Digital imaging of cephalometric radiographs, part 2: image quality

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There are many potential benefits in producing digital images from conventional radiographs. For the patient, there is reduced exposure to radiation; for the clinician, storage, manipulation, transmission, image enhancement, and semi-automated cephalometric analysis are possible. But for digital imaging to truly offer significant advantages in cephalometry, the images must yield as much information as is currently available on radiographic films. The properties of conventional film radiography are difficult to match for high spatial resolution, wide dynamic range, and image acquisition and storage. The accuracy of digital images has been compared with that of conventional images in chest radiography,[1] mammography,[2] and musculoskeletal radiology.[3,4]

The quality of a digital image is strongly dependent on the spatial resolution, the relationship of the gray level values of the pixels to the optical density of the radiograph and the image display. The number of pixels and gray levels that are required to produce an image of acceptable quality will vary depending on the image itself. Images which contain a large amount of detail depend more on the number of pixels rather than the number of gray levels.

Spatial resolution

Spatial resolution is the ability to record separate images of small objects that are placed closely together; it is measured in line pairs per mm (lp/mm). The smaller the pixel size, the more detail in the image and therefore the greater the resolution. The smallest detail detect-

Abstract

The aim of this study was to compare the diagnostic quality of conventional cephalometric radiographs with that of digital image counterparts. The random error associated with angular and linear measurements recorded on the digital images was greater than on the conventional radiographs. In addition, there was a systematic error producing statistically significant differences in the majority of angular and linear measurements between the digital images and the conventional radiographs. The errors that occurred with some measurements were of sufficient magnitude to be of clinical significance, particularly in a cephalometric situation where a high degree of accuracy is required. It is therefore suggested that, for digital imaging of cephalometric radiographs, a pixel matrix larger than 512 x 512 with more than 64 gray levels is required to maintain the diagnostic quality of the original radiograph.

