

## TECHNICAL REPORT

# Anatomically shaped cranial collimation (ACC) for lateral cephalometric radiography: a technical report

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Lateral cephalograms in orthodontic practice display an area cranial of the base of the skull that is not required for diagnostic evaluation. Attempts have been made to reduce the radiation dose to the patient using collimators combining the shielding of the areas above the base of the skull and below the mandible. These so-called “wedge-shaped” collimators have not become standard equipment in orthodontic offices, possibly because these collimators were not designed for today’s combination panoramic–cephalometric imaging systems. It also may be that the anatomical variability of the area below the mandible makes this area unsuitable for standardized collimation. In addition, a wedge-shaped collimator shields the cervical vertebrae; therefore, assessment of skeletal maturation, which is based on the stage of development of the cervical vertebrae, cannot be performed. In this report, we describe our investigations into constructing a collimator to be attached to the cephalostat and shield the cranial area of the skull, while allowing the visualization of diagnostically relevant structures and markedly reducing the size of the irradiated area. The shape of the area shielded by this “anatomically shaped cranial collimator” (ACC) was based on mean measurements of cephalometric landmarks of 100 orthodontic patients. It appeared that this collimator reduced the area of irradiation by almost one-third without interfering with the imaging system or affecting the quality of the image. Further research is needed to validate the clinical efficacy of the collimator.

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## Introduction

It has occurred to many in our profession that a lateral cephalogram, an X-ray exposure that is frequently used in orthodontics, displays a larger area of the skull than is required for diagnostic evaluation. X-rays are potentially harmful, especially for younger patients, who make up most of the population undergoing orthodontic treatment.<sup>1</sup> In line with the recommendations of the International Commission on Radiation Protection and other national and international guidelines, clinicians are advised to restrict the area of exposure to the

area of interest to ensure maximal radiological hygiene.<sup>2–4</sup> Early orthodontic cephalography depicted the complete skull. Modern cephalometric machines use rectangular collimation of the beam to limit exposure to the regions that have diagnostic value.

Even with appropriate rectangular collimation, there are still considerable areas on the image where no diagnostic orthodontic information is found. These regions are located above and behind the base of the skull and the petrous part of the temporal bone, and below the mandible.<sup>5</sup> Additional collimation was described by L’Abee and Tan<sup>6</sup> in 1982 and a joint working party of the British societies of orthodontists and maxillofacial radiologists in 1985.<sup>7</sup> They proposed that wedge-shaped collimators could be used to shield the

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area above the base of the skull and below the mandible, that only left visible an area restricted to the maxilla and mandible. These collimators were designed to be placed approximately halfway between the X-ray source and the cephalostat as part of a dedicated cephalometric installation. In 1999, Mandall *et al*<sup>8</sup> investigated the diagnostic value of conventional cephalograms that were modified to appear as if they were produced using wedge-shaped collimation. They found that cephalometric imaging using modified collimation was feasible for patients wearing orthodontic fixed appliances. In 2003, Gijbels *et al*<sup>9</sup> also advocated the use of a wedge-shaped collimator mounted on the X-ray tube. It achieved more than 40% dose reduction when tested on a phantom head with inserted dosimeters (Figure 1). In 2009, Alcaraz *et al*<sup>10</sup> designed and tested a prototype of a wedge-shaped collimator that could be mounted on a specific combination panoramic–cephalometric imaging system. They found up to 60% dose reductions but concluded that the area below the mandible was not effectively shielded without individual modification of the collimator for each patient. In 2012, Lee *et al*<sup>11</sup> modified the wedge-shaped collimator used by Gijbels *et al* and evaluated the dose using Monte Carlo simulation. They also found approximately 60% dose reduction.

