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Original paper

A novel concept for CT with fixed anodes (FACT): Medical imaging based on the feasibility of thermal load capacity

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A B S T R A C T

Focussing primarily on thermal load capacity, we describe the performance of a novel fixed anode CT (FACT) compared with a 100 kW reference CT. Being a fixed system, FACT has no focal spot blurring of the X-ray source during projection. Monte Carlo and finite element methods were used to determine the fluence proportional to thermal capacity. Studies of repeated short-time exposures showed that FACT could operate in pulsed mode for an unlimited period. A virtual model for FACT was constructed to analyse various temporal sequences for the X-ray source ring, representing a circular array of 1160 fixed anodes in the gantry. Assuming similar detector properties at a very small integration time, image quality was investigated using an image reconstruction library. Our model showed that approximately 60 gantry rounds per second, i.e. 60 sequential targetings of the 1160 anodes per second, were required to achieve a performance level equivalent to that of the reference CT (relative performance, RP = 1) at equivalent image quality. The optimal projection duration in each direction was about 10 µs. With a beam pause of 1 µs between projections, 78.4 gantry rounds per second with consecutive source activity were thermally possible at a given thermal focal spot. The settings allowed for a 1.3-fold (RP = 1.3) shorter scan time than conventional CT while maintaining radiation exposure and image quality. Based on the high number of rounds, FACT supports a high image frame rate at low doses, which would be beneficial in a wide range of diagnostic and technical applications.

Introduction

Third-generation computed tomography (CT) scanners incorporate an X-ray tube and a detector arrangement that mechanically rotate around the patient. Current clinical CT scanners and most industrial CT scanners operate on this principle.

During recent decades, volumetric CT imaging has advanced with the advent of spiral acquisition [1,2] and the progression to multidetector row CT (MDCT) scanners [3]. During continuous movement of the couch, these systems acquire sufficient information in a helical path for reconstructing images from raw projection data. An increased number of detector rows provides the advantages of thinner slices, shorter scan times, and reduced motion artefacts.

Particularly due to the rapid increase in the number of installed detector rows, there is a desire to obtain sufficient volume coverage in the axial direction during a single rotation, in which the X-ray tube rotates around in the gantry. However, a wide X-ray beam has a number of drawbacks, such as increased scattering, overscanning, and cone-beam artefacts at large cone angles. Various approaches and novel concepts have been proposed to address different issues [4–10]. Besides, the approaches of the fourth-generation CT and the electron beam CT (EBCT) [11] are currently not in widespread use. Recently, an inverse-geometry CT (IGCT) system was proposed to achieve a scanned volume during a single gantry rotation that was essentially free of cone-beam artefacts [12–15].

Scanning a volume during a single rotation is limited by the gantry rotation time because centrifugal force can become destructive. Taking this mechanical restriction out of a system, the maximum temperature at the focal spot of an X-ray anode poses a serious limitation for the scanning time.

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In this paper, we described a concept for CT based on a ring of stationary X-ray sources, as proposed by Foster and Müller [16–18] from our group. The investigations of possible achievable image frame rates were closely related to potential performance. In general, a number of medical applications can benefit from a high image frame rate for a volume, including cardiac imaging, CT angiography, perfusion studies, and other demanding imaging applications.

The potential performance of a conventional CT is primarily limited by the thermal load capacity of the X-ray anode. Thus, we began with studies on the thermal load capacities of anode focal spots. For these studies, a CT concept was outlined that had no mechanical restrictions due to gantry movements and that allowed for a high image frame rate, which was coupled with operated rounds in the stationary X-ray source ring at doses normally used for patients. The aim of the paper is to provide a conceptual theoretical framework for CT with fixed anodes based on the feasibility of thermal load capacity. However, this paper does not cover technical feasibility of the source ring and does not consider detector performance or efficiency. Since detectors need to be developed as per their specific requirements, we used as a benchmark today's acquisition of X-ray attenuation without an adaptation to the novel concept. Furthermore, the detection properties of the currently used integration times are extrapolated linearly to small time ranges. This means that the same total energy and photon fluence per projection yields identical image quality.

Basic concept

The basic concept for CT with fixed anodes (FACT) is illustrated in Fig. 1.