Key Words

Cephalometry • Digital imaging • Image quality

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Figure 1
Design of study

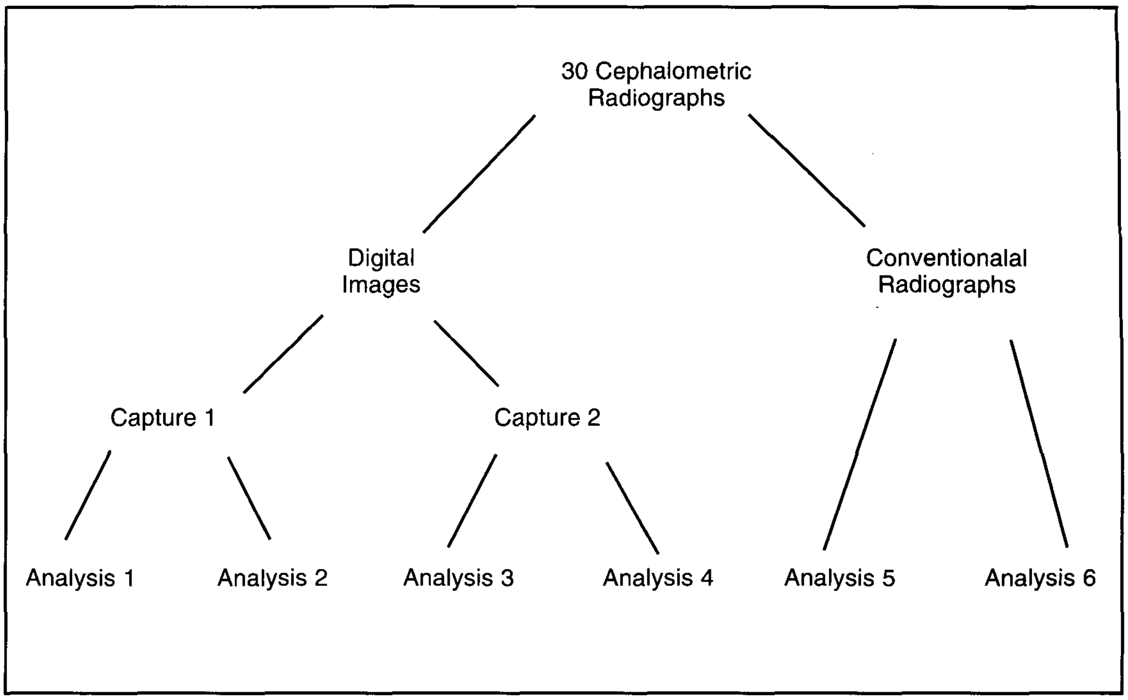

Figure 1

able by the human eye is 0.1 by 0.1 mm. To provide digital images of radiographs with at least as much information as is available in the original conventional radiograph, pixels no larger than 0.1 mm are required,[5] giving a spatial resolution of 5 line-pairs per mm (lp/mm). The optimal pixel size for a given application will be the one just small enough to allow an acceptable level of diagnostic accuracy while reducing data storage requirements to a minimum.

Several studies have been carried out to assess the spatial resolution required for different clinical applications. In clinical practice the diagnostic quality of digitized chest radiographs increases significantly as the pixel size is reduced, at least to the 0.1 mm level (5 lp/mm).[6,7] The use of pixel sizes substantially larger than 0.1 mm may result in some loss of diagnostic accuracy. The spatial resolution required for musculoskeletal radiology depends on the clinical condition being diagnosed. In general, musculoskeletal radiology requires a higher spatial resolution than chest radiography, a spatial resolution of 8 lp/mm is necessary for skeletal images, but for chest and gastrointestinal images a spatial resolution of 4 lp/mm is adequate.[8] The spatial resolution of most film/screen combinations used for musculoskeletal radiography is equivalent to 10-12 lp/mm.

Optical density

Film blackness is measured by optical density, which is calculated from the logarithm of the ratio: light incident to light transmitted by a film. A logarithmic scale is used, as this corresponds to the human eye, which also responds in a logarithmic manner to light intensities.

The quality of digital images is related to the number of gray levels and how the range of gray level values is related to the optical density of the region of interest on the conventional radiograph. However, image enhancement techniques, such as histogram equalization, can be used to ensure maximum use is being made of the gray scale available and may improve the diagnostic quality of the image.

For chest radiography Fraser et al.[9] suggest that a 12-bit (4,096 gray levels) image is required to adequately reproduce the wide dynamic range present on the radiograph. However, Bramble et al.[10] using the model of sub-periosteal resorption in the hand showed that diagnostic quality was maintained when the gray levels were reduced to 7 bits. Wenzel,[11] in assessing the requirements of 3 x 4 cm intraoral periapical radiographs, found that diagnostic accuracy was maintained when the gray levels were reduced to 6 bits.

Image display

With improving technology, the limitations of pixel size and the number of gray levels can be overcome and the limiting factor in the quality of digital images will be the spatial resolution of the display monitor, which is dictated by the number of raster lines.[12] Monitors displaying up to 625 lines are routinely used for viewing of digital images. Where image quality is particularly important, a 2,048-line monitor should be used to give comparable resolution to a radiographic film.[13]

Errors in cephalometry

Errors in landmark identification have been shown to be the greatest source of error in cephalometry.[14,15] As the digital images used in this study are captured from the original radiographic film, they are subjected to the same projection errors. Two additional sources of error may also arise: errors in landmark identification related to a loss in image quality, and errors due to calibration. Calibration of the digital image is required to enable measurements to be made in millimeters and degrees on the digital image.

The reliability and validity of landmark identification on the original cephalometric radiograph and the corresponding digital image were compared using a coordinate system and commonly used angular and linear measurements. As a result of the limiting spatial resolution of the digital image, relocation of the coordinate system between analyses is subject to a significant error. Therefore the results of the angular and linear measurements are presented here, as they are clinically more relevant and are less affected by the error in the method.

Aims of the present study

The aim of this study was to compare conventional cephalometric radiographs with their digital counterparts with regard to the validity and reproducibility of angular and linear measurements.

