Influence of developer exhaustion on accuracy of quantitative digital subtraction radiography

An in vitro study

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Objective. The aim of the study was to evaluate the influence of developer exhaustion on accuracy of quantitative digital subtraction radiography.
Study design. Six objects, each incorporating a section of dry human mandible, were radiographed with 4 exposure times. Baseline films were processed in fresh solutions, whereas follow-up films were processed in fresh and in increasingly exhausted solutions (ie, 1, 2, and 3 weeks old). Bone loss and bone gain were computer simulated in 17 regions of interest on baseline radiographs. Area and volume of changes in mineralization were measured in subtracted images, obtained by subtraction of baseline from their corresponding follow-up radiographs. Friedman's 2-way analysis of variance by ranks and Wilcoxon signed-rank test were used for statistical analysis.
Results. Because of exhausted developer, bone loss was relatively underestimated from 6.6% to 16.5% ($P < .05$), whereas bone gain was relatively overestimated from 9.7% to 16.7% ($P < .05$).
Conclusions. This in vitro study demonstrates that films for quantitative digital subtraction radiography should be processed in fresh developer or error might be introduced.
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Dental radiography is the main diagnostic tool for detecting bone loss or gain in periodontology.[1] Because conventional radiography requires a change in mineralization from 30% to 60% to become visible,[2] small changes, although clinically important, may remain undetected.

When Gröndahl et al[3] introduced digital subtraction radiography (DSR) in dental radiography, the assessment of small changes in alveolar bone mineralization, superimposed with other anatomic structures,[1] had become possible. Visualization of these changes was further improved by the methods developed for contrast enhancement[4] or color conversion.[5,6] Moreover, methods have been proposed to quantify changes in mineralization.[7-10]

A drawback of DSR is the requirement of highly standardized radiographic procedures, that is, projection geometry, exposure conditions, and film processing, to avoid possible misinterpretation of the subtracted image. Some of these discrepancies can be minimized or even eliminated by methods proposed for contrast correction[11-13] and geometric alignment.[14] However, these methods should be used carefully because they might introduce additional errors.

The density and contrast of radiographs are influenced by processing time, temperature of developer,[15] and exhaustion of developer.[16] The latter is the combination of aging and depletion.[16] In previous studies, film processing conditions were standardized and fresh developers were used,[6,8,9] hence poorly reflecting the conditions met in clinical practice. Many factors that could introduce error in DSR have been studied,[17-21] but we are not aware of any published report dealing with the influence of developer exhaustion.

The aim of this study was to assess the influence of developer exhaustion on the accuracy of quantitative DSR.

MATERIALS AND METHODS

Two dry human mandibles were sectioned into 6 sections, each 28 mm long, including 1 to 3 sound teeth. To prevent movement, the teeth were fixed into their sockets by cyanoacrylic glue (Pattex; Henkel, Düsseldorf, Germany). To standardize the projection geometry, 6 radiographic objects were constructed (Fig 1). Each consisted of a ring, fitting exactly to the end

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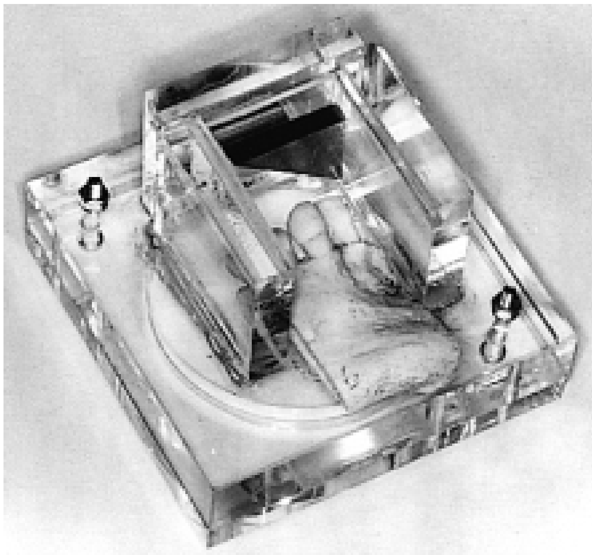

Fig 1. Radiographic object (including section of mandible), aluminum block (attached to aluminum wedge), acrylic plate, and ring for cone of x-ray machine.

of the x-ray machine cone, to which a 19.5-mm thick acrylic plate was mounted to simulate soft tissue. A section of mandible and the film holder with an aluminum gray level calibration wedge (25 × 15 × 5 mm) were rigidly attached to the plate. An additional aluminum block (15 × 5 × 5 mm) was aligned to a thinner end of the wedge to facilitate its detection on the radiograph.