The generation of a primary X-ray beam from an X-ray tube follows the same principle that has been known for over a century. A rotating anode X-ray tube, which conventionally revolves in a gantry around an object, is replaced in FACT by a stationary source ring of fixed anodes. In the current study, 1160 fixed X-ray anodes were used, analogous to the reference CT specified in Table 1.

For theoretical analysis, the beam at a single fixed anode allows being switched on and off at any frequency. The fixed anodes in the source ring were used in sequential operation. Due to the restricted exposure time for each direction, the required number of projections for typical image information was acquired using multiple gantry rounds (~20). Projection data were combined during pre- or post-processing to acquire equivalent information analogous to the principle used in the reference CT.

Throughout these studies, we chose parameters of our design in accordance with the reference CT, which was also used as a benchmark to determine the performance of our novel concept. The operating data for this reference CT (see Table 1) were based on SOMATOM Definition, Siemens Medical Solutions, Forchheim, Germany.

Using an impact angle close to the right angle to the target surface, as considered by us at 84° (anode angle of 6°), the following approximate relation [19] applies to electrical X-ray tube power (P_{el}) and thermal focal spot power (P_{th}):

$$P_{th} \approx \frac{1}{2} \cdot P_{el} \tag{1}$$

This approximation applies to both fixed anodes, used in the FACT concept, as well as the rotating anode, used in the reference CT. Preliminary simulations of energy deposition in the focal spot confirmed this approximation within a deviation of 1% for the considered acceleration voltages of 80 kV, and even of 120 kV. We thus only present the simulation results at 80 kV.

Methods

In the following, the thermal load capability of a single fixed anode is first studied and compared with a rotating anode. Subsequently, the fixed anode is used as an isolated and independent module in the arrangement for the FACT concept.

Simulations of the thermal loads for a single anode

3D simulation models

In a simulation model, each fixed anode in the source ring of FACT was usually modelled as a sandwich of a high-Z material, a body with high thermal conductivity, and a heat bath for cooling: The square body was made of copper (Cu) with a base area of 25 mm by 3.2 mm and a height of 20 mm. Towards the focal spot, the tungsten (W) target layer of 0.5 mm thickness was adjoined without contact resistance. On the opposite side of the copper body, a heat bath at 300 K for cooling was defined. Away from the heat bath for all other surface boundary conditions and for the worst case scenario, a thermal insulation was chosen (see also Fig. 2).

This fixed anode model was extended to a rotating anode model analogous to the principle used for the reference CT (see Table 1). Our model of a rotating anode with a radius of 60 mm had the same sandwich configuration as the fixed anode defined above. The non-conventional use of copper as a base for a rotating disk was

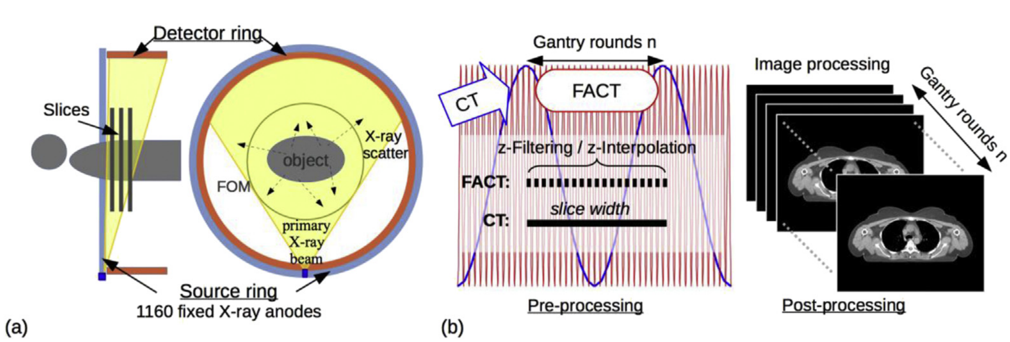

Figure 1. Basic concept for FACT. (a) Geometric relationships of a FACT with a single source ring and a detector ring. (b) At helical source path for FACT, compared to that of a multi-slice spiral CT, the reconstructed images are normally determined by pre-processing. Alternatively, the information for the reconstructed images could be combined during post-processing, as employed in Section *Medical Imaging*. (Additional figures can be found in supplementary data, Fig. 1e).