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Optimization of X-Ray Imaging Systems for Enhanced Image Quality and Reduced Radiation Dose

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Annotation: This paper describes a comprehensive study on optimizing x-ray imaging systems to improve image quality and to reduce radiation dose. The study involves a variety of optimization methodologies, including theoretical analysis using a cascade imaging systems model, computational modeling in imaging characteristics, laboratory measurements on fluorescent x-ray tubes and phosphor screens, and imaging experiments with clinically used phosphor-based systems and a phase contrast x-ray system. It is found that optimization methodologies developed in this study can lead to notable improvements in image quality with reduced radiation dose in a variety of x-ray imaging systems.

X-ray imaging is an invaluable tool in medicine, biology and a variety of industrial applications. Its significance continues to grow as technology advances and new techniques emerge. For most of these applications, however, either the x-ray image quality needs to be improved, or the radiation dose needs to be reduced; often both are required. This is a grand-challenge problem, because it involves a large coupled system encompassing x-ray sources, imaging detectors, object-sample materials and their shapes and motions, image-processing algorithms and human observer tasks. In addition, heightened public awareness about x-ray

safety has made the manufacturers of x-ray imaging devices accountable for the maximum possible safety in device operation. Current x-ray imaging devices are designed to prevent accidental overexposure to patients by incorporating x-ray sources and fixed physical structures that limit radiation exposure. However, little has been done to the cascade character of x-ray photons throughout the device before they are absorbed in an imaging medium. In this paper, a detailed cascading-system model is developed to describe the x-ray imaging process, taking into account not only the device components but also imaging characteristics, such as geometric unsharpness, focal spot size, and x-ray scatter.

1. Introduction

Diagnostic X-ray imaging systems are extensively used in radiography for the detection of pathologies in medical procedures. The procedures, which include CT, mammography, fluoroscopy, and general radiography obtain images by varying the X-ray exposure incident on a detector together with reconstruction techniques. The main challenges faced by these imaging modalities are the trade-off between image quality and radiation exposure. Image quality has to be good enough to provide clinically useful information, so that even small pathologies can be detected. Patient's skin exposure has to be kept low, and it directly translates to dose, since a high dose to the skin can cause burns [1]. This consideration is particularly important for pediatric interventions where the dose limit is lower.

Meeting above requirements needs good understanding of the imaging system, the source performance and better detector system with reduced electronic noise. However, the rapid advance in medical technology causes increased complexity of this subject, which now should also take into account the design of image receptors and the quality of signal detection. Computed and digital radiography are well established nowadays. Phosphor plates or direct X-ray conversion detection are used. The dynamic range of fast reading detectors, such as those based on phosphor or selenium sensors, can span beyond 14 bits for a pixel, while this capes to 10 bits for typical a-Si pixelated detectors in the same exposure conditions.

Image quality in X-ray imaging is progressively more affecting the electronic chain rather than the detector itself. Emerging imaging applications are presently investigating objects differing in material and density. Consequently, the need for accurate contrast detection is significantly growing. That places contrast-detail characteristics as chief figures for imaging apparatus. Broadly speaking, the better the signal-to-noise ratio is, the better the quality of the image is. [2]