An x-ray machine (IRIX 70L; Trophy, Vincennes, France) operating at 70 kV and 8 mA was used. Cone length was 20 cm, focus-to-object distance was 30 cm, and object-to-film distance was 0.5 cm. All objects were radiographed with 4 different exposure times (0.06 seconds (s), 0.12 s, 0.20 s, 0.36 s) on size 2 Kodak Ektaspeed Plus film (Eastman Kodak, Rochester, New York) just before processing. This procedure was performed 5 times, and films were processed in fresh developer and in developer that was 1, 2, and 3 weeks old. The film processing time schedule is shown in Table I. Each of the resultant groups, named from A to E, contained 24 radiographs of the 6 objects exposed with 4 exposure times. Because the dental film processor was also in clinical use, an additional 32 films were processed every week, for a total of 216 films.

All films were processed with a Periomat 1306 dental film processor (Dürr Dental GmbH, Bietigheim-Bissingen, Germany) which has a heater to keep the temperature of the solutions constant (ie, 24°C). The heater was switched on 8 hours per day and 5 days per week. The volume of developer in the film processor is 1000 mL, and the manufacturer does not provide any instructions about replenishment. During the experiment, the transportation mechanism was regularly cleaned and solution levels were checked twice a week, according to manufacturer's instructions.

Table I. Film processing time schedule

Group	*Age of developer (wks)*	*Number of already processed films*
A	0	0
B	0	0
C	1	80
D	2	136
E	3	192

Radiographs were masked, back illuminated, and captured by a monochrome charge-coupled device video camera (Sony XC-77 CE; Sony, Tokyo, Japan) with a 50-mm lens (Cosmicar Videosys TV Lens; Asahi Optical Co, Tokyo, Japan) and a 10-mm adapter ring. All radiographs exposed with the same exposure time were captured with equal aperture to preserve changes in brightness and contrast. Radiographs were digitized (730 × 530 pixels, 8 bit) by a frame grabber (Meteor Matrox; IMAGIC Bildverarbeitung AG, Glattbrugg, Switzerland) installed in a PC-compatible computer. UTHSCSA ImageTool for Windows Version 2.00 (University of Texas Health Science Center, San Antonio, Texas) was used for image acquisition, processing, and analyses. To reduce noise, each radiograph was captured 16 times and averaged. The images were subsampled by merging 4 adjoining pixels into 1 with the average gray value.

The radiographs from follow-up groups B to E were automatically aligned to the corresponding radiographs from baseline group A. The optimal translation and rotation, which brought images into alignment, were found by optimizing a similarity measure between the images.[22] Central parts of the aligned images with the resolution of 264 × 254 pixels formed the final 120 image experimental database.

Brightness of radiographs was expressed by mean gray level. Contrast of radiographs was expressed by the coefficient of variations, which is defined as standard deviation or mean. The image of the aluminum wedge was used to calculate aluminum thickness corresponding to 10 gray levels.

For each exposure time, 17 regions of interest (ROI) were selected on the images from group A. The ROIs of 25 × 50 pixels were located on the top of the alveolar bone adjacent to the tooth. To avoid having more than 1 ROI in a single image, some of the images were digitally copied. This resulted in a set of 17 images for each exposure in the baseline group A. Finally, the set was digitally copied into 2 baseline sets named the "bone loss set" and the "bone gain set." In the images from the "bone loss set," the gray levels of all pixels in ROIs were increased by 10. ROIs in the follow-up images

