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X-ray detectors in medical imaging

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ABSTRACT

Healthcare systems are subject to continuous adaptation, following trends such as the change of demographic structures, the rise of life-style related and chronic diseases, and the need for efficient and outcome-oriented procedures. This also influences the design of new imaging systems as well as their components.

The applications of X-ray imaging in the medical field are manifold and have led to dedicated modalities supporting specific imaging requirements, for example in computed tomography (CT), radiography, angiography, surgery or mammography, delivering projection or volumetric imaging data. Depending on the clinical needs, some X-ray systems enable diagnostic imaging while others support interventional procedures. X-ray detector design requirements for the different medical applications can vary strongly with respect to size and shape, spatial resolution, frame rates and X-ray flux, among others.

Today, integrating X-ray detectors are in common use. They are predominantly based on scintillators (e.g. CsI or Gd_2O_2S) and arrays of photodiodes made from crystalline silicon (Si) or amorphous silicon (a-Si) or they employ semiconductors (e.g. Se) with active a-Si readout matrices.

Ongoing and future developments of X-ray detectors will include optimization of current state-of-the-art integrating detectors in terms of performance and cost, will enable the usage of large size CMOS-based detectors, and may facilitate photon counting techniques with the potential to further enhance performance characteristics and foster the prospect of new clinical applications.

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1. Drivers shaping healthcare and X-ray imaging

Several global trends are shaping current healthcare systems. Among them is the change of demographic structures in many developed countries where the population pyramids are either stationary or even contracting while life expectancy is increasing. This and other factors lead to an increasing occurrence of diseases such as cardiovascular diseases, cancer, stroke or diabetes which are among the leading causes of death. Another continuing trend relates to an ever increasing number of disease patterns which can be treated by applying minimally invasive techniques rather than by open surgery. Healthcare information technology has become an integral part within hospitals and networks as digital imaging modalities are connected to picture archiving systems (PACS) and hospital or radiology information systems (HIS/RIS) and as the whole clinical and administrative workflow in hospitals is increasingly supported by software solutions and processes. Emerging rural healthcare in developing countries facilitates a broader access of the population to the local healthcare systems. As the annual fraction of GDP spent on healthcare has increased in many countries over the years, solutions to control or reduce overall cost are required and have led to more outcome-oriented reimbursement schemes.

These general trends influence the design and performance of current and future X-ray systems such as computed tomography scanners, C-arm systems for vascular or surgical X-ray imaging, general radiography or mammography systems. Systems used for interventional procedures will furthermore need to support image fusion with other imaging modalities or enable integration of other equipment such as ablation, mapping or navigation devices.

Future developments of X-ray detectors will have to support the increasing clinical demands and new applications, assist improved workflows, reflect the increasing awareness of efficiently utilizing X-ray dose, and be cost-efficient.

2. Clinical applications

Shortly after the discovery of X-rays by W.C. Röntgen in 1895, X-ray imaging was established as the first medical imaging technique and has continuously evolved while new imaging modalities such as magnetic resonance, positron emission tomography (PET) or ultrasound were introduced. Today the medical applications of X-ray imaging as well as the X-ray systems enabling the related clinical tasks are manifold. In the following a broad but far from exhaustive overview of clinical applications

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for important diagnostic and interventional X-ray modalities is provided.

Radiography which covers chest, trauma, pediatric, orthopedic and general examinations has evolved in many radiology departments during the past two decades from a technique dominated by analog screen-film combinations to a digital technique based on flat detectors. Radiography has profited from that change in many ways. While not possible for film, the separation of acquisition medium (detector) and display medium (monitor) has permitted optimizing these parts of the image chain independently and introducing image processing as a means to further improve image quality substantially. Workflow has improved because of the instant image display, eradicating the time-consuming development of film. It has further profited from connecting the X-ray units with HIS/RIS, allowing the download of predetermined worklists including patient information and examination type. PACS has eliminated film loss and enabled instant and simultaneous image access by physicians from different locations. The introduction of flat detectors with high detective quantum efficiency (DQE) [1] has led to dose reduction in skeletal and chest radiography [2]. Portable, wireless detectors have further broadened the spectrum of usability, by providing free positioning. The introduction of digital radiography has facilitated techniques such as image-composing to cover the whole body, dual-energy subtraction methods capable of removing bony structures by an appropriate linear combination of two chest images taken with different X-ray spectra, or the alternative and more dose-efficient method of applying bone-suppression algorithms on a single standard chest image.