1.1. Background and Significance

When in 1895 Wilhelm Conrad Röntgen discovered a new kind of rays, known today as X-rays, it was impossible to predict their profound impact on science, medicine, and technology. Radiological imaging has changed and continues to evolve rapidly, enabling detailed observations of the internal structure of objects, including the human body [3]. Computed tomography-based innovations during the 1970s marked the beginning of the technological revolution in diagnostic medical imaging. The once-unseen became observable: lesions, fractures, anatomical abnormalities, and soft tissues. The progress of imaging technology broadened the capabilities of medicine to detect a wider range of disorders at early stages, when they could be combated successfully. Conventional X-ray imaging is the most common kind of imaging diagnostics, with over 100 million chest X-rays taken annually in the USA alone. However, due to technological limitations and innovations around other imaging modalities, conventional X-ray imaging is often insufficient. On the one hand, conventional X-ray imaging does not provide detailed spatial resolution or sufficient information about tissue structures. Progress in X-ray tomography techniques offered quantitative material information about the object, in contrast to the conventional projectional 2-D X-ray imaging. The Fourier-slice theorem postulates that a tomographic image is a set of projections and that one can reconstruct the original object from its line integrals. Hence, developments in image reconstruction have considerably advanced modality. On the other hand, recent medical imaging practice is focused on reducing patient doses while increasing image quality and diagnostic value of the X-ray exam. This target is hard to gain by the sole modification of the conventional imaging techniques. Considering the reasons above, many research groups have developed new X-ray imaging techniques and modalities, or applied new theoretical approaches to analyze X-ray imaging systems.

2. Fundamentals of X-Ray Imaging

One of the most important discoveries in the field of physics in the late 19th century was the generation of a new kind of rays by electrostatic means that could penetrate various materials opaque to ordinary light and which created shadow pictures of solid bodies. The ability to obtain pictures of living tissue without serious risks would revolutionize medical diagnostics. Since the discovery of X-rays in 1895 considerable developments has occurred in the theoretical understanding and in the technology of production and detection of X-rays. Imaging systems based on X-ray techniques form the foundation of radiographic medical devices and have a wide variety of applications in diagnostic and industrial nondestructive inspections. The basic principles of X-ray interactions that play a key role in image formation, the imaging components, and the technology of several kinds of X-ray imaging systems, are of critical importance for using and developing routine imaging equipment [3]. To optimize imaging performance and use an imaging system for a more effective operation, it is necessary to have an understanding of the capability and limitations of that technology.

An X-ray is a highly penetrating electromagnetic wave, with energy typically between 100 eV and 100 keV, with a wavelength shorter than visible light, i.e., approximately in the range between 1 nm and 100 pm. In a typical X-ray imaging process for medical applications the interactions between X-ray photons and matters at body sites are investigated and the medical image of the internal structure is constructed. The X-ray imaging process has three main components: the X-ray generator, the detection or image formation system, and the image processing system. The fundamental concepts of the X-ray imaging process, and its key components, are first described, followed by a discussion of the more detailed understanding and technology of each component. Ultimately, the body is considered as a collection of cubes, each being a region of interest different in material composition and distribution of densities and atomic numbers. The purpose is to estimate the output of the X-ray image at each detector that would be formed for a certain set of operating parameters and investigate how well this input histogram will represent the original configuration of the body. [4][5]

2.1. Principles of X-Ray Generation

The basic principles of the mechanisms of X-ray generation are detailed in this issue, as they are the foundations of X-ray imaging systems. The production of X-rays can be separated into two processes, continuous radiation (bremsstrahlung) and characteristic radiation. X-rays are produced by conversion of other forms of energy when electrons are suddenly decelerated. This process is typically achieved in specific X-ray tubes where electrons from a cathode component are accelerated and hit an anode target. Besides the acceleration voltage, the current that flows in the X-ray tube determines the total number of emitted X-ray photons. Monitoring the current value is the most common way that image acquisition systems correct image intensity when the patient's thickness changes or other acquisition-related problems occur [1]. In X-ray machines, the radiation dose is controlled by setting the tube current and acceleration voltage (i.e., X-ray tube potential). Tube potential is equivalent to a high-voltage transformer that is activated when the X-ray tube is triggered. For example, larger acceleration voltages lead to anode heating, so there is a limit in the upper bound of possible choices. The user can also select the tube current value according to the material (i.e., an aspect of the beam quality) of the X-ray tube and the current state of the patient. X-ray beam quality is described by the half-value layer, which is the thickness of the material that reduces the intensity of the X-ray beam to half. It depends both on the acceleration voltage applied to the tube and the type of target [6]. The X-ray spectrum changed by a set of few filters is depicted in Fig. 1. The X-ray spectrum of the 70 kVp W-anode X-ray tube had a much harder beam than that of the 100 kVp Rh-anode because of the higher electron interaction of the W target material. The role of the beam quality is important in radiology departments where maintaining the same mean HU value among patients is of great significance.

