim – offers CT-like scanning with MR. And like Spiral CT, TimCT offers a huge potential. Tremendous improvements for many applications are already visible on the horizon, e.g. interactive or even automatic adaptation of table velocity, controlled by bolus speed [8, 29]; simultaneous acquisition of multiple contrasts in one table stroke [15]; combination of Continuous Table Move with dynamic imaging [4, 5, 7]; tumor staging [19] – to name just a few.

MR – CT Analogies

Although magnetic resonance imaging (MRI) and computed tomography (CT) are fundamentally different in the way the images are generated, there are some striking analogies in the historical development of both modalities.



MR in the 80s – The Decade of Magnets

One could call the 80s the "decade of magnets". The main topic at that time was the question for the optimal field strength – 0.5T, 1T or 1.5T. MR systems at that time had only one RF channel and slow gradients.

The CT analogy at that time was the question for the best detector material, gas or solid state. CT scanners in the 80s had slow rotation times and only one detector ring.

MR in the 90s – The Decade of Gradients

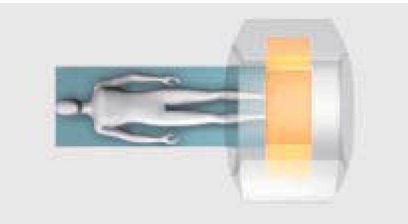
Gradient performance was the most critical question in the 90s. Both gradient amplitude and slew rate were increased by orders of magnitude, up to the limit where gradient performance is no longer limited by technology, but by the patient's peripheral nerve stimulation limit.

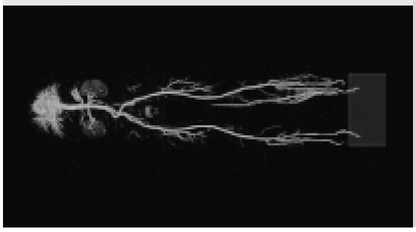
At the same time, CT saw an increase in rotation speed, up to more than 3 rotations per second.

MR in the 2000s – The Decade of RF

RF technology and Parallel Imaging have been the primary focus in this decade, with an increase of the number of RF channels and the development of "high-density" coils. Siemens introduced Integrated Panoramic Array (IPA) as early as 1997, and Tim (Total imaging matrix) technology in 2003, with up to 102 seamlessly integrated coil elements and up to 32 truly independent RF channels. There is even a prototype with 128 RF channels. Tim offers high flexibility, accuracy and speed, with high PAT factors in all body regions and all directions.

The CT analogy to RF technology is multi-detector technology, also offering larger coverage in less time, with higher image quality and spatial resolution.





MR in 2006 – TimCT

Now, in 2006, Siemens pioneers TimCT – Continuous Table move, powered by Tim. Peripheral run-off studies can be done faster, and TimCT tremendously facilitates the workflow. The potential of TimCT for peripheral angiography and for other applications is huge.

MR's TimCT is very similar to CT's spiral technology. Both technologies enable seamless scanning – with high speed and ease of use.

Actually, spiral CT scanners have been available for more than 15 years. One might take this as a proof point that it was about time that MR caught up with CT in this technological perspective. Actually we expect that MR systems without TimCT capabilities will be similarly shunned in a few years as CT scanners without spiral capabilities would be today.

Requirements for *syngo* TimCT

Scanning with Continuous Table Move (in analogy to Spiral CT) and not wasting time for multiple Scan–Stop–Adjust procedures sounds straight-forward and easy. However, it is not trivial. The MR system has to meet numerous requirements to make TimCT possible. Here is a list of all the technical requirements and how these are met by *syngo* TimCT.

Table Requirements	
Shielded table drive The electronics of the patient table need to be shielded. An unshielded table would result in electronic interferences and consequently image artifacts.	*syngo* TimCT ✓ Actually, the patient tables of all Tim systems are shielded. Siemens had the vision of TimCT years ago and prepared the scanners accordingly – which made it much easier to implement TimCT and makes it easier to upgrade to TimCT, too.
Software-enabled table motion For routine clinical use, manual table motion is of course no alternative. It is imperative that the table can be moved from the console, easily and flexibly. The remote table move capabilities need to cover the whole scanning distance.	*syngo* TimCT ✓ Software-enabled table motion is standard with all Tim systems. One major aspect here is that the cables of the Tim coils are very short and – unique to Siemens – plug into the table, thus reducing the risk that the cables get jammed during the table move.
Control of table speed with high accuracy For sub-millimeter image resolution, the accuracy of the patient table has to be accordingly high. Furthermore, software-controlled sub-pixel correction has to be implemented. [1]	*syngo* TimCT ✓ All Tim systems feature an accurate control of table speed and position. In addition, a sub-pixel software correction is implemented with TimCT.
Software Requirements	
Sequences Imaging sequences supporting Continuous Table Move are required.	*syngo* TimCT ✓ TimCT FastView and TimCT Angiography are available with the new T-class generation of scanners (software *syngo* MR B15). The flexible architecture of IDEA, our sequence programming tool, facilitates the development of TimCT sequences.
Image processing The measured raw data need to be corrected, processed and displayed automatically in order to guarantee a smooth workflow.	*syngo* TimCT ✓ With TimCT, image processing is fully integrated, including corrections (see below), fully automated image reconstruction of the full FoV, Inline MPR, and Inline Subtraction & Inline MIP for angiography.
Graphical slice positioning Beyond the "standard" capabilities, graphical slice positioning needs to offer specific features, e.g. independent control of intrinsic FoV and total scan range, control of active coil elements etc.	*syngo* TimCT ✓ With the Tim Planning Suite, we were already prepared for most aspects of TimCT graphical slice positioning. With T-class, an intuitive (color-based) control of intrinsic FoV and total scan range has been added.

