Digital Image Processing in Radiology

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To our wives for support
and our parents who encouraged creativity

Preface

The digital imaging process offers unique opportunities in the application of biomedical engineering techniques to improve health care delivery. The purpose of this text is to acquaint the reader with certain activities that have already shown promise and to explore future possibilities to extend the usefulness of this method of diagnostic inquiry. Although we have been engaged in digital imaging for quite some time, many of the applications described in this text represent exploration into the future of digital radiography.

The format of the text begins with a historical presentation of the early evaluation of digital radiography by several pioneering groups. This is followed by a discussion of the general principles involved, but in the context of their application to the advancement of clinical usefulness of digital radiography. Afterwards, digital radiographic techniques are discussed under the common format of organ systems with in depth exploration of novel methods by which digital radiography can be employed. Other chapters address specific advantages of the technical characteristics of digital radiography and will follow the overall theme of improved data acquisition, storage, manipulation, and transfer.

The recognition that analog information can be represented by discreet bundles of data is not a new phenomenon. Digital processing of signals and imaging has been carried out for quite some time. However, only recently have developments in radiographic equipment, computers, and information transfer techniques served to significantly increase the potential of diagnostic imaging.

The history of digital radiography has been one characterized by the maturing of a novel imaging technique. Initially, there was almost unbounded enthusiasm and optimistic predictions regarding the value of digital radiography along with the commitment to using digital principles to develop filmless departments of medical imaging. With the implementation of many of these creative ideas, certain realities appeared and a more conservative attitude has generally been adopted. In fact, at present there probably exists a posture of conservative over-reaction in which many medical imaging specialists find it fashionable to note that digital radiography's greatest use is in arteriographic studies, permitting small doses of contrast media to be employed.

The authors and editors of this text believe that appropriate application of existing technology and development of techniques in related areas will ultimately result in the occurrence of many of these enthusiastic predictions for digital radiography in the future. The ability to create images that adequately portray the arterial and venous vasculature, a simultaneous physiological measure by observation of the handling of contrast media and subsequent perfusion, may allow digital imaging techniques to provide the same information that is usually determined by a series of conventional studies.

Although one cannot deny the importance of the realization that health care resources are limited nor the effects of regulatory intrusion upon the medical delivery system, digital radiography appears to be affected on a positive basis. Even though competing modalities such as pulsed Doppler real-time ultrasound and magnetic resonance imaging will surely be employed as definitive methods of inquiry in certain diseases, digital radiography will continue to remain the procedure of choice in many others. The Tax Equity and Financial Responsibility Act (TEFRA) of 1982 and the application of diagnosis-related groups (DRG) method of prospective payment will have profound influence upon the choice of methods for diagnostic evaluation. Since digital radiographic studies allow procedures that were previously invasive in nature to be performed from an intravenous injection of contrast media on an outpatient basis, these policies will increase the use of digital radiography. The potential for reduction in radiation dose for studies by digital techniques is also a compelling consideration for their increased future application.

The authors and editors of this text hope that it will prove useful to the reader for exploring some of these promising avenues of applications and will impart in an understandable manner the basic principles employed in this most promising technique.

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Contents

CHAPTER 1

Historical Perspectives on Photoelectronic Digital Radiology

S. NUDELMAN, Ph.D.

INTRODUCTION

Background

During the past 10 years, we have seen the beginning of a technological and clinical revolution in diagnostic radiology. In the early 1970s, computerized tomography (CT) emerged which married photodetectors to a digital computer in order to acquire and display transaxial tomograms. In the autumn of 1976, we saw the first intravenous angiography (IA) of carotid arteries from greyhound dogs. Since that time, the procedure has become diagnostic for all the body's arteries, except the coronaries which remain a continuing challenge. This procedure combines photoelectronic imaging devices (i.e. the x-ray intensifier and video camera) and the digital computer to generate superbly enhanced images of arteries from the intravenous injection of contrast media.

Both CT and IA have demonstrated remarkable successes without the use of photographic film. They reveal that prior conceptions were ill advised regarding the necessity of film for high resolution compared to photoelectronic devices. It also became clear that precisely controlled contrast enhancement was more beneficial and easily offset losses in resolution. Accordingly, expectations are now high that combinations of photoelectronic imaging devices (PEID) and computers will serve for most diagnostic procedures in radiology. One can foresee a markedly declining role for film.

