REVIEWS

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Filmless Radiology – Digital Radiography Systems

Radiologia bez zdjęć – systemy radiografii cyfrowej

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Abstract

The article presents new digital radiography systems. The principles of digital radiography and differences between traditional and digital radiography units are discussed. Two types of digital radiography systems are compared. The principles of the Picture Archiving and Communication System (PACS), Radiological Information System (RIS), and Hospital Information System (HIS) connected with digital radiography are presented. The benefits of digital radiography for hospitals, radiologists, physicians, and patients are discussed (**Adv Clin Exp Med 2009, 18, 6, 641–648**).

Key words: digital radiography, PACS, RIS, HIS.

Streszczenie

W pracy przedstawiono nowe systemy radiografii cyfrowej. Omówiono zasady ich działania oraz różnice między systemami cyfrowymi i klasycznymi. Porównano dwa podstawowe rodzaje systemów cyfrowych. Zaprezentowano podstawowe reguły działania systemów, związanych z radiologią cyfrową: systemu archiwizacji obrazów i komunikacji – PACS, radiologicznego systemu informacyjnego – RIS oraz szpitalnego systemu informatycznego – HIS. Opisano korzyści, jakie niesie zastosowanie radiologii cyfrowej dla szpitali, lekarzy i pacjentów (**Adv Clin Exp Med 2009, 18, 6, 641–648**).

Słowa kluczowe: radiografia cyfrowa, PACS, RIS, HIS.

The enormous progress in technology observed in the last few decades involves all branches of medicine; no specialty, however, has developed as many new technologies as radiology and imaging diagnostics [1]. However, when one considers the changes that occurred in recent decades, one thinks primarily of new imaging modalities: ultrasound (USG), computerized tomography (CT), magnetic resonance imaging (MRI), interventional radiology, and also nuclear medicine, which is now a separate specialization. Despite significant progress in the development of new imaging modalities, conventional radiology still constitutes 60-70% of all examinations carried out in hospital departments of imaging diagnostics [2]. At the same time, the principles of performing conventional X-ray pictures have not changed over the past several decades. Evaluating X-rays taken in the 1930s and '40s, i.e. 60–70 years ago, one finds that their quality does not differ significantly from those taken today. Is it possible that the enormous progress in technology has omitted classical radiology? New digital radiography systems offer a great chance for change.

The Principles of Digital Radiography Systems

In conventional radiography, X-rays pass through the patient's body and fall onto a traditional radiological cassette containing intensifying screens and X-ray film. The intensifying screens, covered with a luminophore (calcium ortho-

tungstate, rare earth elements), change most of the X-radiation into visible light, which falls onto the X-ray film covered with emulsion, causing its darkening and thus producing images. At present, two basic systems of digital radiology have been introduced: computed radiography (CR), also known as indirect radiography, and direct radiography (DR).

Indirect radiography systems use cassettes in which the conventional X-ray film has been replaced by a special charged plate covered with crystalline phosphorus compounds. The plate functions as an multiple-use intensifier enabling the image of the investigated object to be read, stored on a computer hard disk, and then erased. The cassettes used in digital radiology are compatible with traditional, currently used radiological units. Thus there is no need to replace the whole diagnostic device, but only one of its elements. Electrons in the phosphorus crystalline network are moved to a higher, unstable energy level under the effect of X-radiation and they create a hidden image. To view the image, special scanners have to be used. The radiographer carries the cassette to a viewing station, entering the proper identification of the patient's demographic data. Then the plate is scanned, line by line, with a helium-neon laser beam [3]. This makes the electrons transit from the higher energy level to a lower one, i.e. from the excited state to a state of quiescence. The process is accompanied by the emission of electromagnetic radiation in the range of blue visible light. The intensity of the emitted radiation is directly proportional to the stream of electrons, which in turn is converted into a digital X-ray picture. The digital image is transferred to a diagnostic workstation.

