Nuclear Instruments and Methods in Physics Research A 629 (2011) 350–356

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

Dedicated scanner for laboratory investigations on cone-beam CT/SPECT imaging of the breast

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ARTICLE INFO

Article history:
Received 28 July 2010
Accepted 20 October 2010
Available online 5 November 2010

Keywords:
Breast computed tomography—SPECT/CT multimodality imaging

ABSTRACT

We describe the design, realization and basic tests of a prototype Cone-Beam Breast Computed Tomography (CBBCT) scanner, combined with a SPECT head consisting of a compact pinhole gamma camera based on a photon counting CdTe hybrid pixel detector. The instrument features a 40 μm focal spot X-ray tube, a 50 μm pitch flat panel detector and a 1-mm-thick, 55 μm pitch CdTe pixel detector. Preliminary imaging tests of the separate CT and gamma-ray units are presented showing a resolution in CT of 3.2 mm^{-1} at a radial distance of 50 mm from the rotation axis and that the 5 and 8 mm hot masses (^{99m}Tc labeled with a 15:1 activity ratio with respect to the background) can be detected in planar gamma-ray imaging with a contrast-to-noise ratio of about 4.

1. Introduction

In the last three years, the Italian Institute for Nuclear Physics (INFN; Technology Research Committee) has approved research projects (BREAST-CT in 2007–2008, and BCT in 2009–2011) for investigation of the scientific and technological aspects of a new X-ray imaging technique, proposed for diagnosis of breast cancer [1,2]. This technique consists of X-ray Computed Tomography (CT) of the breast with a dedicated scanner employing X-ray cone-beam irradiation geometry and a flat panel digital detector, with the woman in the prone position and one breast at a time freely pending from a hole in the patient bed. In the following, we briefly summarize the rationale for this imaging modality and its requirements, in order to introduce the design and performance tests of the dedicated laboratory CT scanner under realization.

The need for a dedicated CT device arises from the need to reduce the radiation dose to the non-target chest tissue. In fact, early studies in the 1970s investigating the role of CT in breast cancer screening employed conventional scanner technology in which the X-ray beam passed through the thorax and exposed the non-breast tissues to high radiation doses. Moreover, cardiac and respiratory motion artifacts also contributed to poor image quality, and all these concerns led to the dismissal of the (conventional) breast CT technique in breast cancer screening programmes. In the recently proposed Cone-Beam Breast CT (CBBCT) technique, now under study in a number of research centers [3], only the breast tissue and part of the chest wall are exposed to the X-ray beam, thus confining the radiation dose to the breast only.

At present, the gold standard for breast cancer diagnosis is X-ray mammography, usually performed in two views of each breast. Breast CT is a 3-D imaging technique of an uncompressed breast, employing harder X-ray beams than those in mammography. Breast CT has the ability to visualize tissue lesions separated from overlying normal tissue structures, which introduce a structural background related to the morphology of the normal glandular tissue. In order to be proposed as a dose-comparable technique to mammography in breast cancer screening, CBBCT has to deliver a mean glandular dose (MGD) not exceeding the equivalent MGD for two view mammography for the equivalent average breast (the European guidelines for quality assurance in digital mammography indicate a maximum value of 2.5 mGy for one-view, for an average compressed breast of 5.3 cm) [4].

The average uncompressed breast diameter (to be imaged in CBBCT), as measured at the chest wall, was found to be 14 cm [5], corresponding to 5 cm for the same compressed breast as imaged in conventional mammography [6]. With an uncompressed breast, the requirement of a MGD of about 5 mGy (50% glandular fraction, for a 14 cm diameter breast) combined with good image quality, can be achieved using W-anode X-ray tubes operated at typically 80 kVp tube voltage, with X-ray tube currents in the order of a few mA, flat panel digital detectors operated at 30 frames per second (fps), scanning times in the range 10 – 20 s [1] and optimal magnification factors in the range 1.4 – 2.2 [7]. This scan time is much longer than in mammography but short enough for operating in a breath-hold condition.

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doi:10.1016/j.nima.2010.10.093

The first of such prototype scanners has been built at University of California at Davis; similar prototypes have been developed at the University of Rochester [2], Duke University [8], M.D. Anderson Cancer Center [9] and the University of Massachusetts, Worcester [10]. In the European Union, an FP7 Project (‘‘Dedicated CT of the female breast’’) led by University of Erlangen, Germany, was started in January 2008 [11], but no dedicated scanner development has been reported yet. The first clinical trials were started by the UC Davis group in 2004 and reports have been presented recently by this group [12] and by the University of Rochester group [13]. It has been speculated that CBBCT could be pursued as a means of detecting breast cancer masses with dimensions lower than the minimum dimension of tumors diagnosed in conventional mammography [3]. This would represent a significant improvement in diagnostic power, since detection of a smaller sized tumor implies a lower chance for cancer metastasis and a higher chance of efficacy of the therapies, thus a higher patient survival rate.

The above USA groups have developed dedicated CBBCT clinical scanners with one or few degrees of freedom as regards the gantry movements, and some groups are investigating the addition to their X-ray CT scanner for *anatomical* imaging of a second scan head for *functional* imaging, e.g. for Single Photon Emission Computed Tomography (SPECT) [8] or Positron Emission Tomography (PET) [14] with radiotracers injected in the body and accumulating preferentially in the breast lesions.

Our group at the University and INFN Napoli has realized a prototype scanner for laboratory investigations on CBBCT [15]. The table-top scanner could host, on the same rotating gantry, detector units for PET or SPECT. At the same time the device modularity allows one to implement the digital breast tomosynthesis technique for technology comparison.

