Demonstration of Digital Radiographs by Means of Ink Jet–Printed Paper Copies: Pilot Study

Tomas Kirkhorn, Mikael Kehler, Johan Nilsson, Kerstin Lyttkens, Berth Andersson, and Nils-Gunnar Holmer

Different digital medical images have been printed on paper with a continuous ink jet printer, and the quality has been evaluated. The emphasis has been on digital chest radiographs from a computed radiography system. The ink jet printing technique is described as well as the handling of the image data from image source to printer. Different versions of paper prints and viewing conditions were compared to find the optimum alternative. The evaluation has been performed to maximize the quality of the paper images to make them conform with the corresponding film prints and monitor images as much as possible. The continuous ink jet technique offers high-quality prints on paper at a considerably lower cost per copy compared with the cost of a film print. With a future switch-over from diagnosing of digital images on film to diagnosing them on monitors, hard copies for demonstration purposes will occasionally be needed. This need can be filled by ink jet–printed paper copies.

KEY WORDS: medical imaging, hard copy, ink jet printing, radiography digital.

WITH THE INTRODUCTION of digital radiography, it was prophesied that film would be abandoned as a medium for demonstration and interpretation in a few years. However, film is still used today, and even the strongest adherents to digitization now believe that film is a necessity that cannot be discarded. Interpretation of examinations on monitors can make film superfluous for diagnosis, but it is preposterous to think that every radiologist can have access to an image database; therefore, another medium for demonstration is needed. The silver content of conventional film makes it very expensive; therefore, we have developed a low-price alternative in which the radiographs are printed on paper using the ink jet technique.

From the Department of Electrical Measurements, Lund Institute of Technology, and the Department of Diagnostic Radiology, Lund University Hospital, Lund, Sweden.

Address reprint requests to Tomas Kirkhorn, Department of Electrical Measurements, Lund Institute of Technology, PO Box 118, S-221 00 Lund, Sweden.

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MATERIALS AND METHODS

Printer Technique

The printer is based on the Hertz continuous ink jet technique shown in Fig 1.[1,2] By forcing ink under high pressure through a fine glass nozzle, a 10-μm jet of ink is generated having an exit velocity of approximately 60 m/s. By vibrating the nozzle with a piezoelectric crystal, the jet breaks up into separate and equally sized drops at a rate of 1 million drops per second.

The flight path of the continuous train of drops is electrically controlled by means of charging and deflection. A control electrode is located around the jet at the point of drop formation. By applying a control voltage of +80 V to the control electrode, negative charges will be attracted to the jet tip, and the drops being generated will become negatively charged. If instead the control voltage is equal to zero, the generated drops will be uncharged. Shortly after leaving the control electrode, the train of drops enters a static deflection field of 1,000 kV/m. The drops that have been charged will be deflected and caught under a knife edge while the uncharged drops continue unaffected through the deflection field and finally reach the recording paper. Thus, by switching the control electrode voltage between 0 and +80 V with a maximum frequency of 1 MHz, each individual drop can be caused to reach the paper or not.

Figure 2 shows the principle of the ink jet printer. The nozzle and the electrode system described above are assembled in the print head, which is situated in front of the paper-carrying drum. While the drum is rotating with a surface speed of 4 m/s, the print head is slowly moved sideways by a stepping motor at a rate of one image line per drum revolution. By monitoring the drum rotation with a shaft encoder, every pixel around the drum can be addressed. The operation of the printer is controlled by the control logic unit, which also transforms the image information sent from a Macintosh II fx computer (Apple Computer, Cupertino, CA) to a suitable signal for the on/off switching of the ink jet.

Different gray levels can be generated in each single pixel.[1] This true halftone ability is due to the small size of each individual drop: one drop deposited in a 100 × 100-μm² pixel results in a 30-μm diameter dot. By adding additional drops in the same pixel, the dot increases in size until the entire pixel is filled (Fig 3). In the present printer, the drum surface speed is adjusted so that 31 consecutive drops are available for each pixel. Thereby 32 different density levels (including white) can be created in 1 pixel. These discrete density levels are further mixed over a small area of adjacent pixels with an error-diffusion algorithm.[3] In this way, the number of reproducible density levels has been extended to 256.