In direct radiography systems, X-rays pass through the patient's body and fall onto a flat digital panel which converts the X-rays into electrical impulses which in turn are converted into a digital image. The panel is permanently integrated with the X-ray unit and the obtained image is transferred directly to the workstation without the radiographer's participation. There are two types of direct radiography detectors available, known as indirect-conversion and direct-conversion detectors. Currently, the most commonly used digital panels consist of two main elements: a luminophore and an indirect-conversion detector matrix [4]. The luminophore usually consists of a layer of cesium iodide which converts the X-radiation into visible light, as in conventional radiology. Luminophores currently applied in digital systems are modified by the use of substances improving their technical parameters. Thus thallium (Tl) is often added to cesium iodide to create a channeled (needle-like) crystal structure similar to that used in fiber optics [4, 5]. In this way a high conversion rate of X-radiation into visible light is achieved while maintaining a high spatial resolution due to the lack of light dispersion. The second element of the digital panel, the detector matrix (photodiodes), consists of amorphous silicon (indirect-conversion detectors) or selenium (direct-conversion detectors) with properties of an anisotropic semiconductor. After excitation with light, each photodiode generates a current charging an elementary condenser. The arrays of charges are then converted into a digital radiological image and transferred to a diagnostic workstation [3–6].

The Advantages of Digital Radiology in the Hospital

Significant technological progress has resulted in the appearance of more and more new diagnostic modalities on the market. Hospital administrators expect from radiology departments a significant cost reduction and evaluate the possibilities of purchasing and exploiting new diagnostic devices from their economical point of view [7]. For healthcare providers considering the purchase of new diagnostic devices, the availability of reliable knowledge on the financial aspects of the purchase and exploitation of new equipment is thus indispensable [8].

The increased use of imaging techniques has contributed to a constantly increasing deficit of qualified personnel, i.e. radiologists and radiographers, in highly developed countries. Staff deficits also result from the fact that the increased use of imaging techniques, especially in conventional radiology, is not associated with improved effectiveness in the work of radiologists and radiographers. It is believed that in the future this situation may lead to a prominent deficit of radiologists in developed countries. It is postulated that the introduction of digital radiology systems, by improved work efficiency, may decrease this deficit by 20% in the next 10 years [1, 9]. Improved work efficiency of radiology departments and radiologists after introducing digital radiology and PACS (see below) has been confirmed by other authors [10–13]. The problem of an inadequate number of highly qualified professionals also concerns radiographers. In the USA, only 42% of radiology departments claim to be fully staffed with radiographers, with an average of 2–2.8 vacancies in conventional radiology departments [14]. It is believed that in view of the increased number of radiological examinations, there may be 75,000 radiographer vacancies in the USA in 2010 [15].

The effectiveness of a radiology department is determined mainly by the effectiveness of the radiographers' work [16]. It is closely related to the time necessary to perform a radiological examination. The time required to obtain a conventional X-ray picture differs by 300% in different conventional radiology departments [17]. It is determined by the number of necessary procedures, the competence of the professionals, and their burden with administrative duties. For these reasons, comparing patient examination times is essential in evaluating analog and digital radiography units in the same medical center.

A statistically significant ($p < 0.001$) shortening of the time necessary to perform a radiological examination by means of the indirect digital method compared with conventional radiology was demonstrated. In different radiological departments, the time saved varied from 2.4 to 6.6 minutes for postero-anterior and lateral chest X-rays, which was 31–47% of the time necessary to perform a conventional image. In the case of cervical spine X-rays, the time saved varied from 5.1 to 12.0 minutes in different departments, which was 37–58% of the time necessary to take conventional pictures [18]. Comparing the time necessary to perform a radiological examination in four departments equipped with both direct and indirect digital radiology systems, a significantly shorter time ($p < 0.001$) of examination with direct digital radiology was obtained at all the investigated centers. The mean duration of examination with the use of direct systems was 2.2–5.2 minutes, depending on the department, while with the indirect systems it was 4.3–10.8 minutes. The mean time saved varied from 1.7–6.3 minutes, depending on the department. Then the individual activities of the radiological examination, such as patient preparation and positioning, exposure, and post-acquisition processing of the image, were analyzed. The most essential difference between the evaluated systems concerned transforming the image after exposure, this being 101.4–114.6 seconds. In the case of indirect radiology systems, transformation of the image consisted of three stages: carrying the plate from the X-ray machine to a plate reader (scanner), transferring the image to a workstation, and post-acquisition processing of the image. In the direct radiology systems the transformation of the images after exposure consists of two stages: transferring the image to a workstation and post-acquisition processing. Moreover, the time necessary to transfer the image to the workstation was 3 seconds in direct systems and 20–46 seconds in indirect systems [3]. This means that if conventional systems are replaced by digital systems, especially direct ones, work efficiency may rise significantly and thus the number of X-ray pictures may be increased while having fewer radiographers and accessory staff members. It should be noted that the results of earlier studies did not show a statistically significant shortening of examination time with the use of digital systems, but they were carried out on an older type of digital X-ray machines [19].