Few of the components, systems, and concepts now being explored for use in diagnostic radiology are new. They have evolved over many years in nonmedical applications, such as for low light level, visible, and infrared applications pursued in behalf of the National Aeronautics and Space Administration, the National Science Foundation, the Atomic Energy Commission, the Department of Defense, and the broadcast industry. Many scientists and engineers famous for their contributions in these areas are generally unknown in medicine. Accordingly, this paper presents an overview of photoelectronic devices finding their way into radiology with a brief history of their conception and evolution. It is hoped that it will present the reader with an appreciation of the 75 years of unrelated effort expended to arrive at IA, and the identities of pioneering scientists essential to our progress.

PE-DI-R

A photoelectronic digital radiology (PE-DI-R) system comprises components devoted to image acquisition, image processing, interactive display and archival storage. When required, it incorporates a means for hard copy. System components are analog and digital in nature (Fig. 1.1) although a practical system for a clinical procedure could now be assembled entirely analog, but not vice versa.* This paper is concerned exclusively with image acquisition devices and systems, being an area ripe for new concepts and approaches to diagnostic radiology.

Photoelectronic devices used for image acquisition systems comprise solid-state and vacuum tube components. The devices most commonly used today are shown in Figure 1.2*d*, identified as the demagnifying x-ray image intensifier (XII) optically coupled to a TV camera whose

* Thus we refrain from using the popularized term "digital radiology" and prefer the descriptive and accurate designation "photoelectronic digital radiology" (PE-DI-R). It clearly distinguishes between PE-DI-R and film digital radiology (FI-DI-R). We anticipate emergence in the years ahead of image systems with different applications, such as in diagnostic medicine (PE-DI-M), ophthalmology (PE-DI-O), endoscopy (PE-DI-E), and dermatology (PE-DI-D).

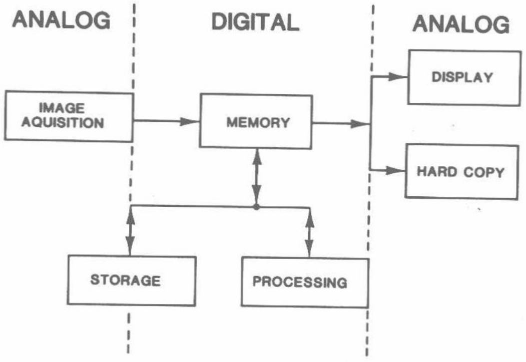

Figure 1.1. A photoelectronic digital radiology system designating analog and digital components.

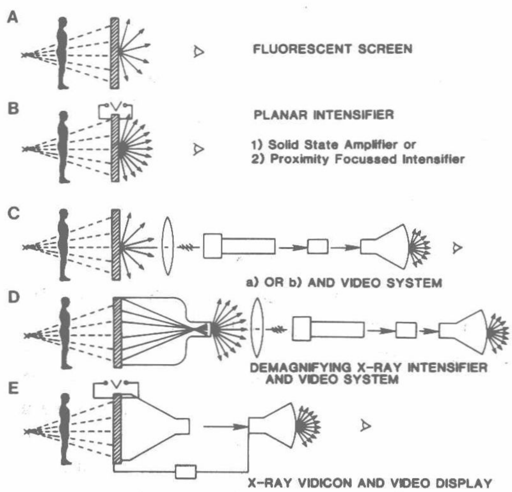

Figure 1.2. Photoelectronic x-ray image acquisition and display system.

output is fed into a display. Comments related to these components, as well as the appearance of digital memory, will be provided in "History Prior to 1976." Those pertinent to the other systems shown in Figure 1.2 will be deferred to "Where Do We Go From Here" where expectations for the future are discussed. Described later are the one-dimensional detector arrays that provide scatter discrimination ("Systems with Scatter Discrimination") and the two-dimensional scanning read-out solid-state panels ("Systems with Large Area Solid-State Sensor Panels").

HISTORY PRIOR TO 1976

This chapter is primarily concerned with the historical development of PEID and their relationship to the overall development of "temporal" intravenous angiography. In the presentation of this history, a broad division identified with the year 1976 is seen. In 1976, all the components essential to intravenous temporal angiography appeared on the scene in radiology. Prior to that time, progress in PE-DI-R was extremely slow and burdened with a community of unbelieving potential users, both in research and in clinics. There were a few exceptions as early as 1973, however, which included M. P. Capp (University of Arizona), W. Kuhl (Philips), J. W. Motz (United States National Bureau of Standards), and R. Schneider (Bureau of Radiological Health). They are among the heroes who dared think that a radiological world without film was possible. Perhaps the bravest of all was M. Siedband who in 1968, filed a patent for photoelectronic radiology which included discussion of concepts for energy and temporal subtraction (120). Unfortunately, components essential to its success did not evolve until years later. Today there are many new supportive voices and the pace of Research and Development has quickened. In fact where research and development (R & D) had been almost leisurely, today one is urged to move quickly for fear of getting run over by the concentrated effort now being expended in industry and university medical centers alike.