According to the above principles, a printer has been constructed for the printing of monochrome images (black and white) with a spatial resolution of 10 pixels/mm. The

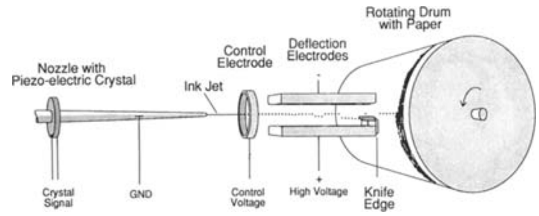

Fig 1. A continuous ink jet is ejected from a 10-μm nozzle. Through stimulation by a piezoelectric crystal, the jet disintegrates into 1 million drops per second. At the point of drop formation, a control electrode is located by which each generated drop can be charged. When the charged drops enter a static high-voltage field generated between the two deflection electrodes, they are deflected and caught below a knife edge. Uncharged drops travel unaffected through the deflection field and reach the recording paper. Thus, by switching the control voltage, the ink jet can be on/off switched at a maximum frequency equal to that of the drop formation.

drum dimension is matched to a paper size of 356 × 254 mm, which corresponds to the standard film print size in the computed radiography system.[4] A full print is completed in approximately 4.5 minutes.[2]

Image Selection and Data Conversion

Images were selected to represent various matrix sizes used in digital medical imaging: from 256 × 256-pixel matrices generated by, eg, computed tomography (CT) and magnetic resonance imaging (MRI) up to 2,000 × 2,000-pixel digital radiographs from a computed radiography (CR) system using imaging plates. Because digital chest radiographs are among the most critical for diagnosis, our major emphasis in this pilot study was on this kind of image.

Chest images were derived from a CR system, Digiscan (Siemens AG, Medical Engineering Group, Erlangen, Germany), at the Department of Radiology, Lund University Hospital. The image matrix size was 1,760 × 2,136 pixels. Seven patient images and three phantom images were selected. The former were all postoperative supine anteroposterior-view images taken in the ward. Features included tubes and central venous catheters and in 2 patients, pneumothorax conditions. The phantom images contained a 5-mm tumor simulation in the right lung field and/or a 10-mm tumor simulation in the mediastinum.

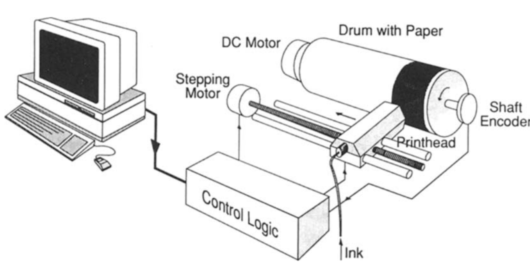

Fig 2. In the ink jet printer, the nozzle and electrode system are assembled in the print head, which is slowly moved along the quickly rotating paper bearing drum. The image information is entered from a computer to the control logic unit that controls the on/off switching of the ink jet.

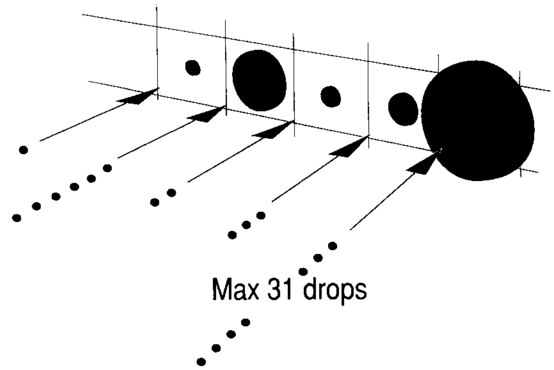

Fig 3. True halftone generation: the printed dot size is controlled by the number of ink drops deposited in the pixel.

The images were transferred from an optical disc via a host computer (MicroVax II, Digital Equipment Corporation, Maynard, MA) to a Siemens Litebox viewing station, which is basically a Macintosh computer with an advanced graphics interface. From the Litebox the image data were transferred to an external hard disc from which the data were finally transferred to the Macintosh II fx computer controlling the ink jet printer.