Materials and methods

Image capture facility

In this study a Machine Vision Target System (MVT3020) was used as the digital computer with a Pulnix TM-760 video camera to capture the digital image. The size of the field captured can be altered by adjusting the camera-to-radiograph distance. A clear image is obtained by adjusting the aperture and focus of the camera. The digital images are calibrated using a calibration target to enable "world units" (millimeters and degrees) to be measured directly from the digital image.

Radiographs are mounted on a light box and captured using the camera, which converts the analogue image into a digital format. The camera and radiograph are enclosed in a light-proof box to ensure maximum contrast during image capture. The image consists of 512 x 512 pixels with 64 gray levels (6 bits).

Conventional digitizer

The radiographs were digitized on a GTCO digipad 5A connected to an IBM-compatible microcomputer. Landmarks were identified using a cursor directly on the radiographs, which were secured to the illuminated surface of a digitizing tablet.

Before measurements were made on the digitizer, the accuracy of the digitizer was confirmed using a photographically-etched graticule for both angular and linear measurements. Twenty-five different measurements were made of 100-mm distances on the photographically-etched graticule in both the X and Y dimension. The mean value obtained was 99.96 mm with a standard deviation of 0.1 mm.

Design of study

Sample

Thirty cephalometric radiographs taken at the radiology department, Manchester Dental Hospital, were used in this study. The radiographs were taken with the following equipment:

Unit: Cranex Dc Ceph. Model SL-4/PT-7C/C.
Output: 75 - 80 Kv and 10 mA.
In this study the radiographs were taken at 75Kv 0.6 sec.
Screen: Kodak Lanex regular screens.
Film: Fuji HR-L

The sample was randomly selected, disregarding the quality of the radiograph or the malocclusion present.

Exclusion criteria:

1. Obvious malposition of the head in the cephalostat.
2. Incisors unerupted or missing.
3. Unerupted teeth overlying the apices of the incisors.

The 30 radiographs were captured twice to give 60 digital images, capture 1 (30 images) and capture 2 (30 images). Landmark identification was then carried out on two separate occasions by one operator on each of the 60 digital images and on each of the 30 conventional radiographs (Figure 1). This yielded six different analyses on each of the 30 radiographs: two on the conventional radiograph, two on the first digital image (capture 1) and two on the second digital image (capture 2). The study was designed in this way to enable a comparison to be made between the digital images and the conventional radiographs and to assess the effect of image capture.

Landmark identification was carried out on the original radiograph using the conventional digitizer and on the digital image using a mouse that controls a cursor on the displayed image. The same analysis was carried out on each system, and the landmarks were digitized in the same

Figure 2
Landmarks used and three fiducial points.

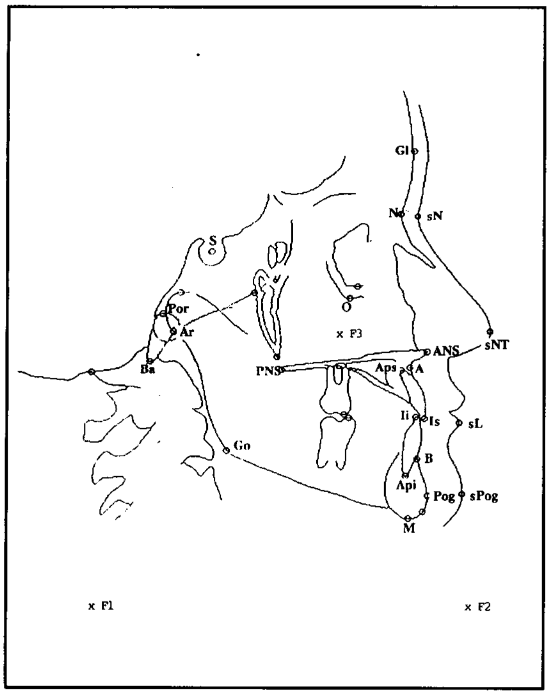

Figure 2

Table 1
Random error. Angular measurements.