The X-ray Image Intensifier

GENERAL COMMENTS

The history of vacuum tube x-ray intensifiers and low light level intensifiers prior to 1971 is covered nicely by Combee et al, McGee, and Morton and Schnitzler (24, 80, 90). It is also treated by Nudelman in a survey including solid-state devices (94). The earliest publications on image amplification using electronic devices appeared in 1934 by Holst and his colleagues (60) and by Kiepenheuer (67). McGee notes, however, that the first proposal for light amplification using the input photoelectronic photocathode and output phosphor concept came from an anonymous inventor at the Philips Lamp Company, the Netherlands in 1928 (101). Lallemand (74) began his work in 1936 on intensifiers which eventually led to the successful development of devices using photographic film for permanent recording at the device output, rather than a phosphor. Other pioneers working to develop image intensifiers include Bruche and Schaffernicht (13), Heimann (49) and Zworykin and Morton (143). These devices evolved into the low light level and near infrared-sensitive tubes developed during World War II and described by Morton and Flory (89), and Krezik and Vand (68).

Intensifiers have been developed with proximity focusing, electrostatic focusing, and magnetic focusing. They have been demonstrated in a multistage cascaded structure to achieve higher gain than available from a single stage. Most recently the channel multiplier has evolved as a means of achieving high gain. It was conceived by Farnsworth (32) and developed over the years by Oschepkov et al in 1960 (97), Goodrich and Wiley in 1962 (40), and Adams and Manley in 1965 (2).

It is clear that intensifiers were conceived over 50 years ago. They have evolved into a wide variety of structures with sensors responding to high energy electrons, radiation (gammas and x-rays), as well as to lower energy (vacuum ultraviolet-visible-near infrared). They have also evolved into solid-state devices which have been discussed elsewhere by Nudelman (94).

Intensifiers appear in three basic structures. Two have already been mentioned (with output surfaces being a phosphor for light imaging and amplification, and with film for permanent recording). The third is located at the front end of a television tube where the intensifier provides gain and improves the video tube's ability to operate at a lower light level. In this structure, the tube contains a target with two functions: it serves as the output surface of the intensifier and as the input storage surface of the TV tube. Photoelectrons striking this surface cause charge gain. Targets have been made from glass, semiconducting materials, crystalline, and noncrystalline materials. Early targets provided gain of two to five electrons stored for every photoelectron striking the target, while later the high gain KCl and silicon targets evolved providing reported gains of 200 to 300, and 2000 to 3000, respectively. The tubes using such targets are the Image Orthicon, Image Isocon, and SEC and silicon intensifier tube (SIT) (38, 39, 91, 105).

The earliest of these television tubes using an intensifier for gain was the Superemitron which provided regular TV broadcasts in England in 1937 (76, 82).

The wide variety of these devices have their counterparts in x-ray intensifiers. The most commonly used is the large area input XII with a diameter of 150 to 550 mm, demagnifying electron optics, and a small diameter output phosphor disk of 16- to 35-mm diameter. Recently a practical 22-cm diameter proximity-focused tube emerged, made in both one and two state gain structures (134). Earlier a proximity-focused XII which uses a channel multiplier was developed, but to date it has not found its place in diagnostic radiology.

X-RAY-SENSITIVE DEVICES

The Demagnifying XII

Combee described in 1971 the early history and state of the art for x-ray intensifiers (24). He notes the long time that passed between the earliest work on light amplification in 1934 and Coltman's pioneering work on XII in 1948 (23), when vacuum tube devices of sufficient performance became possible. This was followed by the work of Tol and Oosterkamp (130) and Teves (129).

The modern demagnifying x-ray intensifier is usually lens-coupled to a television camera as shown in Figure 1.2*d*. It is the paramount intensifying system in use today. Other intensifying devices are possible, although they have proven unsuccessful for one reason or another in the past. However, times change, the state-of-the-art in components improves, and component improvements may well lead to device rejuvenation.