The paper prints were to be compared mainly with film hard copies. The CR images recorded on film were automatically level adjusted and high-pass filtered using an unsharp-mask algorithm in the CR system.[4] Because the filter-processed image data could not be extracted from the Digiscan, the image data had to be transferred to the Macintosh computer in a raw nonprocessed format, each pixel represented by 10 bits. Consequently, the transferred image data had to be level adjusted and processed to give images with similar diagnostic information as the film prints recorded by the Digiscan laser recorder. For this purpose, we used commercial software, Adobe PhotoShop (Adobe Systems Inc, Mountain View, CA).

The monitor of the Macintosh computer and the available software for displaying and processing the images were only capable of handling 256 gray levels. Therefore, after entering data in the Macintosh computer, the original data were reduced from 10 bits per pixel to only 8 bits. This was performed in three steps. First, an initial reduction to 8 bits was made over a range limited by the minimum and maximum 10-bit values in the original image data. Second, using Adobe PhotoShop, a window setting was performed, ie, new minimum and maximum levels were selected. The new minimum and maximum values were converted to corresponding values in the 10-bit image so that no information would be lost because of the window setting. In the third step, these 10-bit values were used for a conversion from the original 10-bit data image to the final 8-bit data image.

As mentioned above, further processing of the image data had to be performed to approach the diagnostic information level automatically delivered on film by the CR system. Therefore, edge enhancement using unsharp-mask filtering was applied in Adobe PhotoShop. Finally, before the image was sent to the printer, the data were converted to the printer data format in a special deduced software. With the format-conversion software, different γ curves were also applied to the image data to simulate the monitor γ curve and the film process γ curve. The monitor γ curve was estimated by visually comparing a test image having linear input levels from 0 to 255 on the monitor with an ink jet print of the same input values. The γ-curve of the film process was determined by measuring the transmission density from a Society of Motion Pictures and Television Engineers (SMPTE) test image film print.

Bone images with a 750 × 900-pixel area, selected from a 2,368 × 1,768-pixel image, were transferred from the CR system and handled in the same manner as the chest images above.

MRI-images of 256 × 256 pixels were recorded on floppy discs from a Beta 3000 (Fonar Corp, Melville, NY) at the hospital. These images were described using up to 13 bits per pixel. The reduction to an 8-bit format was performed with the same three-step conversion process as described for the chest images above. However, to produce ink jet prints similar in size to the corresponding film prints from a multiformat camera, each image was magnified three times; ie, each image pixel was printed as 3 × 3 print pixels (0.3×0.3 mm^2), generating the final print size of 76.8×76.8 mm^2.

CT images with a matrix of 256 × 256 pixels with 12 bits per pixel were derived from the internal hard disc of the Siemens Litebox (demonstration images). We have also derived CT images from clinical work at the hospital. As with the MRI, the CT-image data were reduced to 8 bits per pixel. Each pixel was also magnified three times before being printed.

Digital-subtraction angiography (DSA) images were derived from a magnetic tape containing demonstration images from Philips Medical Systems (Shelton, CT). The images with 512 × 512 matrices and 10 bits per pixel had been recorded on the tape after being adjusted with correct window settings. Therefore, no further adjustment was performed beyond the bit reduction to 8 bits. To enlarge the image, each image pixel was replicated 4 × 4 times before being printed.

Print Substrate

Two different kinds of papers were used: a Baryta coated paper (Zanders Feinpaper AG, Bergisch Gladbach, Germany) and a special matte-coated ink jet paper IJ Mattcoat NM (Mitsubishi Papermills Ltd, Tokyo, Japan). These two different papers were selected through a series of tests for several qualities. The Baryta was chosen because it showed minimal disturbing fiber structure when it was used with transillumination, which makes it suitable for use on a light box. The matte-coated paper was chosen because it gives a smooth and dense print that is suitable for normal viewing conditions using reflected light, ie, when viewed as ordinary photographs.

The Baryta paper was evaluated for use with both transmitted light and reflected light. Because it showed different density versus amount-of-ink responses when used with transmitted and reflected light, the image data were adapted for the two viewing manners. The special ink jet paper was used only for viewing with reflected light. Consequently, three versions of each image were printed.