Although high percentages of dose reduction were reported, these collimators are still not commonly used in orthodontic practice.<sup>12</sup> There are three possible reasons for this. One explanation is that today's orthodontic offices use combination panoramic–cephalometric imaging systems. Mounting a collimator on the X-ray tube or halfway between the X-ray tube and the patient is not practical with these machines. Another problem with these modified designs is that individual mandibles vary substantially in size, shape and location when projected on the cephalogram. Investigators using phantom heads to test collimators did not take into account this anatomical variability, which requires individual adjustment of the shielding. Without adjustment, there will either be too much shielding in patients with mandibles that grow or are located lower than average or not enough shielding for patients who have smaller or more superiorly located mandibles.<sup>10</sup> Finally, a wedge-shaped collimator may block imaging of the cervical vertebrae. Depiction of the cervical vertebrae has become desirable since the developmental stages of

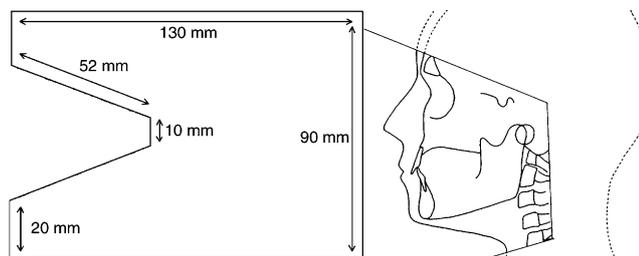
these vertebrae have been used as indices of skeletal maturation.<sup>13</sup>

In contrast to the mandible, there is less variation in the size and shape of the base of the skull because the chondrocranium follows a well-defined developmental path. In addition, growth of the base of the skull is almost complete by the time cephalograms are made for orthodontic purposes.<sup>14</sup> The position of the base of the skull on the cephalogram is dictated by its close association with the external auditory canals, which are used to stabilize the head of the patient during cephalography. Although there is still considerable bone growth around the meatus after the age that orthodontic diagnostics are first performed, this growth is in the direction of the X-ray beam and therefore does not displace the image of the base of the skull on the cephalogram as the patient matures.

Therefore, wedge collimation may reduce the patient's radiation dose, although the technique has not found acceptance in clinical orthodontics. If and when the lower half of the collimation could be eliminated and the collimator redesigned for the combination panoramic–cephalometric imaging systems, it could find its way into orthodontic offices leading to reduced radiation dose from cephalography.

A suitable collimator for combination imaging systems would be attached to the ear post of the cephalostat that is closest to the X-ray source. A wedge-shaped collimator with this type of mounting was described by Cipollina and Jerrold<sup>15</sup> in a 1984 US patent. The border of a wedge-shaped collimated beam relative to the base of the skull is, in general, an arbitrarily chosen oblique line that parallels the base of the skull. Because the projection of the base of the skull is stable, it should be possible to design a collimator with a lower edge that approximates the base of the skull more closely. A “one-size-fits-all” collimator that can be permanently attached to the ear post and does not require adjustments or disassembly would facilitate the implementation of wedge collimation.

The aim of this study was to evaluate whether a collimator for the cranial area of the skull could be constructed and attached to the cephalostat that would markedly reduce the area of irradiation while preserving the view of diagnostically relevant structures. To undertake this study, the shape of the area to be shielded was determined from the cephalographic anatomy of orthodontic patients. To determine whether this shape led to substantial reduction of the irradiated area of the patient, areas were measured. A collimator, referred to in this article as an anatomically shaped cranial collimator (ACC), was constructed that shielded this area. This collimator was tested to determine if it shielded the intended area and the following were secondary questions. (1) Does the ACC affect the exposure settings of the machine? (2) Does the ACC lead to reduced quality of the cephalogram or interfere with other exposure modalities of the machine? (3) Is it possible to use the ACC with different imaging systems?



