Digital intraoral radiography – determination of technical properties and application evaluations

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Stockholm 2002

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ABSTRACT

Digital registration of intraoral radiographs was introduced about 1990. One of the first systems on the market was the Sens-A-Ray™ (Regam Medical Systems AB, Sundsvall, Sweden). At the time of the introduction, it was deemed important to determine basic technical properties for this system. Methods to determine such properties for digital systems did not exist and were developed as the scientific investigations progressed.

The technical properties first determined for the Sens-A-Ray™ were the *Dose response* function, the resolution defined as the *Line Spread Function (LSF)* and as the Modulation *Transfer Function (MTF)*, the *Dark current* and the *Signal-to-noise ratio (SNR)*. In a further study the noise characteristics were calculated as the *Noise Power Spectrum (NPS)* and as the *Noise Equivalent Quanta (NEQ)* From this last parameter the efficiency of the system to detect incident photons was calculated, the *Detective Quantum Efficiency (DQE).*

Employing the methods developed for determining the LSF and MTF for the Sens-A-Ray™ system, these parameters were also determined for three other systems, the RVG™ (Throphy Radiologie, Paris, France), the VIXA/Visualix™ (Gendex, Des Plaines, Ill., USA) and the Flash Dent™ (Villa Sistemi Medicale srd, Buccinasco, Italy).

At the introduction of digital intraoral systems, the display function was linear on computer monitors, which means that grey level values were directly converted to light intensity levels. Dentists used to viewing conventional film radiographs found the digital images not "film-like", which is due to the contrast properties of digital images. In order to investigate the subjective preference of the display of digital images a study was performed, which showed that a curved display function was preferred. An analysis of the function preferred by the viewers showed that this function *de facto* made the digital images more "film-like". In this connection, an important fact turned out to be that the curved display function approximately compensates for the exponential attenuation of x-rays, as radiographs are exposed. The consequence of this compensation is, that equal steps in object thickness are shown with approximately equal steps in light intensity on a computer monitor.

When new image registration systems are introduced, it is important also to test applications in addition to technical parameters. In this dissertation, the Sens-A-Ray™ system was employed in a longitudinal study of bone inflammation in rats. The inflammation was introduced by intravenous injection of *Staphylococcus aureus* Periodical identical radiographs were exposed. The results show several advantages of digital radiographic techniques in animal studies.

Implant therapy has become a standard method to replace lost teeth. A literature search could find no study comparing digital and conventional techniques in assessing implants, and thus such a study was deemed important. The study shows that the diagnostic yield using digital techniques was fully comparable to conventional film techniques, and showed a tendency to better results.

The determination of technical parameters as well as the evaluations of applications show that digital techniques have such properties that conventional film techniques can suitably be replaced.

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This dissertation is based on the following papers, which will be referred to by their roman numerals.

I. Welander U, Nelvig P, Tronje G, McDavid WD, Dove SB, Mörner A-C, Cederlund T: Basic technical properties of a system for direct acquisition of digital intraoral radiographs. *Oral Surg Oral Med Oral Pathol* 1993; 75:506-16

II. Welander U, McDavid WD, Sanderink G, Tronje G, Mörner A-C, Dove BS: Resolution as defined by line spread and modulation transfer functions for four digital intraoral radiographic systems. *Oral Surg Oral Med Oral Pathol* 1994; 78:109-15

III. Welander U, McDavid WD, Mörner A-C, Tronje G, Tokuoka O, Fuchihata H, Nelvig P, Dove SB: Absolute measures of image quality for the Sens-A-Ray direct digital intraoral radiography system *Oral Surg Oral Med Oral Pathol Oral Radiol Endod* 1995; 80:345-50

IV. Mörner A-C, Welander U, Tronje G, McDavid W.D, Fuchihata H, Tokuoka O: Linear or curved display of digital radiographs - results of a "Beauty Contest". *Oral Radiology* 1998; 14:1-9

V. Mörner-Svalling A-C, Hienz S, Heimdahl A: An uncomplicated method for making periodical identical radiographs of experimental bone lesions in the rat. A technical report. *Scand J Lab Anim Sci* 1998; 25: 113-120

VI. Mörner-Svalling A-C, Tronje G, Andersson L, Welander U: Comparison of the diagnostic potential of direct digital and conventional intraoral radiography in the evaluation of periimplant conditions. *Clinical Oral Implants Research.* (Accepted).