Evaluation

A consensus group was formed that consisted of three radiologists (one senior experienced radiologist and two chest radiologists) and four imaging scientists. This group evaluated each single ink jet–printed image, and for every patient or phantom chose the paper and viewing method considered to show the different structures best and determined if any improvements could be made. After each meeting, the images were reprocessed according to the consensus. After each change a new consensus was procured, and the process continued until the best possible result was obtained.

RESULTS AND DISCUSSION

Figures 4 through 8 show ink jet prints of images derived from the different imaging devices used in this study. All the images were printed on the special ink jet paper for viewing with reflected light.

The evaluation results from the consensus group showed that in the majority of the cases, the special ink jet paper (IJ Mattcoat NM) was considered superior to the Baryta paper, and the chosen viewing method was using reflected light. Because viewing with reflected light is not the traditional viewing manner, the result was somehow unexpected. Therefore, the first evaluation meeting was followed by additional efforts to adjust the gray levels in the Baryta paper prints for an enhanced result from these transmission images. However, in the follow-up evaluations the reflection images on the special ink jet paper were still found to be superior. Finer structures in the image could be seen slightly better on this paper. Compared with the original radiograph on film, all details evaluated were clearly visible on the paper print.

If the diagnostic interpretation of radiographic images is intended to be made on a monitor with a hard copy only as a supporting demonstration image, then the quality of the ink jet paper print is high enough. If the diagnosis is to be made on a hard copy, the ink jet print quality is still high, but improvements must be made on either the printing technique or the image data. Using optimum processing on the image data, it should be possible to reach a diagnostic quality on the paper prints equal to or better than that of today's film prints.

The time necessary for the production of an ink jet print is too long compared with other image-producing modalities, but it can be short-

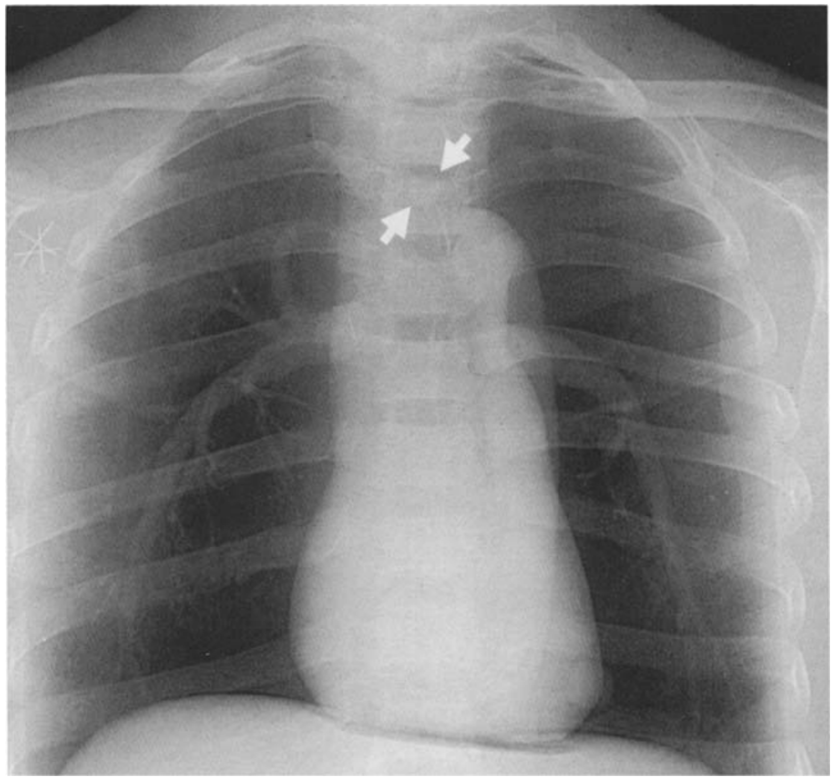

Fig 4. Ink jet print on paper of a chest phantom radiograph with a 10-mm mediastinal "tumor" derived from a CR system. The other test objects were fixed and not included in the study. The original image has a matrix size of 1,760 × 2,136 pixels, giving a print size of 176.0 × 213.6 mm². The part of the image shown here (1,570 × 1,460 pixels) is reduced in size to 70%.