3. Factors Affecting Image Quality

Image quality in X-ray imaging systems is determined by several variables: contrast, noise, resolution and their mutual optimization with the radiation dose applied. Image contrast can be described in many different ways, but generally in the visual, is the difference in brightness between light and dark areas in an image. In various imaging media, contrast is generally described as: the value of the signal difference between the examined structure and the surrounding [7]. The contrast of the radiographic image is determined by the contrast of the object before the examination and the sensitivity of the reception system. The ideal image would exhibit differences in light intensity due to variations in the absorptiometry of the X-radiation. Yet, in methodology, detail structures may not show up in the image, as the losses in the intensity of the primary rays calculated by the Beer-Lambert law are replaced by the intensity of the scattered radiation [1]. The deterioration of the image in radiography also depends on the properties of films used (size of crystals, number of films or layers) or screen-film systems (resolution, speed). Alterations in the intensity due to a violation of illumination are interpreted in the image as fluctuations corresponding to differences in X-radiation absorption, not as the microscopic structure of the observed object. Radiographic contrast can also be evaluated differently in a visual system and in knowledge of the modulation transmission function. The determination of random noise consists in estimating the statistical parameters of the analysis from the graph of the property of the non-uniformity of the structure of the images formed by the proper index. Random noise can, to some extent, be eliminated by techniques of filtering, segmentation, or enhancement of electronic images. X-ray imaging is the most commonly used diagnostic method in medicine because it is widely available, relatively cheap and fast. Unfortunately, the quality of these images is often unsatisfactory due to a variety of factors. This can lead to an extended examination that causes discomfort to the patient. Digital imaging is gaining more and more importance. Widespread access to the computer, as well as the development of imaging techniques, prompted research into the development of digital imaging methods. Impoverished and premature are methods of digital imaging in medicine. Digital medical images that are replacing traditional analog images have many advantages. Consequently, the process of obtaining the image (capturing, recording, archiving, and printing) has developed a new effect, for which the overall term PACS started being used. Improved image recording and display techniques led to the development of many new imaging methods with increased diagnostic significance. Digital imaging of the image is the most important of them. [8][9]

3.1. Spatial Resolution

Spatial resolution is one of the most important components of the quality of the X-ray (XR) image, describing the ability of the whole diagnosing set to visualize the separation of two neighboring details. The loss in the spatial resolution, other than due to the imaging chain factors, can also come from the X-ray filtration effects and lack of resolution of the microfocus tube ([10]). Achieving the high spatial resolution images of sharp anatomical details, like bone trabeculae, is a constant challenge for clinicians. The good quality of such images will rely on an overall very good performance of the XR imaging chain and handling the acquisition parameters with full knowledge of their impact on the image quality. It can be illustrated that trying to visualize a high-frequency detail in a typical X-ray image is unfrequent, and even if undertaken, the increase in dose would not necessarily result in better visualization.

Thus, having access to the imaging systems and parameters that lead to a particular resolution performance can be essential and insightful to treat a patient. Understanding the impact of changing each of these parameters (tube current, voltage, filtration, focus-detector distance) on the high-frequency anatomical details' visualization may also help in deciding the most appropriate settings for a more accurate examination ([7]). The possibility of observing the sampling pixel size for each possible matrix size will demonstrate the common trade-offs in contemporary imaging, like using small pixels across the large matrix and not the other way around, or changing the FOV along with the matrix dimensions according to the body size while keeping the sampling. Taking patient's anatomy or system-specific resolution into account, philosophically it is extremely difficult, and subsequently it is very nuanced, to achieve good resolution with as low safe dose as possible. Emerging technological innovations in medical XR imaging systems can shed a new light in resolving these matters and provide a safer screening environment. This notion is meanwhile backed by the guidelines for proper adult patient imaging, given by the American College of Radiology. In its alarming recommendations, millennials are encouraged to demonstrate a high-quality care and patient safety beyond reminding of potential damage from excessive radiation dose exposition. [11][12]