**Figure 1** Wedge-shaped collimator (left) and schematic representation of the position of the collimator on the cephalogram. Reproduced with permission from the British Institute of Radiology, from Gijbels *et al*<sup>9</sup>

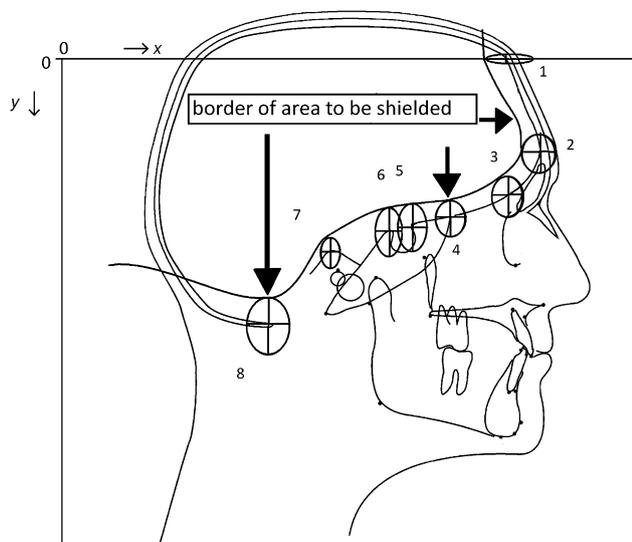
We did not study the shielding of the area under the mandible because of its variable anatomy and position in relation to the cephalostat. This area should be shielded using another method, such as a thyroid collar, which is not addressed in this study.

## Materials and methods

### *Determining the shape of the area to be shielded*

The cranial landmarks used the most in current conventional cephalometric analysis are located at or below the base of the skull and the petrous part of the temporal bone. Ideally, the border of the shielded area is located immediately superior to these structures. From posterior to anterior, the border of the area to be shielded follows the inner contour of the posterior cranial vault, progresses over the petrous part of the temporal bone, follows the clivus over the sella turcica and, finally, proceeds along the roof of the orbits into the internal contour of the frontal bone (Figure 2).

To determine the location of this boundary on cephalograms, we chose eight “border landmarks” to evaluate (Figure 2). One hundred cephalograms from consecutive patients undergoing orthodontic treatment planning at the office of one of the authors were used. The mean age of these patients (60 females and 40 males) was 13.0 years [standard deviation (SD), 6.6 years]. The study patients were 95% Caucasian, 3%



**Figure 2** Border of the area to be shielded. Schematic representation of the “border landmarks”, Points 1 to 8: 1—frontal bone at edge of beam; 2—most anterior inner contour of frontal bone; 3—roof of orbit; 4—pterygoid-sphenoid intersection; 5—anterior clinoid; 6—posterior clinoid; 7—ridge of the petrous part of the temporal bone; 8—most inferior inner curvature of occipital contour. The points are represented by a cross inside an oval; the dimensions of the oval represent the size of 1 standard deviation (SD) (horizontal direction for  $x$ -coordinate and vertical direction for  $y$ -coordinate), except for Points 5 and 6, where they represent 2 SDs

Asian and 2% North African. The cephalograms were made using a Morita Veraviewepocs<sup>®</sup> 3D X550 X-ray unit (J. Morita Company, Kyoto, Japan) equipped with a charge-coupled device sensor and operated at 90 kV and a tube current with a programmed shift [maximum of 10 mA, the density compensation (DC) setting], with an exposure time of 4.9 s per exposure. The border landmarks were identified, and their coordinates were recorded using Viewbox software v. 3 (dHAL Software, Kifissia, Greece). The mean  $x$ - and  $y$ -coordinates and SD were determined for each border landmark using Microsoft Excel<sup>®</sup> 2003 software (Microsoft Corporation, Seattle, WA).

The mean coordinates of the border landmarks were plotted on a graph using SolidWorks<sup>®</sup> 3D Computer-Aided Design (CAD) software v. 2011 (Dassault Systèmes SolidWorks<sup>®</sup>, Waltham, MA). A line was drawn that followed the co-ordinates, which represented the mean inferior border of the area that was to be shielded. A collimator that casts its shadow along this line would result in too much shielding in half the patients. This would lead to loss of diagnostic information. Use of the SDs of the measurements to determine the required distance from the mean line allowed us to adjust the shape of the shielded area to reduce the risk of too much shielding.