ened easily. First, the diameter of the drum can be diminished; it was given the present diameter to have room for the same two versions of an image as being recorded on the film hard copy in the CR system.[4] However, only one has ever been needed, and by changing the diameter the time can be halved. A further time reduction can be obtained using a multinozzle print head. Nilsson et al[5] have already described a four-color ink jet printer using four nozzles, one for each of the primary colors cyan, magenta, yellow, and black. Thus, replacing the different colors with only black will allow the printing time to be reduced to less than 1 minute, which is less than the time required for the laser-recording and film-developing process.[4]

The weakness in gray-level reproduction by the ink jet printer lies in the very lowest densi-

Fig 5. Ink jet print on paper of a bone radiograph from a CR system. The image matrix of 750 × 900 pixels was selected from a 2,368 × 1,768 image. The print size of each image is 75 × 90 mm². The image is shown as an "ordinary" radiograph (A) and as an unsharp-mask filtered version of the same data (B). This example shows the important role of image processing for the final print result.

Fig 6. Ink jet print on paper of an MRI image. The original image matrix had 256 × 256 pixels. Before being printed, the image was magnified three times. Thus, the print size is 76.8 × 76.8 mm².

ties. The difference between no drop and one drop in a pixel is too great. This gives an inferior small-detail reproduction in these low densities. The problem can be solved by means of a combination of different inks; preliminary tests have showed promising results.

As mentioned earlier, this ink jet technology is not limited to only black-and-white printing but is also realized for full-color printing. Nilsson et al[5] and Johansson et al[6] have described the technique of color ink jet printing of color Doppler ultrasound images and evaluation together with a medical ultrasound specialist.

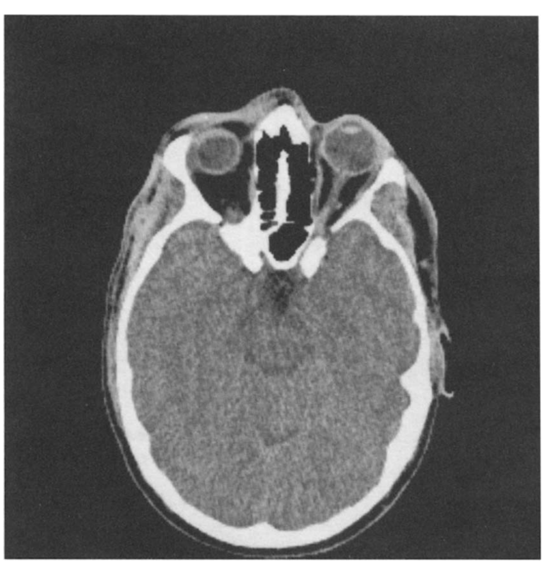

Fig 7. Ink jet print on paper of a CT image. The original image matrix of 256 × 256 pixels was magnified three times before being printed. Thus, the print size is 76.8 × 76.8 mm².

As stated above, the best results were obtained with the images printed on the special ink jet paper for viewing with reflected light, which is not the traditional way of viewing radiographs. However, this viewing method brings important advantages: it eliminates the need of a light box and makes demonstration of the radiological examination possible anywhere. The paper copy can be carried by the patient back to the referring clinician.

The economic gain of using ink jet paper prints will be considerable when compared with today's expensive film. The cost of an ink jet print on paper is approximately one tenth of that of a film print. Together with digital storage of the radiographic images, the paper copies will eliminate a film archive, because these copies are so inexpensive that they can be discarded after use. The present archives are space consuming, and the handling of films in the archive is heavy work.

Experience with CT has shown that despite the possibility of evaluating the examinations on a monitor using diverse forms of image processing, film is still used by most radiologists for the final evaluation.[7] The main reasons for this are the slowness of the viewing system and the difficulty of mastering the abilities of such a system, not to the superiority of the film. As a hard-copy medium for images from modalities with a small matrix such as CT (Fig 7), MRI (Fig 6), and ultrasonography,[6] the ink jet prints ought to have sufficient quality, even for diagnostic purposes. However, if digitization is to be meaningful and its potential fully exploited, the evaluation work should be based on powerful monitor systems instead of hard copies.