Forsan et haec olim meminisse iuvabit

Virgilius, Aeneiden, i. 203

INTRODUCTION

In the late 1980's, digital radiographic systems, designed to replace intraoral film radiography, first began to appear on the market. The first system using a full size CCD detector capable of directly converting x-ray energy to an electronic signal was the Sens-A-Ray™ (Regam Medical Systems AB, Sundsvall, Sweden). As such, it was deemed worthy of thorough investigation to learn if it could replace film-based radiography. Because there were at the time no known or established methods to determine essential technical properties of digital systems, such methods were developed in parallel with the investigations. In order to evaluate the potential of direct digital intraoral radiography certain physical properties should be known, such as the sensitivity, which is directly related to the dose to the patient. Properties of registered and displayed image data such as resolution and noise characteristics should also be known. Although there is no direct relationship between these physical parameters and the diagnostic yield, the information given by these parameters provide important information when comparisons between different imaging media are made.

Physical image properties investigated in this dissertation were:

Dose response

In digital radiographic systems the dose response defines the dependence of grey level values on exposure. In digital systems the dose response is most often plotted as a function of exposure and not the logarithm of exposure. Grey level values represent light intensity on computer monitors. Thus, on computer monitors, low grey level values represent high exposures.

Signal and noise characteristics

Signal and noise are independent quantities. The signal conveys information and is dependent on the attenuation in the object, while noise forms an unwanted pattern, often randomly distributed and irregular, which overlays the signal. The dominating cause of noise is quantum fluctuations in the x-ray beam. Additionally, noise may originate from the radiographic system, e.g., in digital radiography electronic noise and noise from the presence of a dark current. Although they are independent, signal and noise are both affected by resolution.

Signal

Resolution

The resolution in digital radiographic systems may be defined by several parameters. A resolution limit may be defined by the Nyquist frequency, which is easily calculated from the pixel spacing, 1/(2 x pixel spacing). The Nyquist frequency defines the frequency where there is no longer any recorded signal, whereas all frequencies lower than the Nyquist frequency will be represented by a recorded signal. However, the Nyquist frequency carries no information about the signal contrast except the value of 0 for the Nyquist frequency itself. A parameter that does carry information about the signal contrast is the *Modulation Transfer Function (MTF)*, which may be used as a measure of sharpness. The MTF describes the amplitude or relative contrast by which sine functions of different frequencies are modulated by an imaging system. Thus, a MTF value of 1 indicates that the full amplitude is transferred by the imaging system, while a MTF value of 0 indicates that no signal at all is transferred. A one-dimensional MTF may be calculated from the *Line Spread Function (LSF)*, which is the normalised intensity distribution of the image of an infinitesimally narrow line. When the LSF is known the MTF may be calculated as the absolute value of the Fourier transform of the LSF.

A limit frequency may be calculated from the MTF or the LSF that is known as the *Noise Equivalent Passband* (N_e) that defines a cut-off frequency below which an idealised MTF is 1 and above which this MTF is 0.

The definition of the MTF presupposes that data are sampled continuously. Since digital systems have pixels, data are sampled discretely. A way to circumvent the problem of calculating a MTF from discretely sampled data is to calculate a so-called *Presampling MTF*. The presampling MTF represents the signal before it is discretely sampled by pixels in a digital radiographic system.

Noise

Noise may be quantified as the *Noise Power Spectrum (NPS)***.** (Munroe *et al*. 1987). The two-dimensional NPS may be calculated over an area in a radiograph as the modulus of the Fourier transform of the relative exposure divided by the area. The NPS has the dimension of area and expresses the average area occupied by individual photons per area unit, usually mm^2. A one-dimensional NPS may be calculated employing, e.g., rotational averaging of the two-dimensional NPS.

Combined signal and noise

Noise Equivalent Quanta

Assuming that all noise in a radiographic imaging system is due to the statistical fluctuation of x-ray photons emitted by the tube, signal and noise characteristics may be combined employing the concept of *Noise Equivalent Quanta (NEQ),* which may be calculated as the reciprocal of the NPS, representing the noise, multiplied by the squared MTF, representing the signal. The NEQ describes the number of photons captured by the system per area unit (Sandrik & Wagner, 1982, Munro et al 1987, Workman & Brettle 1997).