Another reservation concerning the use of digital radiology is that this modality does not use any X-ray film. Radiologists and physicians from the same medical center evaluate the image on the screens of diagnostic workstations (for diagnosis) or personal computers (for reference only). The patients and physicians from other hospitals receive the images on a CD or DVD. These are several times cheaper than X-ray films and many images can be stored on one CD and many more on a DVD. Moreover, in digital radiology the costs associated with sewage utilization after development of the films are avoided.

The experiences of computerized tomography laboratories which first abandoned X-ray films point to a significant cost reduction. Kusakabe demonstrated that the operating costs of a computerized tomography laboratory in which X-ray films had been replaced by "filmless" technology decreased in the first year by 36%. Seventy percent of the savings concerned floating costs and the remaining 30% fixed costs [20]. The lack of X-ray films also means the possibility of closing traditional archives and using the premises for other purposes as well as savings in the work of accessory staff.

Another important advantage of digital radiology is that the examinations do not have to be repeated at the cost of the radiological laboratory. It is estimated that 12% of the most common chest X-rays performed with the use of conventional X-ray systems have reduced quality, while 3% cannot be interpreted at all. For this reason, they have to be repeated, which increases the cost of the examination and puts the patients at risk of an elevated exposure to X-rays. Sometimes the patient has to come to the laboratory a second time. After the first indirect digital radiology systems were introduced in the 1990s, the number of images of reduced and unsatisfactory quality fell to 5% and 1%, respectively. In the case of chest radiographs at the patient's bedside with the use of conventional technology without automatic exposure control, 22% of radiograms were of reduced technical quality and 8% could not be interpreted at all. After the introduction of indirect radiology systems, the number of radiograms with reduced or unsatisfactory quality fell to 8% and 1%, respectively [21]. This was confirmed by the findings of

Sheung-ling Lau et al. They demonstrated that after the introduction of digital radiology and PACS, the number of low-quality images that could not be interpreted decreased from 2.1% to 1.3% [21]. On the other hand, in a recently published study, Foos et al. analyzed 288,000 CR images and found that the rate of unsatisfactory quality images was 4.4% at a university hospital and 4.9% at a community hospital. It must be noted, however, that the authors did not compare rejected analyses of CR and conventional film-screen systems. They also pointed out inconsistencies in the data used for rejected analyses by several investigators [22].

Currently used digital devices using both indirect systems of phosphate plates and direct silicone digital detectors significantly eliminate the possibility of poor-quality images due to wrong exposure parameters or patient movements during the exposure. According to the manufacturers' data, they give a correct diagnostic image both when the film has been underexposed, with exposure reaching only 25% of the optimal, and in situations of overexposure, with exposure equal to 400% of the optimal [23]. In a recently published study, Walsh et al. assessed the image quality of indirect and direct digital radiology systems obtained from six different manufacturers. The image quality evaluation was based on detector assessment protocols and included pixel value measurement as well as subjective evaluation (Leeds Test Objects). The patient was simulated by a tissue-equivalent material with gradual difference in thickness. The authors found that the dynamic range of digital detectors in CR and DR systems is much wider than in conventional film-screen systems, decreasing significantly the possibility of poor quality of the images due to overexposure [24]. This was confirmed by studies investigating the reasons for poor quality of X-ray examinations using conventional and digital X-ray systems. A wrong selection of exposure parameters was the main reason for poor quality of the pictures. In conventional systems it was the cause of 38.6% of all rejected pictures. In digital systems the percentage of poor-quality pictures due to wrongly selected exposure parameters accounted for 7.4%. Moreover, the percentage of rejected pictures due to the patient's movement at the moment of exposure decreased from 6.5% in conventional systems to 2.3% in digital systems. 55.4% of poor-quality pictures in the digital systems were due to improper patient positioning, while in the conventional systems it was the reason for 28.2% of the poor-quality pictures [23]. In the study by Foos et al., reject analysis of CR images showed that positioning errors and anatomy cutoff were responsible for unsatisfactory quality images in 45% of such images in a community hospital and 56% in a university hospital. Improper exposure parameters accounted for 14% of rejects at the community hospital and 13% at the university hospital. Patient motions were the cause of 11% of all rejected pictures in the community hospital and 7% in the university hospital [22].