The main feature of this scanner is the use of fine pitch detectors (50 μm) and mini or microfocus X-ray sources (from 5 to 100 μm focal spot size). These features give the potential for high spatial resolution in the reconstructed CT images, a key point for effective detection of microcalcifications (i.e. small calcium deposits in the breast with a size less than half a millimeter). We use this device for technology assessment and comprehension. The use of this scanner in a clinical environment has a number of drawbacks at present, mainly related to the limited tube current that imposes scan times of a few minutes, low frame rate and reduced detector sensitivity. However, the use of breast holders to limit the organ motion during a scan would permit longer scan times than presently performed in all CBBCT scanners in clinical use.

Following our efforts for the realization of a semiconductor compact gamma camera based on a CdTe pixel detector [16,17], we have designed a small field of view (FOV) SPECT head to be mounted on the CBBCT gantry, in order to assemble a CBBCT/SPECT hybrid scanner dedicated to the breast. Our goal is to provide a limited FOV functional (SPECT) view of suspected regions fused with high resolution anatomical (CT) view of the whole breast.

The CBBCT part of this scanner has been upgraded with respect to the setup described in a previous work [15]; the present version features a new mechanical assembly, completely re-designed and re-assembled in order to assure very high mechanical stability and precision, required for the higher spatial resolution of the microCT imaging. This work describes this new laboratory instrument and presents separate tests of the two imaging units.

2. Materials and methods

The hybrid scanner (SPECT and CT) dedicated to the breast, under development at the University and INFN Napoli, is composed of a CBBCT scanner with a rotating gantry [15] on which is placed a compact semiconductor gamma camera.

2.1. CBBCT scanner

The CBBCT prototype (Fig. 1) is a modular, bench-top system consisting of a step-motor rotating gantry, a W-anode X-ray tube, a CMOS CsI:Tl Flat Panel Detector, custom acquisition software and a commercial cone-beam CT reconstruction software. Step-motor translation/rotation stages allow one to regulate image magnification, the detector tilting angle and the height of the X-ray tube below the ‘‘patient bed’’ and that of the detector.

2.1.1. X-ray sources

Either of the two X-ray sources can be mounted on the scanner. The first source is a computer-controlled (RS-232 interface) minifocus X-ray tube (SB-80-250, Source-Ray Inc., Bohemia, NY, USA; continuous output, fixed anode, forced air cooled), operated between 35 and 80 kVp with a tube current of up to 0.25 mA. The tube has a tungsten anode, a carbon fiber window, a 50 μm minimum focal spot size and an inherent filtration of 1.8 mm Al. Additional filtration of the beam is provided by a 0.2 mm Cu filter. At 80 kVp, the measured half value layer was 5.6 mm Al. The ripple is $<1\%$. A four-blade W collimator in front of the X-ray source allows one to produce a true cone-beam, a half cone-beam or a fan beam. The beam can be switched on and off via the software (with a 0.25 s rise time). Tests shown here refer to this X-ray source. The second source available is a microfocus X-ray tube (Hamamatsu model L8121-03), a 75 W tungsten-anode tube operated in the range $40-150$ kV with a tube current of up to 500 μA. The focal spot size at 80 kV ranges from 7 (at 120 μA tube current) to 50 μm (at 500 μA). Its computer control is via a serial interface.

2.1.2. Flat panel detector

The CMOS Flat Panel Sensor model C7942CA-02 (Hamamatsu, Japan) is a high resolution sensor, composed of a matrix of 2400×2400 pixels. A needle-structure CsI:Tl scintillator plate (0.2 mm thickness) is flipped on the photodiode array surface, for X-ray indirect detection. The Flat Panel detector has 2240×2344 square active pixels of 50 μm pitch (11.20×11.72 cm^2 sensitive area) with a fill factor of 79%. Pixel signal digitization is at 12 bits/pixel. The panel has a 1 mm thick aluminum window (top cover). It can be operated (internal trigger) at a rate of 2 fps (1×1 binning), 4 fps (2×2

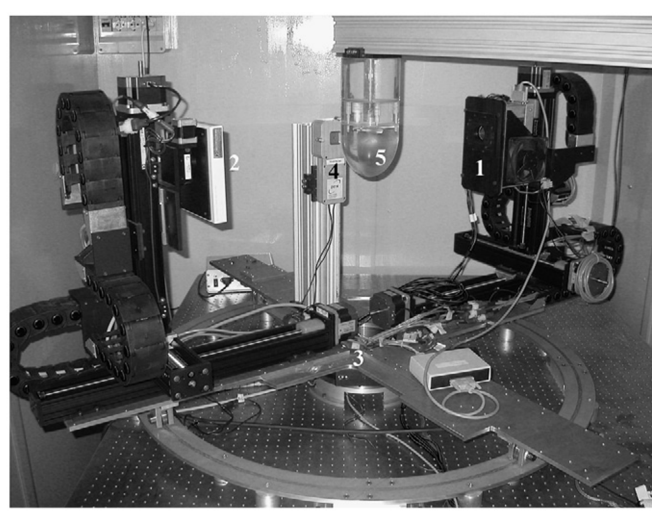

Fig. 1. University and INFN Napoli prototype Cone-Beam Breast CT/SPECT for laboratory investigations: X-ray tube (1), flat panel detector (2), rotating gantry (3), pinhole compact gamma camera (4) and PMMA breast phantom (5). The scanner is mounted on an optical bench (1.5×1.8 m^2) and housed in a shielded (3 mm Pb) camera.