Signal-to-noise ratio

The *Signal-to-Noise Ratio (SNR)* may be calculated as the ratio between the mean signal and the standard deviation of the noise. Provided that the noise has a Poisson distribution, the SNR may simply be calculated as the square root of the mean signal. This is because the mean is equal to the variance in a Poisson distribution.

Detective Quantum Efficiency

The *Detective Quantum Efficiency (DQE)* is a measurement of the relative number of x-ray photons incident on the recording medium that are registered. All radiographic systems are only able to detect a certain percentage of incident photons. The DQE may be calculated by dividing the NEQ by the photon fluence.

Dark Current

A particular characteristic of CCD detectors is the dark current, which adds system noise to the already present quantum noise. Dark current is the name given to spontaneously generated and randomly distributed charges. This current is time and temperature dependent. Thus, when the detector of a direct digital radiographic system warms up, spontaneously generated free electrons are superimposed on the electrons liberated by x-ray photons. The dark current has an effect on the image that is analogous to fogging in film radiography. However, in digital radiography, the dark current may be subtracted.

Display characteristics

Normally, digital radiographs are displayed linearly on a computer monitor, i.e. grey levels in image data are directly converted to brightness. When dentists were first confronted with digital radiographs, they found them not to be "film-like". This indicated that contrast characteristics of digital radiographs were different from those of film radiographs. This prompted a study where the subjectively preferred display of digital radiographs was investigated.

Applications

It is not enough to be able to determine technical properties of new imaging systems, in the present case digital intraoral radiography. One must endeavour to find its uses, and whether these coincide with the applications of the system being replaced, in the present case film radiography, which may be inferior in some respects but still superior in others.

Since radiographic scientific studies on humans must be deferred until one is reasonably sure that they are justified, animal studies are often performed initially when, e.g., new treatment methods are investigated. For a study to be valuable and statistically significant large numbers of animals are often necessary. Animal studies are also subjected to rigorous ethical rules, and animals must be cared for in approved manners. Animal studies are questioned by many people today, and thus all parties concerned should see any method that may bring down the number of animals used as positive.

Periodical identical radiographs, e.g., for subtraction radiography, are used in dental scientific studies. The results are often gratifying, but the method is elaborate and time consuming. Digital radiography and image processing may have advantages in this field. Thus, it was decided to investigate its possibilities in animal studies.

Finally, all clinical applications of film radiography should apply to digital radiography. Today, many studies of different applications of intraoral digital radiography have been performed. Since no study of implant therapy comparing film and digital radiography was found in the literature it was considered of importance to investigate if direct digital radiography may replace conventional film radiography in association with implant therapy.

AIMS

The aims of this dissertation were

- to determine technical properties of direct digital intraoral radiography (Papers I, II and III);
- to study the subjectively preferred display of digital radiographs (Paper IV);
- to study an application of direct digital radiography in animal studies (Paper V);
- to compare the diagnostic potential of direct digital and conventional film radiography in connection to implant therapy (Paper VI).

REVIEW OF INVESTIGATIONS

Paper I
Basic technical properties of a system for direct acquisition of digital intraoral radiographs

The Sens-A-Ray™ (Regam Medical Systems AB, Sundsvall, Sweden) was the first system for direct acquisition of digital radiographs using a full scale CCD detector designed for direct conversion of x-ray energy to electronic signals. As such, it was found to be important to study its basic technical properties.

The CCD detector
The CCD detector developed for the Sens-A-Ray™ system had a thicker sensitive layer of crystalline silicone than conventional light sensitive CCD detectors, compensating for the low absorption coefficient for silicon of the energies of the x-ray beam. The incident x-rays break the covalent bonds of the crystalline silicon, creating electron hole pairs. The charges accumulate in "potential wells" proportional to the incident radiation, and can then be read out, producing an analogue signal, which is converted to a video signal and then digitised. The pixels of the Sens-A-Ray™ were 45 x 45 µm and 256 grey levels from 0 (black) to 255 (white) were registered.