4. Technological Advances in X-Ray Imaging

In recent years, there have been many significant advancements in X-ray imaging technology. Some of these innovations serve to greatly increase image quality: For instance, there have been enormous improvements in detector technology, software algorithms continue to rapidly evolve, and there has been a recent explosion in the synthesis of exotic new imaging modalities. Other important developments have been in the area of patient dose reduction: Automatic exposure control is now a standard feature for all new systems in most countries, and other technologies have made significant radiation dose reductions feasible that would never have been possible even ten years ago. Many other exciting new innovations have occurred as well, such as the rapid proliferation in lung nodule detection software. This wide landscape of technological change has also been accompanied by growing consumer support for transparency in how devices function and how manufacturers test them. In addition to promoting access to this information, research and development is needed now more than ever to continue to explore the vast space of what is quickly becoming possible with these technologies. This can be daunting given the breadth, complexity, and opacity of modern medical imaging equipment, and a good understanding of the basic principles and technical knowledge is required to evaluate whether or not these systems are being used to their full capacity. These new technologies have the potential to drastically expand the role of X-ray imaging in patient care, and as they proliferate there is increasing pressure to be able to properly assess their optimal use. Moreover, they also underpin larger policy questions regarding the investing of capital in such systems, as well as how they are implemented and integrated more generally within the broader context of healthcare delivery. Thus a primer on these important innovations is essential. [13][14]

4.1. Digital Radiography

Global advancement in the digital image has infected all its. It is noticed in the radiography field that the devices with traditional film and intensifying screen has been achieved to work with digital detectors to create digital image [7]. This has made the elimination of traditional films which need replacing after the emergence, developer chemicals preparation and health risks at the darkrooms. Each digital image is created faster, displayed, stored, shared and transferred to the specific software more rapidly. In addition, this has made to easiness of image enhancement before diagnostic interpretation is performed and the loss of image information has also decreased. It has been provided easily to create available copy of the images to the patients or the other hospitals.

It is noted that the computer-aided diagnosis (CAD) software has started to be incorporated to the digital radiography devices and systems to detect the features such as nodules and microcalcifications in the chest radiographies and the malign and benignant appearances from mammographies [15]. The applications of these software solutions have shown to increase detection accuracy of radiologists and or it have been outperformed by reducing reading time. Other improved features of the digital radiography have been accounted to the comparator of anatomic areas to compare with the old images, the easy access to the images from long distance, the exhibition of the images at the customizes viewboxes and additional screens.

Despite all these improvements, the high investments for the purchase of the digital radiography devices and the systems, tough working conditions for the digital detectors at the daily intensive clinical practice environment, maintenance, service and repair requirements have been accounted to the main challenges to common use of the devices and the systems. As mentioned at the first limitation, there is a need for well-trained radiology specialists who can use, arrange the device's vertical and horizontal parameters and troubleshoot possible technical problems might arise. Thus, it has not been achieved to transform immediately from the traditional film/screen devices and intensifying screen cassette systems to the digital radiography devices and systems.