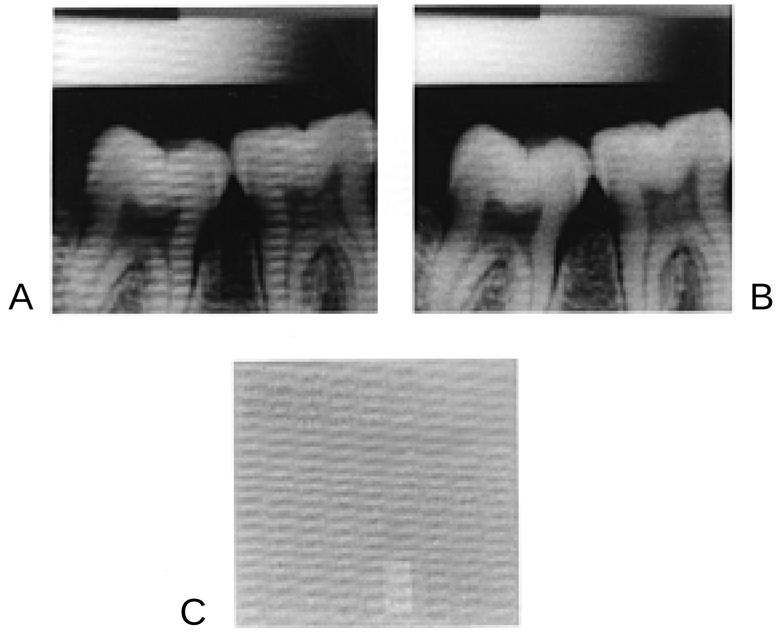

Fig 2. Computer-simulated bone gain. **A**, Radiograph processed in fresh developer with ROI on top of alveolar bone between molars. **B**, Follow-up radiograph, processed in 3-week-old developer. **C**, Subtracted image B–A, showing simulated bone gain as brighter area.

were therefore brighter than the same ROIs in the baseline images. In this way, the bone loss was simulated in the corresponding images from the follow-up groups B to E. Similarly, in the baseline images from the "bone gain set," the gray levels of all pixels in ROIs were decreased by 10 (Fig 2) to simulate bone gain in the corresponding images from follow-up groups B to E.

The areas of simulated change were 1250 pixels (25 × 50) in size, whereas the size of corresponding volumes was 12,500 volume units (1250 pixels × 10 gray levels).

Images from baseline group A were subtracted from the corresponding images from follow-up groups B to E, processed in gradually exhausted developer. Pairs for subtractions were B–A, C–A, D–A, and E–A. Before subtraction, the corresponding images were contrast corrected with the method proposed by Ruttimann et al.[11]

In the subtracted image, a gray level of 128 represented no change. A threshold for mineralization and demineralization was set to ± 9. Hence, pixels having a gray level lower or equal to 119 in the subtracted image were treated as demineralization, whereas pixels with a gray level higher or equal to 137 were treated as mineralization. Gray level changes in ROIs were expressed by 2 parameters: (1) the percentage of ROI showing mineralization or demineralization, expressed by the ratio between the measured and simulated area; and (2) the percentage of measured volume, expressed by the ratio between the measured and simulated volume.

All parameters were expressed as median values with 25th and 75th percentile. For comparison of measured bone loss and gain at different developer exhaustion, Friedman's 2-way analysis of variance by ranks was used.[23] Where differences were found, we compared the subtraction result of pair B–A with the corresponding results of pairs C–A, D–A, and E–A by Wilcoxon signed-rank test. A *P* value of less than .05 was considered statistically significant. All statistical analyses were performed on a personal computer with statistical package SPSS 7.5.1 for Windows (SPSS Inc, Chicago, Illinois).

RESULTS

The brightness of radiographs increased with age of developer (Fig 3), whereas the contrast of radiographs decreased with age of developer (Fig 4). Aluminum thickness equivalent to 10 gray values increased with exposure time: for exposure times of 0.06, 0.12, 0.20, and 0.36 s, the corresponding thicknesses were 0.5, 1.1, 2.2, and 4.5 mm, respectively.

Influence of developer exhaustion on detecting bone loss

Statistically significant decreases in the percentage of ROI showing bone loss were found at 0.06 s and at 0.12 s exposure time for all ages of developer. A decreased value also was found at 0.20 s exposure times, but it did not reach statistical significance (Fig 5). Similarly, statistically significant decreases of the percentage of simulated volume of bone loss were found at exposures of