Dark current
The dark current emanates from spontaneous generation of charges in individual pixels and increases with integration time and temperature. This makes it necessary to clear the detector from such charges before each exposure.

The magnitude of the dark current collected during each exposure was measured for integration times from 1 to 840 ms, with the detector at both room and working temperature.

The mean dark current was plotted as a function of integration time, and was found to be linear for both the "cold" and the "warm" detector. There was a fluctuation, or noise, in the dark current. This electronic noise increased slightly with time.

The dark current was more pronounced at the warm end of the detector, where the electronic components are placed.

The dark current is analogous to the base density and fog in a film based system. It was found to be limited and should not affect relevant information in clinical radiographs.

Dose response
To determine the response functions of the Sens-A-Ray™ detector for different radiation energies, series of radiographs were exposed using homogenous radiation fields for nominal energies of 50, 60, 70, 80 and 90 kVp. Integration times were registered by the system and true exposures in µC/kg were measured with an ionisation chamber connected to a Radiation Monitor Model 1015 (Radcal Corporation, Monrovia, Ca, USA), while the true kVp was measured with a DIGI-X electronic penetrameter (RTI Electronics, Mölndal, Sweden).

The mean and the standard deviation, i.e. the total noise, of the grey levels for all test radiographs were calculated. The dark current was subtracted from the mean of the grey levels for all kVps, and the electronic noise was eliminated from the total noise. Regression analyses gave idealised functions describing the dose response and the quantum noise.

The dose response was found to be linear functions of exposure for all the kVp settings. Also, for all kVp settings, the dose response functions were essentially identical. The reduction of the dynamic range of the system by the dark current and the electronic noise were also linear functions, and corresponded to approximately 15% at 0.25 seconds exposure time, increasing to approximately 25% at 0.4 seconds. The dark current was basically independent of the kVp.

Direct comparisons between the dose response functions for digital and film radiography cannot be made since one function defines grey level and the other density as functions of exposure. However, it may be noted that the exposure range of the CCD detector is narrower than that of a film (Kodak UltraSpeed, Eastman Kodak Co. Rochester, NY, USA). This reflects the fact that the CCD detector is more sensitive to radiation than the film. As a result the patient dose will be reduced.

Because of the relatively high sensitivity of the CCD detector, high precision exposure times must be employed. The dark current of the CCD detector may be subtracted to make the whole grey level range available.

Signal-to-Noise Ratio

Using dose response data, SNRs were calculated for the idealised situation when the dark current and electronic noise were subtracted and only quantum noise was present. SNRs were also calculated for the real situation that included all noise. The result indicates that the addition of the dark current and electronic noise has a limited effect on the SNR since the image forming signal dominates over the dark current and the quantum noise dominates over the electronic noise. SNRs are practically identical for all kVps.

The SNRs were found to be above 10 for exposures higher than 2 μC/kg.

Line Spread Function

Since the pixels in the Sens-A-Ray™ CCD detector are square the LSF is not equal in all directions.

To determine the LSF, test radiographs were exposed using a test object with a 10 μm wide slit (Atomic Products Corporation, Shirley, NY, USA). The slit was inclined approximately 45° relative to the long axis of the detector.

Rows along the slit images were scanned to find the pixel with the minimum signal. Regression analyses determined the positions of the slit images. Fifty image rows were aligned to a common origin at the regression line. Registered data represented the image of the slit perpendicular to its length axis. Pixel data on one side were mirrored to represent a complete LSF. The LSF was fitted by a mathematical expression according to Yin *et al*. where the LSF is defined as the sum of a Gaussian and an exponential function.

The LSF was found to have a dominating exponential part.

Modulation Transfer Function

Presampling MTFs valid for the detector and a plane in the object were calculated from the LSF according to an analytical solution by Yin *et al*. and are presented graphically. Noise Equivalent Passbands (N_e) were 6.51 cycles/mm at the detector plane and 7.49 cycles/mm at the object plane.

Discussion

Digital radiographic techniques offer many advantages over conventional film techniques, e.g., reduction of patient dose, time saving, availability of digital image processing and elimination of film processing errors. The need for further investigations of the new technology, which at the time of the investigation was developing rapidly, was stressed. At the end of the article, some key observations are discussed more fully. In order to compare digital and conventional film radiography, not only basic technical properties should be assessed but clinical studies on diagnostic accuracy should also be performed.