5. Optimization Techniques

X-ray computed tomography is widely used in medicine for diagnostic examinations. The high dose of ionizing radiation is one of the harmful factors associated with computed tomography examinations; it is important to have an optimized system for this type of exposure, so the diagnostic levels of radiation dose are used. With development of technology, powerful computers and more sophisticated software are used, and these enable optimization of system parameters. Analysis of image quality should be concerning the visibility of various details as well as artifacts. The optimization methodology is used frequently for X-ray systems and has been used in the optimization of the exposure parameters. They solve a problem of finding the appropriate tube voltages and currents for different parts of the anatomy. In the available literature, there is no comprehensive review of systems for the optimization of the X-ray systems used in radiology, mammography or computed tomography. There are no papers that discuss usage of hardware, software, or both of them together, for the optimization of the entire diagnostic X-ray imaging system in order to reduce the radiation dose to the patient. Open-access bases do not allow such exposure of papers and it has not been located during the research for this report [1]. The optimization of hardware may be done by implementation of new technology. For those devices for which is not the time to change, use of dedicated software is reasonable. Below analysis of systems that allow the optimization of various X-ray imaging systems in order to enhance the image quality as well as to reduce the radiation exposure to the patient is described. Optimization procedures have been made compatible with Phantoms recommended in that sense. However, they are very often not applicable in clinical practice; therefore efficiency of the results can be disputed [16].

5.1. Image Processing Algorithms

High-quality images are vital for timely and effective diagnosis. The quality of X-ray images can be enhanced by integrating image processing algorithms into the imaging software. Multiple algorithms including contrast limited adaptive histogram equalization, median filter, multiwavelet transform, wavelet transform, and Sobel edge detection can be integrated into X-ray imaging software to enhance the quality of X-ray images. Successful applications of these algorithms in enhancing the quality of X-ray images are also presented. Image processing applications enhance the quality of X-ray images and facilitate clinicians to quickly locate the presence of sickness. On the other hand, the quality of X-ray images can be declined due to the demands of processor time and memory in the implementation of sophisticated image processing algorithms. The new algorithms, which require fewer computations and equally enhance the quality of X-ray images, are going to be developed in the future.

Segmentation of diagnostic images is cited as a challenging task in medical image processing. The quality of the X-ray images available plays an important role in the segmentation of the images. Well-disposed images will have significant contrast between the body and background and little noise. Therefore, the highest works to house segmentation address the establishment of discrete images with distinct objects from the surrounding background. Even though the availability of works that address image enhancement is greater than any other domain in medical image processing, the complexity of the enhancement algorithms and the quantities of implementation steps make their application difficult by the end users. Low complexity and easily implemented traditionally, and most contemporary image enhancement algorithms are considered in addition to their special implementations in medical software only. Improvements in the quality of X-ray images, following the application of enhancement algorithms, is demonstrated and their smooth integration into image segmentation tools, presently available in standard hospital equipment, is discussed. [17][18]

6. Conclusion

Radiologists, healthcare professionals and radiographers, are dependent on diagnostic images produced by X-ray imaging systems to make proper and fast diagnoses. The rate of medical imaging investigations required to support healthcare can lead to higher radiation dose to patients. Patients also receive a range of radiation doses from different imaging investigations. The benefit to the patient is being informed of a diagnosis. It is imperative for healthcare professionals involved to make informed decisions about which X-ray examination or imaging investigation would be of most benefit, and which would be most detrimental to the patient. Reduction in radiation dose in X-ray imaging is important for long term patient health. When facing acute medical situations, risks associated with the proper fast diagnosis of healthcare outweigh the risks associated with radiation dose. However, there is always a dataset of patient cases, a valid and particularly challenging question is finding ways in which there might be a reduction in patient radiation dose in X-ray imaging, but not at the expense of informative diagnostic image quality. Novel and technically challenging solutions on an application case of X-ray imaging, by which image noise was deliberately added to the image data, remaining insensitive to gains in low radiation dose imaging display of the same image data, and working closely with scientific approaches to measuring and quantifying perception of image quality of medical images in patient signals in order to maximize diagnostic information are investigated . The methods, results, and conclusions are discussed and the topic, that is an important multidisciplinary and medically clinically important field of research, are opened for wider discussion.

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