Structures with diagnostic importance near the border include the soft-tissue contour of the forehead and the following landmarks called Nasion, Sella, Porion and Basion. Sella and the forehead are closest to the border. If the collimator shields Sella so that it does not appear on the cephalogram, the image would be seriously compromised because Sella is frequently used in cephalometric analysis. The sella turcica, where landmark Sella is located, is a recognizable and stable feature on the base of the skull and is important for superimposing different cephalograms of the same patient to assess growth or treatment. If the contour of the forehead is not completely visible on a cephalogram, it is usually not necessary to perform additional cephalography. Therefore, to avoid the risk of having to re-take images, a larger margin was determined for Sella than for the forehead when the shape and size of the shielded area was established.

The SDs of the  $x$ - and  $y$ -coordinates of the border landmarks were used to depict a graphic representation of the variability, which were drawn around the mean coordinates of the landmarks as ovals. The vertical radius was the SD of the  $y$ -coordinate and the horizontal radius was the SD of the  $x$ -coordinate. To assure that the risk of shielding Sella was very small, an oval of two SDs was drawn around the border landmarks (anterior and posterior clinoid) near Sella. The inferior border of the area to be shielded was drawn along the superior edge of these ovals (Figure 2).

### *Measuring the reduction of irradiated area*

To assess the reduction of the irradiated areas of the patients, areas were measured on the 100 cephalograms

using SolidWorks CAD software. The coinciding area of the images of each patient's head and the shadow produced by the ACC were measured, and the percent reduction was determined using the total area of the patient's head on the images. The mean reduction, SD, and range were calculated using Microsoft Excel 2003 software.

#### *Construction of the anatomically shaped cranial collimator*

A collimator was constructed to cast a shadow in the shape of the area to be shielded when mounted on the ear post of the cephalostat between the X-ray source and the patient. SolidWorks CAD software was used to make a model of the cephalometric components of the Morita Veraviewepocs 3D X-ray unit. The shape, position and dimensions of ACC to shield the intended area were modelled using a source-to-image distance of 1650 mm, source-to-object (mid-sagittal plane) distance of 1500 mm, magnification factor (MF) of 1.1 for the mid-sagittal plane and geometry with the central beam through the middle of the ear plugs (Figure 3).

The shape and dimensions were programmed into a high-pressure water-cutting machine (ByJet 4022, Waterjet Cutting System; Bystronic, Niederönz, Switzerland) that cut a 1 mm sheet of lead. 1 mm lead was chosen because it attenuates 99% of the X-ray photons at 90 kV.<sup>16</sup> The lead sheet was reinforced with a 2 mm piece of polyvinyl chloride of the same size and shape, which was glued to the sheet. A bracket was fixed to the ACC with two bolts. This bracket was fitted with a rubber lining to precisely match the form of the ear post of the cephalostat. The ACC prototype was then fixed to the ear post that was nearest to the X-ray source at the position relative to the middle of the earplug, which was determined by the computer model (Figure 4). Exposures without patients were made to determine whether the position of the X-ray shadow corresponded with the