	Digital Image (RMS)	Conventional Radiograph (RMS)	F-test
SNA	1.57	0.67	2.3 *
SNB	1.24	0.5	2.5 *
ANB	0.55	0.32	1.7
SNIi	1.34	0.55	2.4 *
1/ to Max	1.15	1.16	0.9
1/ to Mand	1.42	1.09	1.3
MMPA	0.94	0.83	1.1
SN to Max	1.21	0.91	1.3
1/ to 1/	1.45	1.39	1.0
FMPA	0.93	0.79	1.2
Ba-S-N	1.6	1.47	1.1
S-sN-sPog	1.08	0.79	1.4
sNT-sN-sPog	1.03	0.66	1.6
F2-F1-F3	0.14	0.06	2.3*

* = P < 0.05; ** = P < 0.01

predetermined sequence. The landmarks used in this study are illustrated in Figure 2. No more than 10 radiographs were traced in any one session, and each session was separated by a one-week interval to prevent operator fatigue and familiarity with the image. Results were given in X-Y coordinates from which the required angular and linear measurements were calculated.

Three pinholes were placed on each image to represent fiducial points. Pinholes 1 (F1) and 2 (F2) were placed at the bottom of the radiograph parallel to the maxillary plane, and pinhole 3 (F3) was placed approximately in the center of the radiograph. The angle F2-F1-F3 and the linear distance F1-F2 reflect the error in the method, due primarily to the error in calibrating the digital images.

The effect of image capture was found to be insignificant; therefore, to compare the digital images with the conventional radiographs, the data from analyses 1, 2, 3 and 4 were pooled and compared with analyses 5 and 6. Statistical analysis of the angular and linear measurements was undertaken to compare the digital image with the conventional radiographs.

Results

Angular and linear measurements - random error

The random error associated with the digital images and the conventional radiographs is shown in Tables 1 and 2. The square root of the mean of the differences squared between replicate measurements was used as a measure of the random error for both the digital images and the conventional radiographs. An F-test was undertaken to compare the ratio of variances and to determine if there was a significant difference between the random error associated with the digital images compared with the conventional radiographs.

In general, when comparing the digital images with conventional radiographs with regard to angular and linear measurements, there was a greater random error associated with the digital images (Tables 1 and 2). In this study a larger random error was found on the digital images in comparison with the conventional radiographs in 17 of the 22 angular and linear measurements. In five cases, the error was statistically significant. These five measurements all involved the skeletal landmark nasion. The random error associated with the angle F2-F1-F3 and the linear measurement F1-F2 involving the fiducial points was small in comparison with the other angular and linear measurements.

Angular and linear measurements - systematic error

To determine if there was a systematic error or bias between the digital images and the conventional radiographs, a paired t-test was carried out between replicate measurements. The mean value for each of the angular and linear measurements for the 30 radiographs was calculated, using analyses 1, 2, 3 and 4 for the digital images and analyses 5 and 6 for the conventional radio-

Table 2
Random error. Linear measurements.

	Digital Image (RMS)	Conventional Radiograph (RMS)	F-test
S-N	0.95	0.31	3.1*
S-Pog	0.54	0.63	0.8
UFH	1.41	0.91	1.5
LFH	0.42	0.49	0.8
Me-Go	1.81	1.09	1.6
Ar-Pog	0.54	0.61	0.9
Gl-Me	1.27	0.72	1.8
Ba-N	1.97	3.77	0.5
TFH	1.35	0.63	2.1*
F1-F2	0.26	0.14	1.8

* = P < 0.05; ** = P < 0.01

Table 3
Systematic error. Angular measurements (degrees).

	Digital Image	Conventional Radiograph	Mean Difference	t-test
SNA	82.5	80.3	2.2	6.52**
SNB	78.3	77.1	1.2	4.24**
ANB	4.2	3.2	1.0	7.00**
SNIi	81.4	80	1.4	4.59**
$\underline{1}$/ to Max	108.6	108.8	-0.2	-0.79
$\overline{1}$/ to Mand	92.2	91.8	0.4	1.0
MMPA	27.1	26.5	0.6	2.84**
SN to Max	7.1	8.6	-1.5	-6.15**
$\underline{1}$/ to $\overline{1}$/	132.1	132.9	-0.8	-1.65
FMPA	28.8	28.4	0.4	2.29*
Ba-S-N	131.3	131.7	-0.4	-1.43
S-sN-sPog	85.5	84.4	1.1	5.04**
sNT-sN-sPog	30.0	29.1	0.9	3.81**
F1-F2-F3	53.9	54.1	-0.2	-13.19**

* = P < 0.05; ** = P < 0.01

graphs; a paired t-test was also carried out. Tables 3 and 4 show the mean values of the angular and linear measurements for the digital images and conventional radiographs, with the mean differences and associated t-test.