Paper II

Resolution as defined by line spread and modulation transfer functions for four digital intraoral radiographic systems

Four intraoral direct digital radiographic systems were studied: the Sens-A-Ray™ (Regam Medical Systems AB, Sundsvall, Sweden) and the VIXA/Visualix™ (Gendex, Chicago, Ill, USA), both using full size CCD-detectors, and the RVG™ (Trophy Radiologie, Paris, France) and the Flash Dent™ (Villa Sistemi Medicale srd, Buccinasco, Italy) using scintillating layers connected to CCD-detectors by tapered fibre optics and conventional optical lenses, respectively.

The aim of the study was to determine and compare the resolution of the four systems defined using LSFs and MTFs. Furthermore, N_es were calculated.

Methods

Line spread function

LSFs were determined employing the method described in Paper I.

Modulation transfer function

MTFs were calculated from the LSFs.

Results

Line spread function

Graphs of LSFs are shown in the paper. The VIXA/Visualix™, RVG™ and Flash Dent™ all had dominating Gaussian parts of their functions, 60%, 75% and 80%, respectively, while the Sens-A-Ray™ had and a dominating exponential part, approximately 99%.

Modulation transfer function

The MTFs of the different systems are also shown graphically.

From the MTFs, N_es were calculated. They were 6.5 cycles/mm for the Sens-A- Ray™, 4.9 cycles/mm for the VIXA/Visualix™, 3.2 cycles/mm for the RVG™ and 3.8 cycles/mm for the Flash Dent™.

Discussion

The method used to determine LSFs was repeated with inclinations of the slit over 180 degrees, in steps of 10 degrees for the Sens-A-Ray™. The LSFs were not significantly changed depending on direction. Thus the method employed should be reliable for full size CCD detectors for direct image acquisition.

Although there is no direct relationship between the MTF and diagnostic information, the MTF has been proved to be a meaningful measurement of radiographic systems. However, it should be remembered that comparisons should only be made between related techniques. The method presented in this study should be useful for evaluating future systems introduced in the rapidly expanding field of intraoral digital radiography. Comparisons between digital and film based radiographic systems, however, can only be made by studies of diagnostic efficacy.

Paper III

Absolute measures of image quality for the Sens-A-Ray™ direct digital intraoral radiography system

The study was conducted to determine absolute measures of image quality, i.e. NEQs and DQEs of the Sens-A-Ray™ system.

Technical background

As the x-ray beam passes through the patient, it is attenuated. The remaining radiation consists of radiographic information, i.e. the signal, and noise. The signal together with the noise is then registered by the recording system. The MTF is a measurement of how the signal is transferred by the system. The noise is represented by the NPS, which represents noise at different spatial frequencies. The NPS consists of quantum noise and system noise, e.g., electronic noise.

When the signal and noise characteristics are combined, it is possible to determine a quantity, which would give rise to the same SNR if all the noise were quantum noise. This quantity is known as the NEQ and may be calculated as the reciprocal value of the NPS multiplied by the squared MTF over frequency. The ratio of the NEQ to the actual photon fluence is known as the DQE and is a measurement of how efficient a certain system is in detecting x-ray photons.

Measurement methods

Twenty test radiographs exposed to mean grey levels 64, 128 and 196 were acquired at 70 and 90 kVp. True exposures in µC/kg were measured with an ionising chamber. From each radiograph, three areas of approximately 1 cm^2 were selected, and two-dimensional NPSs were calculated over these areas. Ensemble averages of 60 data files for each exposure were then determined and from these one-dimensional NPSs were calculated.

The MTF for the Sens-A-Ray™ system determined in Paper II was used to calculate NEQs from the one-dimensional NPSs.

Half-value layers were used together with mass energy absorption coefficients for air to calculate photon fluences for hypothetical monoenergetic x-ray beams. Then DQEs were obtained by dividing NEQs by these photon fluences.

Results

The NPSs decreased with increased frequency. For both beam energies they also decreased with increased exposure, this decrease being linear for any selected spatial frequency. The system was thus found to be quantum limited.