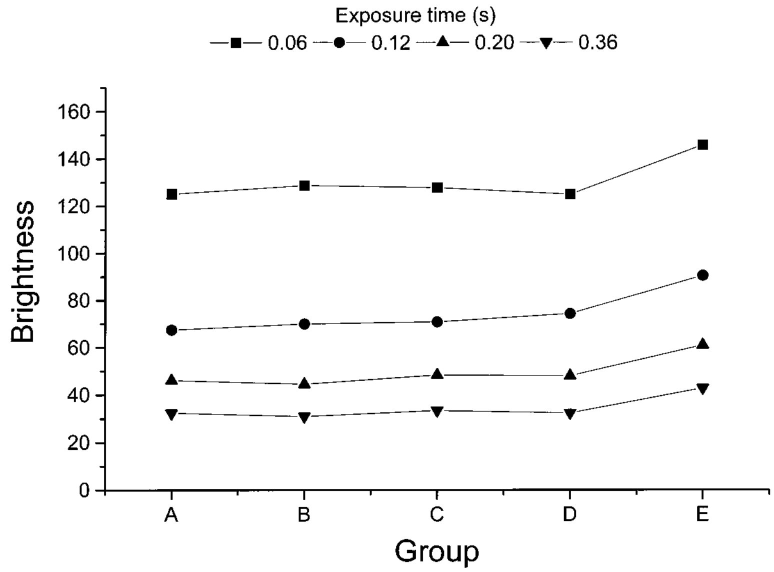

Fig 3. Changes in average brightness of radiographs for different exposure times as function of developer exhaustion.

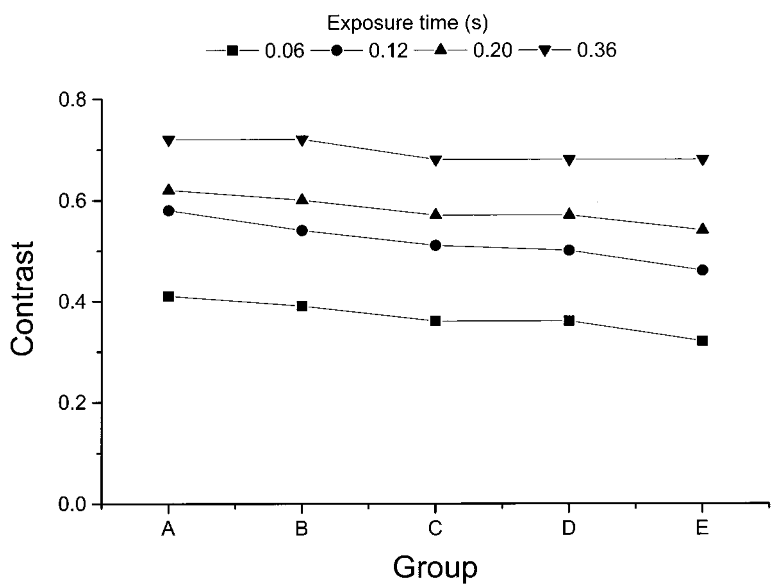

Fig 4. Changes in average contrast of radiographs for different exposure times as function of developer exhaustion.

0.06 s and 0.12 s for all ages of developer. An underestimation in detecting demineralization was also present at 0.36 s, but it was not statistically significant (Fig 6).

Influence of developer exhaustion on detecting bone gain

A statistically significant increase in the percentage of ROI showing bone gain was found at 0.06 s exposure time for 1-week-old developer. For developer that was 2 and 3 weeks old, increases also were found, but they were not statistically significant. Statistically significant increases at 0.12 s were found for all ages of developer (Fig 7). Similarly, statistically significant increases in the percentage of simulated volume of bone gain is found at 0.06 s and 0.12 s at all 3 ages of developer. An increase also was present at exposure 0.36 s but it was not statistically significant (Fig 8).