For most of the angular and linear measurements there was a small but statistically significant systematic error between the digital images and the conventional radiographs. The largest error was associated with SNA, which was an average of 2.2 degrees larger on the digital image than on the conventional radiograph. The measurements constructed from the dental landmarks as opposed to the skeletal landmarks had a lower systematic error. The error due to calibration is reflected in the small but statistically significant systematic error associated with the angle F2-F1-F3 and the linear measurement F1-F2 involving the fiducial points.

The systematic error can be shown graphically by plotting the differences between the digital image value (mean value of analyses 1, 2, 3 and 4) and the conventional radiograph value (mean value of analyses 5 and 6) for each of the 30 radiographs (Figure 3). The 30 radiographs are represented on the X-axis and the difference in degrees between the conventional radiograph and the digital image is represented on the Y-axis. A positive value indicates that the digital image value is larger than the conventional radiographic value. Figure 3 shows an example of some of the angular measurements.

For the angle F2-F1-F3, between the fiducial points, there was a small but significant difference between the conventional radiograph and the digital image due to the calibration error. This is shown in Figure 3a, with the angle F2-F1-F3 having a lower value on the digital image compared with the conventional radiograph for each of the 30 radiographs. However, the mean difference was only 0.2 of a degree. Figure 3b shows the systematic error associated with angle SNA. The angle SNA was measured with a con-

Table 4
Systematic error. Linear measurements (millimeters).

	Digital Image	Conventional Radiograph	Mean Difference	t-test
S-N	75.2	76.2	-1.0	-4.78**
S-Pog	130.0	129.6	0.4	2.68*
UFH	56.7	58.1	-1.4	-5.18**
LFH	70.2	70.5	-0.3	-2.91**
Me-Go	78.0	78.2	-0.2	-0.35
Ar-Pog	115.2	115.1	0.1	0.7
Gl-Me	143.2	144.1	-0.9	-2.6*
Ba-N	114.2	115.5	-1.3	-3.5**
TFH	126.9	128.5	-1.6	-6.0**
F1-F2	101.2	101.4	-0.2	-4.0**

* = P < 0.05; ** = P < 0.01

sistently higher value on the digital image compared with the conventional radiograph. The mean difference was 2.2 degrees. With the angle 1/ to Max there was no significant systematic error (Figure 3c). However, with the angle MMPA, there was a small but significant systematic error or bias (Figure 3d).

Discussion

The production of digital images from cephalometric radiographs poses a particular problem because of the fine detail present on cephalometric radiographs and the wide dynamic range; the operator is generally interested in both soft and hard tissue features. Measuring world units on a digital image captured from a conventional radiograph is an additional problem, as shown by the calibration error in this study.

This study has shown that a digital image, consisting of a 512 x 512 pixel matrix with 64 gray levels, is significantly poorer in terms of image quality than the original cephalometric radiograph. This loss in image quality is related to the reduced spatial resolution and the relationship between optical density of the radiograph and the gray levels of the digital images. The limiting spatial resolution of the Kodak Lanex regular screens, of the type used in this study as quoted by the scientific and technical branch of the Department of Health and Social Security, is 7 line-pairs per mm (lp/mm). This value would have been obtained in the laboratory under optimal conditions. However, in this study a lower spatial resolution of 4.2 lp/mm was measured from the film/screen combination under normal working conditions.

The spatial resolution of the digital image is determined by the size of the pixels. In this case a pixel size of 0.35 mm was obtained when the cephalometric radiograph was captured to a 512 x 512 pixel matrix. With a pixel size of 0.35 mm the expected spatial resolution would be approximately 1.3 lp/mm. In this study a similar figure of 1 lp/mm was measured as the spatial resolution of the digital image.