All NEQs had broad maxima at approximately 2-3 cycles/mm, indicating that SNRs are most favourable at these frequencies.

The mean of the calculated DQE had maxima at approximately 0.030 for 70 kVp and at approximately 0.025 for 90 kVp.

Discussion

Quantum noise is the dominant noise factor in the Sens-A-Ray™ system. This noise decreases with increased exposure. The efficiency of the system to detect photons is relatively low.

Noise is a limiting factor in digital radiography, and images viewed on a computer monitor have a relatively noisy appearance, mainly because of magnification. Objective measurements of noise characteristics are valuable when comparing systems.

Paper IV

Linear or curved display of digital radiographs - results of a "Beauty Contest".

The dose response of CCD based digital systems is linear, as is most often the case of the display function. This makes the visual characteristics of digital images different from film images, which has been pointed out by users. Curving the display function and thus increasing contrast in areas with low exposure and decreasing it in areas with high exposures would adapt the display to the human visual system and could possibly give the images subjectively better diagnostic characteristics. The aim of this study was to determine whether viewers subjectively would prefer a curved display function of digital radiographs.

Materials and methods

Thirty direct digital intraoral radiographs were exposed with the Sens-A-Ray™ system depicting teeth in both jaws.

A computer program was constructed to allow the display function to be curved and the grey scale to be expanded or compressed.

Twenty-nine dentists, 15 radiologists and 14 non-radiologists were invited to view and manipulate the radiographs until these subjectively presented the best possible characteristics for diagnostic work. The viewing was done twice with the two sessions separated by at least one week.

To determine if the original mean grey level of the radiographs influenced the changes made, the radiographs were sorted by the mean grey levels of their root dentine.

Results

Both groups agreed in preferring a curved display function. There were no statistical differences between radiologists and non-radiologists.

A statistically significant correlation ($p<0.001$) was found between the mean of root dentine grey level and the curving of the display. The display was curved more in bright than in dark radiographs.

The increase of the grey level range was 6.5 % on an average and there were no differences between bright and dark radiographs. It seemed that the increase was a compensation for the darkening effect of curving the display.

Discussion

The viewers were unanimous in their preference for a curved display function. Curving the display means an increase in contrast in bright areas and a decrease in dark areas. The response of the human visual system is much less sensitive to light intensity differences in bright than in dark portions of images. Since an intraoral radiograph is dominated by bone and tooth structures that are relatively bright this result may indicate that viewers wanted to enhance contrast in these areas. The fact that contrast is simultaneously decreased in dark areas may be a side effect and not a true preference.

The optical density in a directly exposed film is essentially a linear function of exposure. Optical density is defined as the base ten logarithm of opacity. The reciprocal of opacity is known as the transmittance. The light intensity perceived by the human visual system is proportional to the transmittance.

The graphs shown in the article indicate that the preferred curving of the display does, in fact, result in a more "film-like" grey level representation than the linear scale commonly employed in CCD systems.

An additional advantage of the curved display is that it performs an approximate compensation for the exponential attenuation of radiation when radiographs are exposed. Thus, equal steps in object thickness will be displayed as approximately equal steps in brightness when radiographs are viewed on a computer monitor when the display function is curved in the proper way.

The diagnostic performance with or without curving of the display function must be studied clinically.

Paper V

An uncomplicated method for making periodical identical radiographs of experimental bone lesions in the

rat. A technical report.

When conducting studies, it is often desirable to expose serially identical or similar radiographs to follow up results. In animal studies, this means anaesthetising the animals. If periodical radiographs are exposed using a direct digital technique, the anaesthesia time will be shorter than when films are used due to the fact that films have to be developed. This minimises the risk for loss of animals and, in turn, saves resources.

Aim

The aim of this study was to investigate whether it is possible to expose serially reproducible radiographs on live rats over an extended period of time.

Materials and methods

Female Wistar rats were anaesthetised and bone lesions were created in the ramus or tibia. In order that the lesions would not heal too rapidly the rats were infected with *Staphylococcus aureus* producing osteomyelitis.

A stent was produced with self-curing acrylic resin. This stent allowed all the rats to be positioned in the same way.

Direct digital radiographs were exposed once a week for 12 weeks with the Sens-A-Ray™ system.