Shorter exposure time is another advantage of digital systems. This increases the longevity of the X-ray tube, which is an extremely costly element of the device.

Reiner et al. are among the few authors who compared the effectiveness and costs of indirect and direct digital radiology systems. They compared the expense of the purchase and one year of work of four radiological departments using both indirect and direct digital radiology systems. They demonstrated significantly lower purchase and operation expenses in the case of indirect digital systems. An indirect system may cost from $80,000 to $172,000 (US), while the expenses associated with the purchase of direct systems may vary from $360,000 to $440,000. The cost of one-year service for indirect systems varied from $6,400 to $20,154 and for direct systems from $39,500 to $48,000. The total cost of one year of operation of an indirect device (cost of equipment and service), assuming it is used for 10 years, was over $50,000 lower than of a direct system in each of the investigated departments. The total savings over a 10-year period were from $507,570 to $753,030. At the same time it should be stressed that the study confirmed a significantly increased productivity of direct systems. Depending on the laboratory, the average duration of one examination with the use of direct equipment was 153–347 seconds, while with the use of indirect systems it was 258–523 seconds. Thus the number of patients examined by means of direct radiology equipment was 51–89% higher than in the case of indirect systems. On the other hand, Reiner et al. reported that if the costs of a radiological department using direct radiology system had to be equal to the costs of a department using an indirect system, the direct department would have to use up to 80% of its productive capacity. This is impossible in the majority of working departments [25].

The findings were confirmed by Andriole et al., who demonstrated a significantly lower cost of chest X-ray by means of indirect equipment compared with direct systems. Similarly to Reiner, they stressed that the increased productivity of direct systems did not compensate for the higher costs of purchase and operation of the equipment. If the investment in direct equipment was cost

effective, the radiological department would have to perform the maximal number of images, working continuously [18]. This is practically impossible to achieve and the majority of departments are not able to make appointments for a fixed time, and even if they are, appointments would not exclude the possibility that some patients might be late. Moreover, there are always emergency cases disturbing the schedule. This is a very important problem. It is estimated that delays in currently operating conventional departments during "rush hours" may make up to 6–10 patients wait for an examination [26].

The use of a digital radiology system increases the productivity of a radiological department while at the same time increasing income. It shortens the time the images and reports are available for referring physicians. The system allows immediate access to imaging studies by physicians. It also reduces the delays in work [1, 2, 27, 28].

Information Systems – PACS, RIS, and HIS

Digital radiology uses computer systems for sending, processing, and archiving data, including diagnostic images. The most important are PACS (Picture Archiving and Communication System), RIS (Radiological Information System), and HIS (Hospital Information System), which enable sending the images and text by computer network to numerous places in the hospital.

Every day, radiology departments produce a huge number of diagnostic images (X-ray, CT, USG, MR images) which are necessary for diagnostic purposes and have to be sent to different hospital departments and stored together with the patient's other data. This requires the engagement of a large number of accessory staff, radiographers, and administrative personnel. The process is time and cost consuming. If data are processed electronically, as in CT, MRI, modern ultrasound equipment, and in the systems of direct and indirect digital radiology, they can be sent and stored by means of a computer network. The images are available simultaneously in many places throughout the hospital at viewing stations (they can now be viewed even on personal computers).