Even regarding large-matrix images such as chest images from CR systems (Fig 4), the highest-quality diagnosis will probably be made using monitors. However, hard copies will still be needed, although they will have a subordinate role, that of demonstration only. It will be unnecessary to use film for this task. Instead this

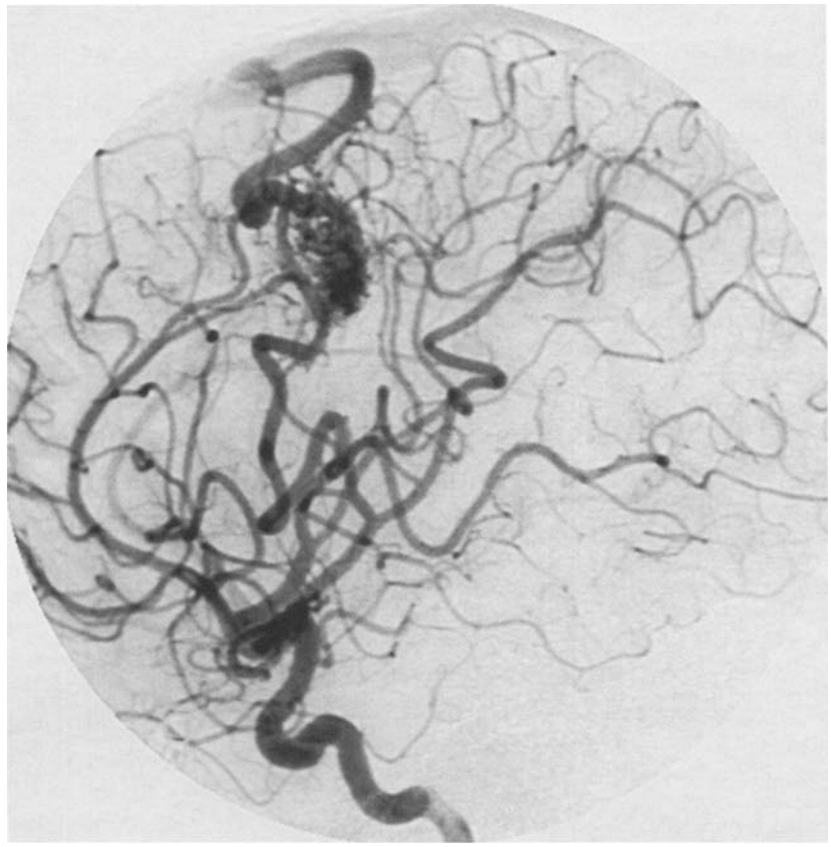

Fig 8. Ink jet print on paper of a DSA image. The original image matrix had 512 × 512 pixels. Before being printed the image was magnified four times. Thus, the print size is 204.8 × 204.8 mm^2.

need for hard copies can be filled by ink jet–printed paper copies.

As discussed above, hard copies for the diagnostic work may not be needed in the future. Our goal has been to make the quality of the ink jet prints as close as possible to that obtained from processed images recorded on film. Further studies with receiver operating characteristic analysis of the result will show how far we have succeeded.

REFERENCES

1. Hertz CH, Samuelsson B: Ink jet printing of high quality color images. J Imaging Technol 15:141-148, 1989

2. Kirkhorn T, Nilsson J: Two true halftone ink jet printers for gray scale and color printing. Report 4/91. Lund, Sweden, Department of Electrical Measurements, Lund Institute of Technology (LUTDEX/TEEM-1042), 1991, pp 1-108

3. Fawcett GS, Schrack GF: Halftoning techniques using error correction. Proc Soc Inform Display 27:305-308, 1986

4. Blume H: PCR Technical Review—Articles from previous issues of Market Vision: 1-16. Shelton, CT, Philips Medical Systems, Inc (articles appeared from December 1986-September 1987)

5. Nilsson J, Johansson T, Holmer N-G, et al: Ink jet color printing of digital medical images. Acta Radiologica 31:414-416, 1990

6. Johansson T, Nilsson J, Almquist L-O, et al: The use of ink jets in ultrasound registrations. Ultrasound Med Biol 17:529-539, 1991

7. Goodman LR, Wilson CR, Foley WD: Digital radiography of the chest: Promises and problems. AJR Am J Radiol 150:1241-1252, 1988