In the literature various values have been suggested as necessary to produce digital images with diagnostic quality comparable to that of the original conventional radiographs. The spatial resolution required is determined by the clinical application. For example, in chest radiography a spatial resolution of between 2 lp/mm[16] and 5 lp/mm[5] has been suggested as necessary. In musculoskeletal radiography, which is more closely related to cephalometric radiography, the suggested spatial resolution ranges from 1.25 lp/mm[3] to 8 lp/mm,[8] depending on the clinical condition being diagnosed. The spatial resolution of 1 lp/mm found in this study appears to be less than the resolution suggested for most other clinical applications.

In diagnostic radiology, the optical density of radiographs ranges from 0.2 to 2.5, with 0.2 representing light areas on the film and 2.5 representing dark areas. The optical density of the cephalometric films used in this study did vary between each film. The optical density of the exposed film was approximately 2.3, soft tissues were 2.1, radiopaque areas on the skull were 0.7, and the unexposed film (or background fog) was 0.2.

The quality of a digital image is determined by the number of gray levels and the sensitivity of gray levels to changes in optical density within the range of interest. If, for example, the optical density of the nasal bone was 2.15 and the adjacent soft tissue was 2.18, the gray level value of the pixel may not be sensitive enough to detect this small change in optical density and the nasal bone would be difficult to identify on the digital image. The systematic error associated with the angular and linear measurements involving nasion indicates that it is identified with a systematic error of approximately 1 mm, identified in a lower position and toward the center of the radiograph on the digital images compared with the conventional radiographs. The systematic error involving the landmark nasion was similarly confirmed from coordinate results.[17] This could be due to a loss in image quality where a fine edge is lost or averaged in, therefore producing a systematic error for certain landmarks.

Whether the loss of image quality found with the digital images used in this study is of clinical significance will depend on the clinical application. Previous studies suggest that a random error of between 0.4 and 2 degrees occurs with conventional cephalometric radiographs for angular measurements, depending on the angle measured.[18] The errors associated with the digital images are greater than this level for several of the measurements, especially SNA with a systematic error of 2.2 degrees.

It may be acceptable to use this system in individual cases to assess dentofacial proportions, but where high accuracy is required, for example in monitoring growth or in studies comparing different treatment modalities, the loss of quality would be of significance.

The use of image processing techniques to enhance digital images has proved to be beneficial