In mammography, the change from screen-film combinations to flat detectors has led to similar changes of improved image quality and simplified workflow. Digital mammography has also enabled new features such as computer-aided detection (CAD) of microcalcifications, integrated stereotactic biopsy, and tomosynthesis [3], a technique generating 3D image data which promises to reduce tissue overlap, improve the separation of lesions, and enhance the visualization of microcalcifications.

Floor-mounted, ceiling-mounted or robotic C-arm systems (Fig. 1) are used for diagnostic and interventional procedures in radiology, cardiology, oncology or surgery environments. Traditional endovascular imaging includes coronary angiography, general angiography and neuroangiography. During X-ray acquisition, iodine-based contrast medium is injected intra-arterially, improving visualization of the vascular structure and thus generating a series of images of diagnostic quality. Digital subtraction angiography (DSA) may be used whenever organ motion is negligible enhancing the visibility by subtracting an image with anatomical background from images containing contrast medium in the blood vessels. Fig. 2 depicts an example of a complete DSA sequence of the cerebral vessel system in a single color-coded image, providing the physician with a better understanding of the contrast flow within the pathology and a visualization of the success after treatment. 3D information may be acquired by a technique often referred to as “flat-panel cone-beam CT”. Here the C-arm rotates around the patient while up to several hundred images are acquired from which volumetric data is reconstructed [4]. Low dose fluoroscopy or roadmapping is applied to visualize devices such as guidewires, balloons, stents or coils used in interventional cases. Common endovascular procedures include treatment of coronary stenoses by balloon angioplasty, coiling of cerebral aneurysms, thrombolysis or treatment of arteriovenous malformations. Many other applications have become routine or are being established, among them radio frequency ablation in electrophysiology, tumor embolization, aortic stent grafting (Fig. 1), transcatheter aortic valve implantation (TAVI) or X-ray guidance during surgical procedures such as spinal fusion.

Fig. 1. Robotic C-arm system used in a hybrid operating room for endovascular aortic repair including coiling of the arteria mesenterica inferior. Courtesy of Dr. Johannes Gahlen, Hospital Ludwigsburg, Germany.

Other specialized X-ray systems include fluoroscopy systems for gastrointestinal studies, myelography, arthrography or the evaluation of urinary tract infections, mobile X-ray systems for bed-side usage, and mobile C-arm systems for intraoperative use in orthopedic, trauma and spine surgery.

Computed tomography, introduced in the early 1970s by G.N. Hounsfield, is an imaging technique based on the reconstruction of the linear X-ray attenuation coefficient as a function of spatial coordinates in the imaging plane. To perform that task, the attenuation of an X-ray beam crossing the object or patient has to be measured from a large number of different angles. Cross-sectional images are reconstructed by applying techniques such as filtered back projection. The extension to volumetric acquisition with multi-slice spiral CT scanners requires a cone beam reconstruction by approximate algorithms such as the one first developed by Feldkamp, Davis and Kress [5]. More recently, iterative maximum-likelihood expectation-maximization methods taking the physical model of the scanner into account have been introduced [6]. Several rendering techniques such as surface rendering, volume rendering or image segmentation are used for 3D visualization of the data. State-of-the-art subsecond multi-slice spiral CT scanners enable a wide range of clinical applications including the visualization of tumors and lesions, cerebral perfusion imaging, i.e. visualizing the blood flow into the brain tissue following an acute stroke or aneurysm fracture, interventional puncture guidance for the extraction of biopsy samples or the detection of the degree of plaque calcification in coronary arteries (calcium scoring). Fig. 3 shows an example of a coronary CT angiogram (CTA) to evaluate the restenosis of an implanted stent. A particular system configuration, called dual-source CT, consists of two X-ray tubes and two detectors in the rotating gantry. This configuration can be used to cover a larger scan volume during one gantry rotation which, for instance, eliminates the need and risk of sedation during pediatric chest scans [7] or it can be used to simultaneously acquire data with different X-ray spectra for dual-energy imaging.

3. Current main-stream X-ray detector technologies

The various clinical X-ray applications are generating specific requirements for the respective medical systems and in turn for

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