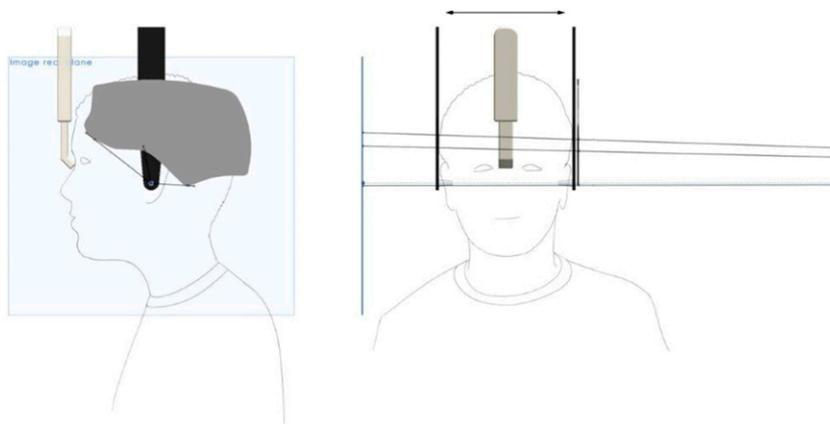
area targeted for shielding. SolidWorks CAD software was used to verify that the actual shielding closely corresponded to the target area by measuring the difference in millimetres between the inferior borders.

#### *Anatomically shaped cranial collimator interference with image formation*

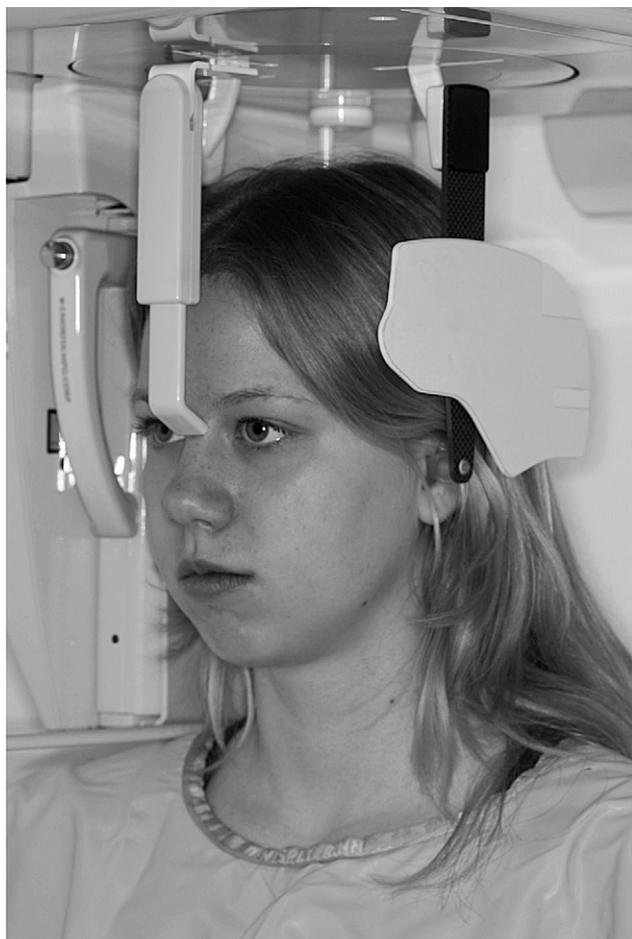
X-ray machines with direct digital sensors, such as the unit used in this research, can modulate their output in relation to the levels of radiation detected by the sensor. When there is a large radio-opaque object in the path of the beam, this automatic exposure control may result in increased output by the generator, which would nullify the effect of the ACC. The Morita machine does not use automatic exposure control in the cephalometric mode but has a DC function. DC results in a programmed shift of the tube current during the exposure to improve depiction of the soft tissues. To determine that DC would not increase the tube current when the ACC was used, four exposures of a phantom head were made as follows: with and without ACC and with and without DC. During these exposures, dose area product values were determined near the generator using an ionization chamber (VacuDAP 2000; VacuTec GmbH, Dresden, Germany).

Images of the phantom head were also used to determine whether the ACC affected the quality of the images. Image subtraction using Emago<sup>®</sup> v.6 software (Oral Diagnostic Systems, Amsterdam, Netherlands) was performed on the images produced with and without ACC.