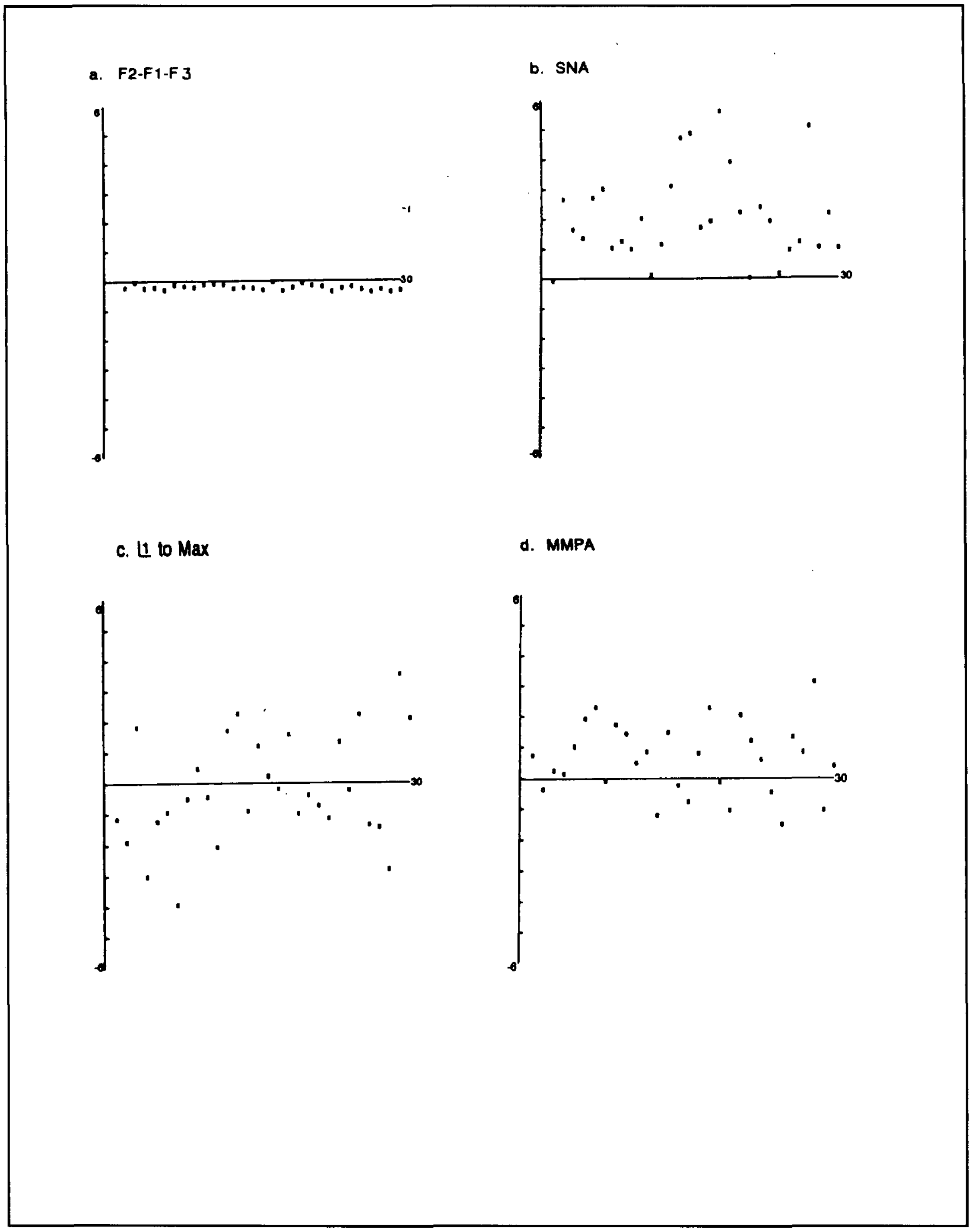

Figure 3

Figure 3
Angular measurements. Systematic error. Difference between mean value of analyses 5 and 6 (conventional radiograph) and mean value of analyses 1, 2, 3, and 4 (digital image) for 30 radiographs. Y-axis scale in degrees. X-axis radiograph.

in some radiographic applications[19, 20] and has been shown to be of benefit in cephalometric radiography.[21] However, if a feature has not been detected in the original capture process, enhancement can be of no benefit. There is another potential problem in using enhancement algorithms, in particular edge enhancement techniques, where an edge may be defined more clearly and landmark identification becomes more reproducible. This reduces the random error associated with landmark identification, but the validity of the landmark may be incorrect and a systematic error may be introduced. Other enhancement features such as contrast stretching or zoom facilities may aid landmark identification but do not affect the spatial resolution of the image.[8]

Improvements in image quality would be obtained by reducing the pixel size, increasing the spatial resolution of the digital image, and increasing the number of gray levels of the pixels. With regard to future systems, the most promising area of development seems to be with the use of phosphor plates to capture digital images.[22, 23] These eliminate the intermediate stage of the conventional radiograph and produce digital images of high spatial resolution with a large number of gray levels.

Conclusions

The following conclusions may be drawn from this study:

1. Calibration of the digital image produces a small but significant error.
2. The spatial resolution of the digital image is less than that of the conventional radiograph.
3. The digital image is unable to match the conventional radiograph in dynamic range and sensitivity to small changes in optical density.
4. The random error associated with angular/linear measurements and landmark identification tends to be greater with the digital images than the conventional radiographs.
5. With the majority of angular and linear measurements there is a systematic error between the digital images and the conventional radiographs. Landmarks on poorly defined edges such as nasion and point A appear to have the greatest error.

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