Results

It is possible to produce serial radiographs of great similarity over a period of time, without losing any of the rats because of prolonged anaesthesia.

Discussion

The method has the potential to save resources such as time, money, care and housing for the animals, as well as allowing a smaller number of rats to be used, as serial sacrifices are not needed. Alternatively, statistics with more power are possible because all rats can be used throughout a study.

Paper VI
Comparison of the diagnostic potential of direct digital and conventional intraoral radiography in the evaluation of periimplant conditions

As digital radiographic systems are becoming more and more common and are replacing conventional film radiographs, it is of interest to know whether any differences in diagnostic accuracy between the two techniques may be expected. Radiographs of implants were chosen, since no *in vivo* study comparing direct digital and film radiographs of implants has been published to our knowledge.

Aims

The aims of this study were to examine whether viewers agreed on observations in direct digital and in film radiographs, and whether there were differences in agreement between the two methods. As a secondary aim, the patients' experience of having radiographs exposed with the two methods was studied.

Materials and methods

Intraoral radiographic examinations of implants were obtained both with direct digital and conventional film radiography. Patients giving their consent were asked to complete a questionnaire concerning their experience of the examinations.

Fifty pairs of radiographs with essentially the same projections and exposures were selected showing 59 implants.

Ten dentists were asked to view the radiographs and evaluate different details. These evaluations were compared statistically, as were the results of the questionnaires.

Results

The viewers showed high agreement in their assessments of radiographs made using both methods, and there were no statistically significant differences. However, there was a tendency to stronger agreement for the direct digital radiographs in four assessed points out of eight. The patients' opinions on the two methods did not differ statistically.

Discussion

The study shows that there are no differences in clinical yield between the two methods. We can therefore benefit from all the advantages of the direct digital method, among all including a low radiation dose to patients and positive environmental effects, when performing radiographic examinations of implants. Patients of today are also taking a more active part in treatment than previously, and this study indicates that they appreciate the advantages of direct digital radiography.

GENERAL DISCUSSION

When new radiographic systems are introduced it is of importance to evaluate their properties in various respects. The first three papers in the present dissertation dealt with determining a number of technical parameters valid for several intraoral digital radiographic systems. Prior to the publication of Paper I there were only a few contributions to this field presenting limited data on the RVG system. In two articles the dose response function and MTFs for this system were published.[ref] A representative MTF for the RVG was also determined in Paper II showing essentially the same function. In Papers I, II and III a number of additional parameters were determined for early versions of the Sens-A-Ray, the RVG, the VIXA/Visualix and the FlashDent systems.

Paper I not only presented basic technical data for the Sens-A-Ray but also introduced methods to determine these data. It was shown that the dark current of the Sens-A-Ray CCD detector was time and temperature dependent but also that its magnitude was low relative to the signal carrying information and thus negligible in clinical work.

The dose response function was found to be linear and independent of radiation energy. A comparison with UltraSpeed dental film (Kodak Eastman Co., Rochester, NY, USA) demonstrated that the CCD detector was markedly more sensitive to radiation than the film.

The SNR was relatively low and only reached a value of about 15 at an exposure that gave full saturation in the pixels. Still, the SNR was considered sufficient for clinical applications. A separation of quantum and dark current including electronic noise demonstrated that quantum noise totally dominated over electronic noise already at very low exposures.

The LSF determined from exposures of a 10 µm wide slit and fitted with an expression which is a sum of a Gaussian and an exponential function has a very narrow peak and marked tails indicating that the exponential part of the expression dominated over the Gaussian part.

Two presampling MTFs were calculated from the LSF, one valid for a plane in the object and one for the detector itself. These MTFs were found to have typical characteristics and reach values of about 0.1 at the Nyquist frequency that is 11.11 cycles/mm considering the pixel size of 45 µm. Noise Equivalent Passbands, N_es, were calculated for the two MTFs. These were 7.49 cycles/mm for the object plane and 6.51 cycles/mm at the detector plane. However, the concept of the N_e may be considered of limited value in digital radiography. In film radiography it is a meaningful value of an approximate limit frequency above which the contrast for higher frequencies becomes too low to detect. Contrast enhancement of digital radiographs makes it possible to increase contrast so that frequencies all the way up to the Nyquist frequency may be perceived.