Software Requirements	
■ **Adjustments** Frequency, transmitter and receiver adjustments must be available over the whole scan range.	*syngo* TimCT ✓ Frequency and transmitter adjustments are performed in a short TimCT Adjustment scan, also during table motion. A time-consuming receiver adjustment is in general not required with all Tim systems, due to the large dynamic range of the receiver.
Image Quality Requirements	
■ **High SNR and high spatial resolution** The requirements for optimal diagnostic quality can only be met with surface coils. In comparison to an integrated body coil, surface coils offer 2-4 times more signal-to-noise ratio (SNR). The benefit of surface coils has often been mentioned in the literature [5, 8, 16, 17, 29].	*syngo* TimCT ✓ With his readily available Matrix coils, Tim is the ideal basis for TimCT. The "high-density" Matrix coils offer highest SNR in all body regions which can easily be translated into high spatial resolution and short scan times.
■ **Gradient non-linearity correction** It is known from the literature that gradient non-linearity correction is basically a must for Continuous Table Move scanning. Without this correction, the lateral anatomy would become blurry – the farther outside of isocenter, the worse [6, 25].	*syngo* TimCT ✓ Inline gradient non-linearity correction is fully integrated into TimCT and automatically performed.
■ **Phase correction** A phase correction in the readout direction is required for coronal scans, in order to avoid a shading pattern in the reconstructed images [11].	*syngo* TimCT ✓ Phase correction is fully implemented with TimCT Angiography.
Speed Requirements	
■ **Parallel Imaging** Parallel Acquisition Techniques (PAT) have become accepted for the majority of applications. PAT is an *essential* tool for higher speed. Especially for peripheral angiography, short scan times (to follow the contrast bolus) combined with high spatial resolution (to be able to diagnose also small vessels and pathologies) are critical [30].	*syngo* TimCT ✓ Again it comes back to Tim, with "high-density" coils in all body regions, enabling Parallel Acquisition Techniques (PAT) in all directions. TimCT is compatible with iPAT using Tim's unique Matrix coil design. Note that Parallel Imaging can *only* be performed with surface coils, not with an integrated body coil. See section "Coil Technology Requirements" below.
■ **Calibration for Parallel Imaging** Coil calibration for Parallel Imaging needs to be possible with a continuously moving table. Many implementations today rely on separate calibration scans that are not integrated into the scan. A large number of these calibration scans would be necessary to cover the whole scan range which would result in very long examination times and low productivity.	*syngo* TimCT ✓ The Auto-Calibration algorithm, standard with Siemens iPAT (integrated Parallel Acquisition Techniques), is the ideal solution for Parallel Imaging with Continuous Table Move. The benefits of Auto-Calibration are covered in [30].

Coil Technology Requirements	
Connection of multiple coils Given the fact that good diagnostic image quality can only be achieved with surface coils, it needs to be possible to connect all surface coils simultaneously for full anatomical coverage.	*syngo* TimCT ✓ Beside having a "high density" of coil elements for optimal image quality, one of the major benefits of Tim is the possibility to simultaneously connect up to 10 coils, with up to 102/76 (3T/1.5T) seamlessly integrated coil elements.
Flexible coil combinations For flexible coverage of arbitrary regions-of-interest, coil combinations are required.	*syngo* TimCT ✓ With Tim all Matrix coils can be combined for seamless anatomical coverage. Elements from different coils can be used simultaneously.
Surface coils plug into patient table With multiple coils being connected for large anatomical coverage, coil cables need to be short and integrated into the table. Long coil cables (e.g. attached to the magnet front) create safety issues during table movement.	*syngo* TimCT ✓ All Matrix coils have very short coil cables that directly plug into the patient table.
Automatic coil detection With a large scan range being covered by multiple coils, it would be extremely cumbersome and time-consuming if the user had to "teach" the system the exact location of each coil element. Therefore, the exact position of each coil has to be detected automatically.	*syngo* TimCT ✓ All Tim systems feature AutoCoilDetect. All coil elements are automatically detected in the localizer scan and depicted in the graphical slice positioning.
Dynamic coil switching Beyond the detection of the coils, it is also necessary to automatically activate and de-activate the coil elements during Continuous Table Move. It would be next to impossible to manually pre-select the coil switching for a continuous scan during table motion. For a discussion of the benefits of dynamic coil switching see [30].	*syngo* TimCT ✓ With AutoCoilDetect (see above), the Tim systems were already prepared for the next step, AutoCoilSelect. Now, the user does not need to take care of coil selections at all, boosting workflow and robustness – and being one of the major revolutionary features that make TimCT possible.
Patient Safety Requirements	
SAR monitor SAR values need to be known for all body locations.	*syngo* TimCT ✓ SAR is checked for the whole scan range in a short TimCT Adjustment scan.