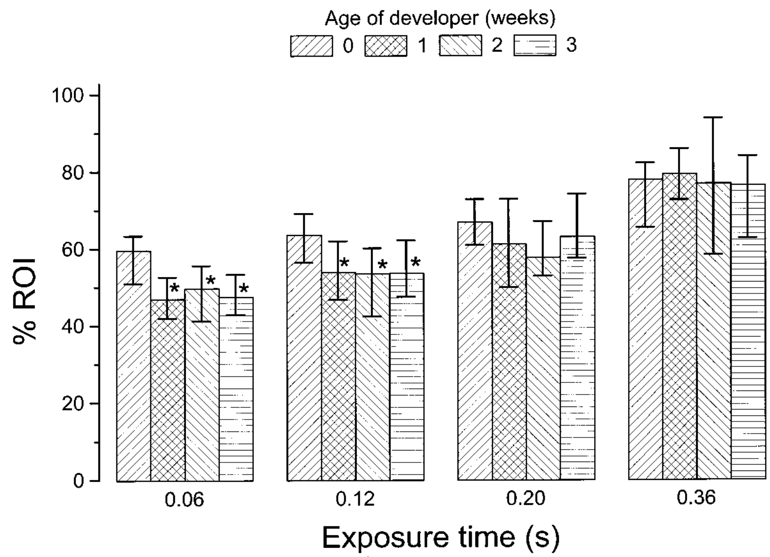

Fig 5. Percentages of area of ROI showing bone loss in subtracted images at different exposure times and developer exhaustion. The bar heights indicate median, and error bars represent 25th and 75th percentile. Asterisks show P < .05, Wilcoxon signed-rank test, compared with the results at week 0.

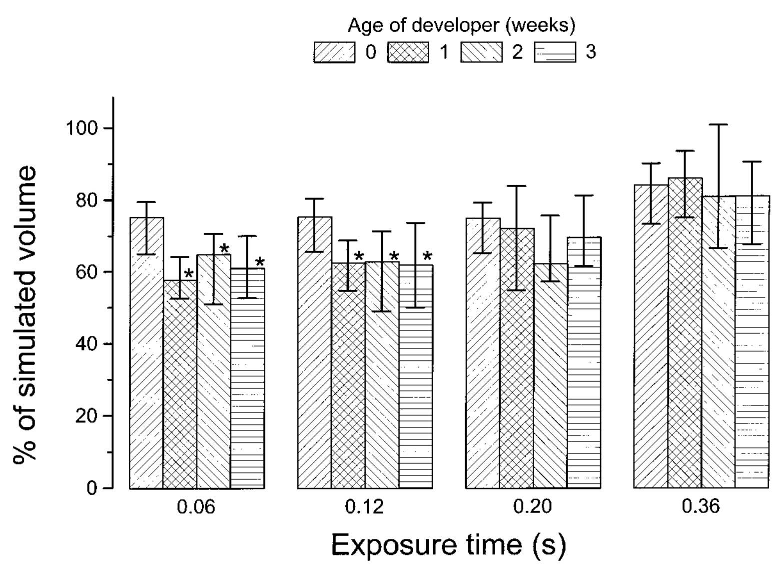

Fig 6. Percentages of measured volume of bone loss in ROI in subtracted images at different exposure times and developer exhaustion. Bar heights indicate median, and error bars represent 25th and 75th percentile. *Asterisks* show *P* < .05, Wilcoxon signed-rank test, compared with the results at week 0.

DISCUSSION

This study demonstrated that developer exhaustion has an influence on accuracy of quantifying changes in alveolar bone mineralization with digital subtraction radiography. Simulated bone loss in ROIs was underestimated, whereas simulated bone gain in ROIs was overestimated.

These results are in accordance with the results of Thunthy and Weinberg,[16] who found that films processed in exhausted developer have higher brightness compared with films processed in fresh developer. The follow-up radiographs, processed in exhausted developer, showed higher mineralization compared with the baseline radiographs processed in fresh developer. Furthermore, Thunthy and Weinberg[16] found that developer exhaustion has a greater influence on films exposed with longer exposures.[16] Our results, however,