The structure of the demagnifying XII is shown in Figure 1.3. It comprises a photosensor which absorbs the x-ray photons and generates light output as scintillations. A photoelectronic emissive layer is adjacent to the sensor layer. Light output from the scintillator is absorbed by the photoelectron emitter and results in electrons being emitted into the vacuum. For every x-ray absorbed, an estimated 150 photoelectrons are accelerated and reimaged at high energies on the output phosphor disc. The high energy electrons bombard the phosphor particles and cause the emission of a bright pulse of light. The combined effect of x-ray photon to photoelectron input gain and photoelectron to light photon output gain leads to a net gain of 100,000 to 200,000 light photons for each x-ray photon that was absorbed in the scintillator and initiated the process. In a modern intensifier, the scintillator is an evaporated CsI layer and 50 to 75% of the incident x-ray photons cause the light output. It is reported to have a detective quantum efficiency (DQE) of 50 to 75% operating with a photon gain ranging from 100,000 to 200,000.

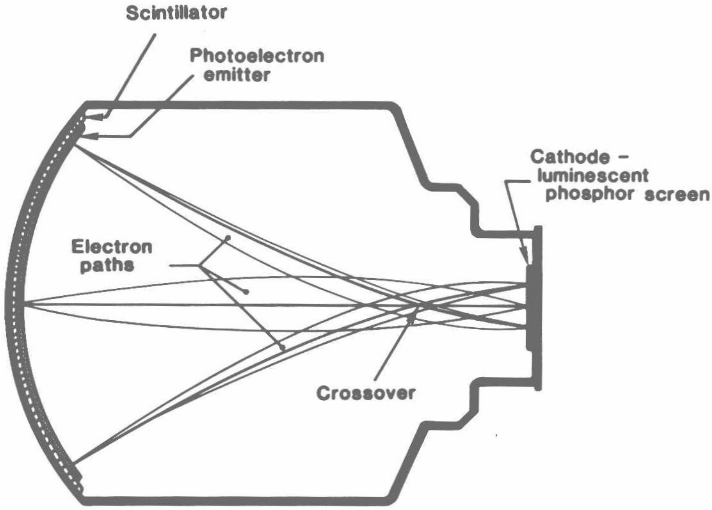

Figure 1.3. The x-ray image intensifier with demagnification.

The x-ray sensor CsI replaced ZnCdS because it provided bulk absorption properties, high efficiency for the generation of light output, and a growth pattern that offered improved resolution. These outstanding properties were first recognized by Bates in 1969 (6) for application to the XII.

The diameter of x-ray intensifiers has grown over the years from 5 to the Philips 14 inch which appeared in 1977 (73) to an intensifier of similar size from Thomson-CSF-CGR in 1981 and to a 22-inch diameter intensifier by Siemens in 1982. Clearly size is not a limitation to the application of XII to procedures in diagnostic radiology.

Most important, performance has not suffered with increasing diameter. Spatial resolution is available with, for example, the trimode Philips having a 3.6 lp/mm limiting resolution for its 14 inch mode, 4.0 lp/mm for 10 inch and 5.0 lp/mm for 6 inch. Varian produced an XII (1982) whose limiting resolution is about 7 lp/mm for 6-inch diameter in a 9″/6″ inch tube.

Veiling glare has also been reduced in large part through the use of fiber optics in the disc supporting the output phosphor screen. Kuhl (73) has managed an extraordinary contrast factor of 36:1 in the 6 inch mode of the Philips 14-inch intensifier. This is also reflected in an improved MTF, particularly at low spatial frequencies.

Finally and perhaps most important, the Philips 14-inch intensifier in 1977 and later the large diameter Thomson-CSF-CGR intensifier in 1981, were able to operate at exposure rates and levels normally used for diagnosis rather than fluoroscopy.

This breakthrough meant a clear departure from past designs. In general, it has been the practice to seek maximum gain in XII to meet the simultaneous needs of fluoroscopy and photographic recording. However, such structures when exposed to the high x-ray flux rates produced at diagnostic level, behave poorly. This occurs when the photoelectronic current flow becomes excessive causing a significant voltage drop in the transparent electrode adjacent to the scintillator, excessive density of photoelectrons in the crossover region, and possible burning of the output phosphor. In practice, increased shading, loss of resolution, and reduced contrast could be expected from high diagnostic exposure levels and rates. The solution was to reduce the photoelectronic gain from the sensor-photoelectron emitter sandwich and when necessary, increase the diameter of the output phosphor disc. The result has provided an impressive level of performance. It has proven clearly satisfactory for pulsed mode IA where extracting vessels of small contrast for visualization is the essential requirement. One can look forward to linear tomography and procedures associated with the remote table as potential users of state-of-the-art XII.

Planar Structures for XII

These structures are identified in Figure 1.2*b* as fluorescent screens, solid-state amplifiers,