In summary

As the literature about Continuous Table Move (CTM) shows, only a few sites worldwide have been working on CTM. The reason for this is the long list of very challenging technical requirements for Continuous Table Move.
All CTM sites so far have been pure prototype installations that have to cope with limitations including a) external control for table motion, b) external image processing, c) scans with the body coil only, no surface coils, and d) no Parallel Acquisition Techniques.
With Tim, Siemens has the ideal platform for the implementation of TimCT. This is expressed with "*syngo* TimCT – powered by Tim".

syngo TimCT Product Implementation

syngo TimCT FastView

TimCT FastView is an extremely fast localizer sequence. It is based on a sequential TurboFLASH sequence, i.e. all slices are acquired in a sequential mode. Each slice is scanned at isocenter while the table is moving. The slice orientation is axial.

The rather coarse spatial resolution allows very fast scanning, with a table velocity as high as 5 cm/sec – e.g., 150 cm can be covered in just 30 seconds.

Benefits of TimCT FastView:

- Inline Technology is implemented: With Inline MPR, sagittal and coronal reformats are automatically generated on the fly.
- TimCT FastView can be immediately performed without any adjustments. SAR (specific absorption rate) is extremely low since only small flip angles are used. TimCT FastView is done with the integrated body coil and can be done independently of any coil used for the specific examination.
- TimCT FastView can even be initiated without laser light positioning, using a preset (user-definable) scan range that e.g. covers the whole spine. This has the potential to increase productivity due to shorter patient setup times.

TimCT FastView is standard with all T-class systems.

syngo TimCT Angiography

TimCT Angiography is optimized for contrast-enhanced peripheral run-off studies in coronal (or sagittal) orientation. It is a high-resolution 3D sequence. TimCT Angiography has the full flexibility of all parameters, as in a "conventional" scan. Additionally, the total scan range can be flexibly increased beyond the intrinsic FoV of the scanner.

Benefits of TimCT Angiography:

- Workflow is facilitated since the whole process is completely automated. The setup of the scan is easier than a conventional multi-step approach, planning steps are reduced by up to 50%. Inline Subtraction and Inline MIP, all automatically processed with Inline Technology, further increase the examination speed.
- TimCT Angiography offers maximum scan time efficiency – no scan interrupts during table move phases as in conventional multi-step approaches. Consequently, the contrast bolus can be tracked faster and/or with higher spatial resolution.
- Tim technology, AutoCoilDetect and AutoCoilSelect, all exclusive to Siemens, make it possible to perform TimCT Angiography with optimal image quality, i.e. with a signal-to-noise ratio that can only be achieved with surface coils.

TimCT Angiography is an option for all T-class systems.

syngo TimCT Adjustments

The TimCT Adjustments cover all adjustments that are required to run a TimCT scan with optimal image quality, fast workflow and full patient safety.

The TimCT Adjustments include Frequency Adjustment, Transmitter Adjustments, SAR Monitoring, AutoCoilDetect and AutoCoilSelect for all locations of the whole scan range. The adjusted values are then dynamically applied to the TimCT measurement on the fly. All connected coils are automically detected during the TimCT Adjustments and then automatically selected during the TimCT measurement.

TimCT FastView does not require adjustments (see above).

The TimCT Adjustments can be run in combination with TimCT FastView (prior to TimCT Angiography), or they will be automatically performed with TimCT Angiography if they have not been done before.

The TimCT Adjustments are very fast and are performed with a table velocity of 5 cm/sec.

Prerequisites

T-class and *syngo* TimCT are available for

- MAGNETOM Trio, A Tim system
- MAGNETOM Avanto
- MAGNETOM Espree
- MAGNETOM Symphony, A Tim system

syngo TimCT is exclusive to the new generation T-class systems, introduced at the RSNA 2006. All Tim systems are upgradable to T-class.

syngo TimCT is compatible with 18 and 32 RF channels, i.e. Tim [76x18] and Tim [76x32] for 1.5T systems, and Tim [102x18] and Tim [102x32] for 3T.

The maximum scan range of all Tim systems is sufficient for a complete peripheral run-off study, i.e. from the renal arteries to the feet. Whole-body coverage is possible with the Telescopic Table which is part of the Tim Whole-Body Suite (optional).

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