To use a combination cephalometric–panoramic imaging system to make posteroanterior cephalograms and hand–wrist exposures, the cephalostat is turned 90°, which moves the ear post with the ACC to the periphery of the field. To determine whether the ACC interfered with these exposure modalities, the positioning of a patient for posteroanterior exposure and hand–wrist exposure was



**Figure 3** Geometry of the projection of the collimator illustration made with the modelling software showing the geometry of the diverging X-ray beam, resulting in enlargement of the shadow cast by the collimator on the image recording plane. The X-ray source is the viewpoint of the image on the left. The X-ray source is to the right of the image that is on the right at the converging point of the three lines representing the divergence of the X-ray beam



**Figure 4** Patient in cephalostat with anatomically shaped cranial collimator (ACC) attached. Patient positioned in the cephalostat of the Morita Veraviewepocs<sup>®</sup> 3D X550 X-ray unit (J. Morita Company, Kyoto, Japan) with ACC mounted on the ear rod closest to the X-ray source

simulated, and posteroanterior exposures were made of a phantom head.

To assess the projection of the ACC when used in combination with other cephalometric machines, computer models were developed with MFs varying between 1.10 and 1.15. This range corresponds to the variation of common X-ray machines with source-to-image distances ranging from 1650 mm to 1150 mm. The difference in projection of the lower border of the ACC on the image plane relative to the different projections of the mid-sagittal plane was assessed in millimetres.

## Results

### *Shielded area*

To determine whether the ACC shielded the intended area, images of exposures made with the presence of ACC were evaluated. SolidWorks CAD software found that the difference between the actual and intended shielding was less than or equal to 1.75 mm.

Measurements of the area of shielding and the projection of the head of the patient were performed on the 100 cephalograms used to design the ACC. On every cephalogram, the area of intended shielding that coincided with the projection of the head of the patient was assessed using SolidWorks CAD software. The area that coincided was expressed as a percentage of the total area of the image of the patient. On average, it appeared that the reduction in the irradiated area was 31.2% (SD, 1.94%; range, 27.2–35.5 %) of the irradiated area of the patient (Figure 5).

### *Effects on image*

The ACC did not change the output of the generator. Dose area product values measured in front of the generator were not affected, whether or not the ACC was used during exposures of a phantom head.

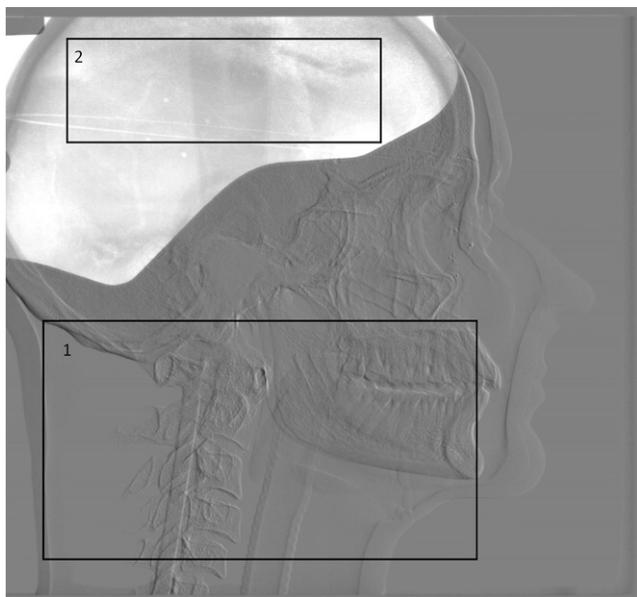
Subtraction of the images made with and without the ACC showed that the mean grey values of the image were unchanged, except for the area shielded when the ACC was used (Figure 6).

The ACC was not found to interfere with posteroanterior exposures. The ear post with the ACC was projected as a thin radio-opaque structure at the border of the image and did not interfere with the projection of the head of the patient. Hand-wrist exposures were made with the cephalostat in the same position and the ear posts positioned as wide as possible. The exposure made with the ear posts in this position did not show the ear posts or the ACC on the image.