The LSFs for the four systems determined in Paper II exhibit certain differences. The weighting factors between the Gaussian and exponential parts of the expression used to fit the functions vary. The LSF for the Sens-A-Ray is totally dominated by the exponential part while that of the other three systems are dominated by the Gaussian part. This is most marked for the Flash Dent. These differences of the LSFs may be explained partly by different pixel sizes and partly by the scintillators and optics used in the RVG™ and Flash Dent™ systems. The MTFs calculated from the respective LSFs demonstrate expected characteristics. The Flash Dent and the VIXA/Visualix have the same pixel size. Still, the MTFs are markedly different. Referring to the above this may be due to the use of a scintillator and optics in the Flash Dent system.

Paper III introduces noise analyses of digital intraoral radiographic systems. From NPSs for three exposures, one low, one medium and one high, at two different beam energies, 70 and 90 kVp, NEQs and DQEs were calculated. The NEQs were practically identical for the two energies. Differences were most certainly due to round off errors during calculations. The functions had broad peaks at about 2 to 3 cycles/mm. In absolute terms, the number of detected quanta, i.e. the NEQs, were relatively low which may be explained by the low absorption of quanta in the silicon of the CCD detector that was not covered by a scintillator layer. Consequently, the number of detected quanta relative to incident quanta, i.e. the DQEs, were low. At 70 kVp the original Sens-A-Ray CCD detector registered about 3% of incident photons at the peak of about 2 cycles/mm and at 90 kVp about 2.5%.

When first introduced, digital intraoral radiographs were displayed linearly on computer monitors, i.e. the grey levels were directly converted to brightness. In Paper IV a subjective study was performed that indicated that viewers would prefer a curved display function. This gave radiographs viewed on a computer monitor more "film-like" characteristics than when linearly displayed. This also has the effect that the exponential attenuation of radiation when a radiograph is exposed will approximately be compensated so that equal steps in object thickness will be perceived as approximately equal steps in brightness. The subjective preference of a curved display function together with the fact that such a function also approximately compensates for the exponential attenuation indicate that digital radiographs should preferably be presented by a curved display function. This has been confirmed recently when algorithms have been derived that more accurately compensate for the exponential attenuation (Welander, in press). It has been demonstrated that this improves perception of contrast details in radiographs exposed using test objects (Welander, in press) and also improves caries diagnosis in an *in vitro* study (Li, in press).

The study of bone lesions in rats using a technique that created periodically matching radiographs turned out to be successful. Thus, digital radiography is a suitable tool for non-invasive examinations in animal studies. Several advantages listed in the review of Paper V are apparent.

Implant therapy is increasingly regarded as the standard treatment of tooth loss. In this case digital radiographic examinations were in Paper VI shown to be at least as reliable as examinations employing conventional film radiography. The study was based on subjective assessments of a number of different essential details when evaluating radiographs of implants. Ideally, a study of this kind should be performed, e.g., using ROC technique. However, this implies that the true diagnosis is available. For obvious reasons this is not possible in a patient study. Still, subjective evaluations may be reliable. In associations with a subjective comparison between the rendering of structural details in two different types of radiographs, Dahlin *et al.* performed an analysis of the validity of the subjective evaluations based on their consistency. It was concluded that "The consistency of both the intraindividual and interindividual evaluations in the present analysis is so high, that the results strongly indicate that a subjective evaluation of image quality is reliable."

Ever since intraoral digital radiography was introduced this technique has been developing rapidly. In the discussion of Paper II it was stated that "It is likely that the data presented in this article will no longer be current within the near future. Detectors as well as computer hardware and software will successively be improved, changing system characteristics such as LSFs and MTFs. As this occurs, the present approach provides a method that may be applied to coming systems to determine comparable data on LSFs and MTFs". These statements may be expanded to include all determined technical properties as well as the analysis of the two applications included in the present dissertation.

CONCLUSIONS

The conclusions of this dissertation were

- technical properties of direct digital intraoral radiography are suitable for clinical applications;
- the subjectively preferred display of digital radiographs is curved;
- direct digital radiography may be used to advantage in animal studies;
- regarding examinations of implants, the diagnostic potential of direct digital radiography is on par with conventional film radiography.

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