PACS is used primarily for the storage, distribution, and viewing of diagnostic images in the digital imaging and communications in medicine (DICOM) format. RIS is a computerized database used for the storage and transmission of text information in radiology departments, such as patients' data, registration and scheduling, reports, and statistical data. A computer system of higher order in hospitals is the HIS. It enables the efficient storage and distribution of all data between departments and diagnostic units in the hospital, including diagnostic images. This system cooperates with PACS and RIS.

To illustrate the advantages of PACS, RIS, and HIS, let us trace the way of an analog radiological picture in a hospital. If a physician requests an X-ray examination, the day of the examination is set. After the X-ray is taken, the radiographer carries the cassette with exposed film to a developing station and then passes the developed film to a radiologist, or in case of emergency, directly to the referring physician. In the majority of cases the referring physician sends the image via messenger to a radiologist for an interpretation and report. The interpreted image is brought back by the messenger to the referring physician, a consultant, the patient, or the image archive. The scheme shows how time consuming and costly the procedure is, especially in hospitals in which hundreds of imaging investigations are performed daily.

In the case of direct radiology and the PACS, RIS and HIS, the image is not carried at all by radiographers or accessory staff, but sent electronically. These results in a significant shortening of time, enables a reduction in hospital staff, and leads to substantially lower expense. The use of digital radiology, PACS, RIS, and HIS significantly improves the efficiency of a radiology department, increasing its income [1, 18, 29, 30]. It reduces the time in which images and interpretations are available to the referring physicians. It allows immediate access to imaging studies by physicians. It also decreases delays in work [1, 2, 27, 28].

Benefits of Digital Radiology to Radiologists and Physicians

The primary benefits of digital radiology to physicians include improved quality of the radiographs and thus better diagnostic possibilities, increasing the chance for the identification of small pathological lesions at an early stage. This is closely associated with the use of workstations enabling processing and highlighting the diagnostic information. Digital radiology systems enable magnification of selected fragments and panning/roaming of the image under analysis. The sensitivity of digital detectors to a wide range of radiation intensity [24] makes it possible to assess both bone and soft tissues on the images obtained in one exposure. The improvement in diagnostic

accuracy associated with the use of a workstation having the possibility to enhance the images has been confirmed in studies on computerized tomography systems, in which workstations were first used for image analysis and management. A statistically significant improvement in diagnostic accuracy was demonstrated for workstations enabling image processing compared with conventional CT images [31]. Pomerantz et al. showed that the use of workstations improves viewing and characterizing pathologies found on conventional CT scans in 67% of cases and allows visualizing clinically significant details which are invisible on pictures in 18% [32].

Another advantage for radiologists is that the images obtained in digital radiography systems do not have to be repeated as frequently as they do in conventional analog systems [23, 24]. This is strictly associated with improved quality, saves the radiologists' time, and makes interpretation faster. Additional advantages of digital systems are also worth mentioning. Their application in a fluoroscopy device enables "frame" analysis of examinations with contrast medium of the gastrointestinal tract in which numerous "freeze-frame" images may be saved on a computer hard disk instead of having to expose several conventional X-ray films. Moreover, a diagnostic workstation facilitates retrospective analysis and consultation of the image with other radiologists or physicians. Commercially available software allows putting the whole limb or the whole spine together on the basis of individual images and automatically corrects artifacts resulting from inaccurate linking of the pictures (overlapping, displacement, rotation, or deformity).

Integrating a digital camera with PACS, RIS, and HIS allows the image to be immediately available for the referring physician or consultant, as described in detail in the section above. Every image can be compared with the patient's other images performed in the same institution (or, to some extent, in different institutions) by retrieving them from the computer archive (or from CD/DVD). In the case of research centers, the introduction of a digital system also means perfect quality of radiographs prepared for scientific presentations [33].