Calculations showed that the differences in collimation by an optimized ACC caused by differences in MF were



**Figure 5** Cephalogram made with anatomically shaped cranial collimator



**Figure 6** Subtraction image of an image with and without the presence of anatomically shaped cranial collimator (ACC). Image as a result of the subtraction performed by Emago<sup>®</sup> v.6 software (Oral Diagnostic Systems, Amsterdam, Netherlands) of the cephalograms of a phantom head made with and without the presence of ACC. Unchanged areas of the image had a mean value of 128 (total scale is 256 Gy values). The mean value of the large rectangular area below the collimator (1) was 125.2 (SD, 7.0), and the value of the rectangular area in the shielded area (2) was 217.7 (SD, 7.9)

very limited. The differences at the central area of the base of the skull were less than or equal to 1.2 mm. The differences at the periphery of the image, which is further from the central beam, were less than or equal to 2 mm.

## Discussion

This report described the design of a collimator for cephalometry. The purpose of its design was to reduce the radiation dose of the patient and to be easily implemented in orthodontic practice. Therefore, it was designed to be used in combination panoramic–cephalometric imaging systems without needing to adjust or disassemble it for individual exposures. The ACC reduced the irradiated area of the patient by almost one-third. The location of the ACC on the ear post of the Morita equipment did not affect the imaging process adversely. In addition, the ACC did not interfere with the other imaging modalities performed by the machine.

A required clinical follow-up study, which is now being carried out in our department, will determine whether the landmarks that are used in orthodontic cephalometry will remain exposed when the ACC is used.

The ACC was based on the analysis of the morphology of the cranial base of 100 consecutive Dutch orthodontic patients, 95% of whom were Caucasian. Therefore, the clinical performance of the collimator must also be

evaluated in populations with different ethnicities. It is conceivable that a collimator with different dimensions will be needed for different ethnicities.

It is important to determine whether the design will be usable on different X-ray machines. In this study, computer modelling established that the different MFs that are used in the currently available machines would have minimal effect on exposures produced using the ACC. The change in the projection of the ACC relative to the change in position of the image of the patient is around 20% of the SD of the variation in the anatomy of the study patients. Therefore, different machines can use the same ACC. However, the mounting on the ear post will require a variety of brackets to accommodate the different types of X-ray machines.

This ACC produced a smaller dose reduction than previously reported for wedge-shaped collimators. The irradiated area was reduced by 27–35%. The actual amount of reduction of the (effective) dose will be determined in a follow-up study. Because millions of cephalograms are taken worldwide each year and a relatively large proportion of orthodontic patients are young, the potential reduction in radiation risk is meaningful.

The Morita X-ray unit used in the development of our collimator did not generate an increased X-ray output in response to the radiopaque shield that was in the path of the X-ray beam, but other machines may increase their radiation output. The use of our collimator will only be viable for these machines if the automatic exposure control function is disabled. There is no problem for machines that use photostimulable phosphor plates because there is no direct feedback by a sensor that would affect the output of the X-ray generator.

To improve the quality of cephalograms, image enhancement software is integrated into cephalometric systems. This ACC shields a large area from radiation, and the image produced using this ACC has a large shadow. It is possible that certain software may react adversely to a large amount of pixels with low grey values. This did not occur with the Morita system used to develop the ACC. Investigations must be performed to determine if the image enhancement software of other systems is perturbed by ACC. The settings of affected software would require adjustments to use this collimator.

In conclusion, this report described a collimator design that reduced the irradiated area of the patient by almost one-third while leaving diagnostically relevant structures exposed and not adversely affecting the function of the X-ray system. The shortcomings of earlier attempts to achieve these goals were eliminated by the current design, which focused on the area cranially at the base of the skull. The inferior border was located at a well-defined distance from and approximated the average anatomical shape of the base of the skull. In addition, the collimator was modified for use with a combination panoramic–cephalometric imaging machines. Further validation studies and research and development are needed before ACC is incorporated into orthodontic practice.

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