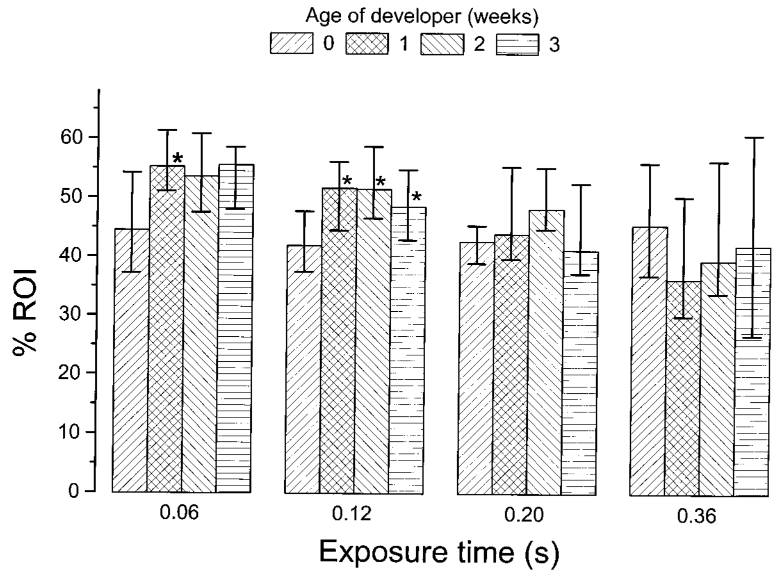

Fig 7. Percentages of ROI showing bone gain in subtracted images at different exposure times and developer exhaustion. Bar heights indicate median, and error bars represent 25th and 75th percentile. *Asterisks* show *P* < .05, Wilcoxon signed-rank test, compared with the results at week 0.

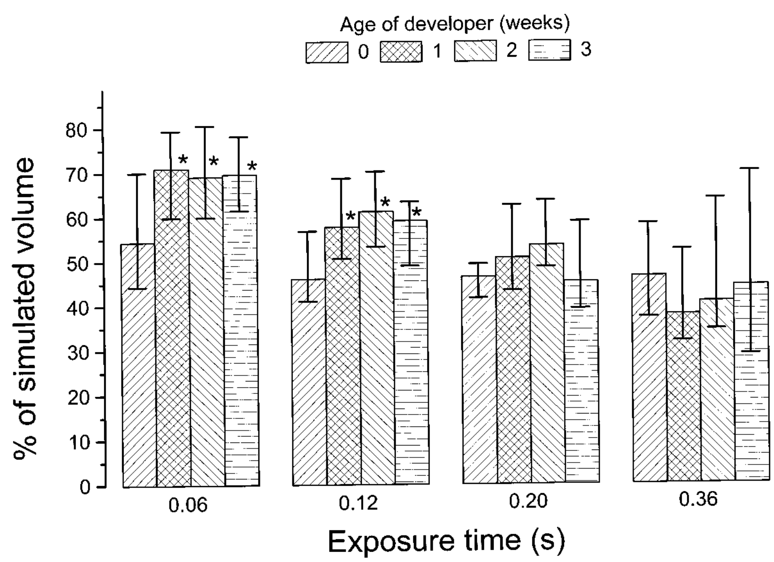

Fig 8. Percentages of simulated volume of bone gain in ROI in subtracted images at different exposure times and developer exhaustion. Bar height indicate median, and error bars represent 25th and 75th percentile. *Asterisks* show *P* < .05, Wilcoxon signed-rank test, compared with the results at week 0.

show statistically significant differences only at shorter exposure times.

Two reasons may account for this disagreement. The first emerges from the procedure of capturing radiographs with a charge-coupled device video camera with which, in order to preserve the changes in brightness and contrast, all radiographs with the same exposure time were captured with equal aperture. Consequently, the whole dynamic range of a frame grabber was not used. The implication was that radiographs with longer exposure times, having lower brightness and contrast, were captured with reduced accuracy because of quantization or digitalization errors.

The second reason lies in the simulation of mineralization change, where gray levels of pixels in ROIs were changed by 10 for all exposure times, resulting in relatively larger changes at longer exposure times. Consequently, the influence of the developer exhaustion at longer exposure times was reduced.

In our study, only one type of film, processing solutions, and dental film processor was used. The comparison of 3 films showed the same qualitative effect of developer exhaustion.[16] Because the developer exhaustion reflects a reduction of the strength, we may assume that the use of other films, processing solutions, or film processors would result in similar findings.

In our study, the well-defined computer simulated changes in mineralization served as a gold standard. The changes were square regions, and gray levels of all pixels were equally changed. Because they did not imitate real changes except the location, further studies are proposed with removing bone[24] or adding bone chips.[10] The influence of size and shape of changes might also be studied. However, the absence of in vitro and in vivo gold standards disables extensive and accurate evaluations.

Nevertheless, we can conclude that developer exhaustion has an influence on the accuracy of assessing small alveolar bone loss and gain with DSR despite methods for contrast correction. Bone loss might be underestimated while bone gain might be overestimated. When setting up a new DSR system for quantifying changes in bone mineralization, film processing should be standardized, and the influence of film, processing solutions, and film processor should be checked.

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