Since the introduction of digital radiology systems into hospitals, the modality has been accepted by the majority of physicians, radiologists, clinicians, and radiographers, who have acknowledged its superiority in acquisition, storage, and transfer of images compared with conventional technology. Braunschweig et al. demonstrated that 80% of radiologists acknowledged the superiority of digital systems in the above aspects to conventional methods, although the evaluation was subjective. Digital systems were comparable to conventional for 14% and worse for 6% of the radiologists. Among clinicians, the digital systems were assessed as better by 67%, comparable by 27%, and worse by 6%. The percentages in the group of radiographers were 80%, 13%, and 7%, respectively. In the case of images taken at the patient's bedside without automatic exposure control, 63% of the radiologists considered the digital systems better than and 37% comparable with conventional systems. The percentages in the group of clinicians were 62% and 38%, respectively, and in the group of radiographers 86% and 14% [21]. Moreover, the aspect of novelty of the digital systems should also be considered. It is connected with a narrow-minded and sometimes even negative attitude of some staff members without any substantial justification. Another disadvantage is the necessity of learning new techniques associated with the operation of digital systems.

Benefits of Digital Radiology to Patients

The primary benefit of digital radiology to patients is substantial; depending on the kind of examination, an up to six-fold reduction in absorbed radiation in direct radiography systems is reported [34–36]. Persliden et al. showed a decrease of X-ray exposure dose to 0.48 mGy in pelvic examination performed by means of direct digital radiology with a flat digital detector compared with 1.37 mGy performed by means of conventional radiography. Moreover, decreasing the dose to a level below standard, high-quality digital images were obtained at 0.24 mGy, thus 5.7 times lower than in conventional systems. The reference exposure dose in EU countries which should not be exceeded is 10 mGy [34]. The calculated effective dose in conventional systems was 0.33 mSv and in digital radiology systems the standard and reduced doses were 0.12 mSv and 0.06 mSv, respectively. The doses were also lower in comparison with indirect digital systems [34]. These findings were confirmed by a study by Strotzer et al., who demonstrated an up to 75% reduction in the effective dose in bone and skeletal investigations by using a prototype digital panel with parameters worse that currently available [35].

In another study, Gavala et al. assessed the effective doses in panoramic radiography using conventional and digital devices. They found that by using standard radiography settings, the effective dose was higher in digital than in conventional systems and was estimated to be 23 and

17 muSv, respectively. Nevertheless, if the lowest possible radiographic settings were used in a DR system, the measured effective dose decreased to 8 muSv and was much less than in conventional systems [36].

Nonetheless, the reduction of radiation absorbed by patients does not apply to computed radiography systems. In a three-year study, Aldrich et al. compared patients' surface doses during chest, abdominal, and pelvic X-ray examination in film-screen, computed radiography, and digital radiography systems. The average entrance surface air kerma (ESAK) doses received by patients during the chest PA examination obtained in film-screen, computed radiography, and digital radiography systems were 0.20 ± 0.07, 1.02 ± 0.63, and 0.07 ± 0.02 mGy, respectively. The average ESAK doses received by patients during abdominal AP examination obtained in film-screen, computed radiography, and digital radiography systems were 5.39 ± 2.91, 5.24 ± 3.03. and 1.75 ± ± 0.56 mGy, respectively, and during the pelvic AP examination 3.30 ± 1.70, 4.78 ± 2.85, and 1.68 ± 0.65 mGy. Although the algorithm of the examination for chest X-rays in CR systems changed and the dose was decreased to 0.24 mGy, it was still not lower than in film-screen examinations [37]. In another recently published study, Compagnone et al. compared the doses delivered to patients in a flat-panel DR system and two CR units. By analyzing five common radiographic examinations (abdominal, chest, lumbar spine, pelvic, and skull), they found that both skin and effective doses were lower in the DR than in the CR systems [38].

Another advantage for patients is associated with the significantly improved quality of radiographs, enabling the identification of pathological lesions at an early stage. The previously discussed lack of necessity of repeating examination means more comfort and a lower radiation dose for some patients. In examinations of the gastrointestinal tract with contrast enhancement, direct digital radiology enables recording the examination and a lower dose of X-ray radiation. It allows the examination to be consulted with other radiologists or physicians, for example prior to a planned surgery.

Full archiving of all the data in the digital radiology department allows the recovery of lost radiographs by retrieving them from the archive, even several years after the examination.

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