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ORIGINAL ARTICLE

Changes in mandibular cortical width measurements with age in men and women

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Abstract
Summary Automated software was used to measure the mandibular cortical width in a large sample of dental radiographs. We determined that cortical thinning normally starts in women at age 42.5 years and accelerates thereafter. We can estimate population referral rates and thus enable cost benefit analyses for osteoporosis detection by dentists.
Introduction Previous studies have shown that the mandibular cortical width is significantly correlated with the bone mineral density at sites which may undergo osteoporotic fracture, e.g. hip. Mandibular cortical width can be determined automatically from dental panoramic radiographs that dentists frequently request, using appropriate software. We study the distribution of cortical width given age to predict those patients requiring further investigation for osteoporosis.
Methods The mandibular cortical width was measured in 4,949 dental panoramic tomograms, in patients aged 15–94 years. The inferior and superior cortical edges were detected automatically using a global active shape model image search, followed by an active appearance model search. Nonparametric statistical analysis and nonlinear piecewise linear/quadratic regression were used to analyse the data.
Results For females, the mean cortical width had a linear increase before the age of 17 years, a period of no change (estimate=3.25 mm, se=0.01) until the age of 42.5 years, followed by a quadratic decrease with age. For males, it had a linear increase before the age of 19 years, a constant value (estimate=0.37 mm, se=0.01) until the age of 36 years and then a slow linear decrease. The rate of decrease in mean cortical width goes from 0.049 to 0.105 standard deviations per year in the 60–80-year-old female age group, in line with published bone mineral density T-score reductions.
Conclusions The pattern of decrease in mandibular cortical width with age was similar to the known pattern of bone loss from the hip, accelerating in women after the age of 42.5 years.

Keywords Active appearance model · Cortical bone · Mandible

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Introduction

Thin mandibular cortical width measurements in dental panoramic radiographs have been used as a predictive measure of systemic osteoporosis [1]. These radiographs are frequently used by dentists and may provide a useful opportunity to contribute to osteoporosis diagnosis, especially if the radiograph is taken for other reasons. In that situation, there is no additional radiation dose due to the osteoporosis investigation. Early detection by dentists would allow the necessary preventive treatment to be instituted; however, what constitutes a normal value of mean cortical width or the expected degree of variation about this measurement in the population is unknown.

Ledgerton et al. [2] showed in a sample of British women that mandibular cortical width generally decreased from the age of 25 years, but this trend accelerated after the age of 60 years. The study was undertaken only in women, and the sample size of 500 subjects (with ten 5-year age groups) was limited by having to perform the measurement task manually. Manual measurement of the mandibular cortical width is usually undertaken in the region directly below the mental foramen, perpendicular to the lower border of the mandible. Detection of the mental foramen may be unreliable, as multiple foramina are sometimes present [3]. Allen et al. [4] showed that the cortical width could be measured automatically using computer image analysis without the requirement for identification of the mental foramen.

In cross-sectional studies, we have observed an association between mandibular cortical width and the bone mineral density (BMD) at important fracture prone sites such as the spine and hip [5].

Our aim in this study was to measure the mandibular cortical width in dental panoramic tomograms from a large sample of men and women and to determine how it relates to the patients' age and gender.

Materials and methods

All dental panoramic tomogram images were collected anonymously from one hospital database (Leuven, Belgium) over a 2-year period, 2006–2008. Radiographs from the same radiography machine at the same hospital site had contributed to a previous study [6], in which the absolute value of scaling between patient and image was calculated using a ball bearing of known size in the image. No calibration object was present in the radiographs for this study, but the same scaling factor has been assumed.

Data

A total of 6,096 Digital Imaging and Communications in Medicine (DICOM) images were received from the Oral Imaging Centre of the Department of Dentistry, Oral Pathology and Maxillofacial Surgery of the University Hospitals, Catholic University of Leuven. All images had been anonymized, and patients had given general informed consent to the use of their radiographic images for research. All images were inspected visually to exclude those that were unusable due to unacceptable quality or evidence of pathology, such as previous mandibular fractures, surgical procedures, cysts or tumours that could have influenced the mandibular cortex. The remaining set to be analysed contained 4,949 tomograms. Patient age and gender were extracted from the DICOM header files: age ranged from 15 to 94 years, and there were 2,386 males and 2,563 females.

Locating the edges of the mandibular cortex

The method of Allen et al. [4] for locating the inferior and superior edges of the mandibular cortex on dental panoramic radiographs used active shape models (ASMs) [7]. In this approach, the edges are found by optimisation—image search for the best fit to a model which had been built by expert annotation of a training set of images. Separate ASMs were used for the left and right halves of the mandible, modelling the region between the gonion and a point below the mental foramen. The ASM could be run either in a fully automatic mode, search being initiated from the mean shape derived from the training set, or by using a manual initialisation defined using four user-specified points (Fig. 1). However the former gave poorer diagnostic ability than the latter due to some search failures and some cases of lateral misalignment, as the edge-search used by the ASM has little information with which to position the shape laterally along the mandible.

Because of the large size of the dataset, we have developed the modelling of the mandible beyond that of Allen et al. [4] to increase the reliability of fully automatic search [8]. Briefly, the shape model was laterally extended by annotating the upper and lower edges of the mandible beyond the gonion to utilise more clues from the curvature of the mandible and therefore improve the lateral positioning. The search is conducted in two phases. In phase 1, a global ASM search is conducted for the combined (left and right) inferior mandible edge (Fig 1). This edge usually displays high contrast and can be located reliably to provide an initial configuration for phase 2: an active appearance model (AAM, [9]) search on the separate left and right halves of the mandible to further refine lateral position and locate the superior border. AAMs allow the search to make use of an image texture model, providing more information than is available to the ASMs. Technical details are given in Roberts et al. [8], in which it is demonstrated that this ASM/AAM hybrid method is more accurate that the ASM method previously described by Allen et al. [4] and gives superior diagnostic performance on the dataset of Devlin et al. [6].

Detection of search failures

This ASM/AAM hybrid method in fully automatic mode gave similar accuracy to the manually initialised ASM on

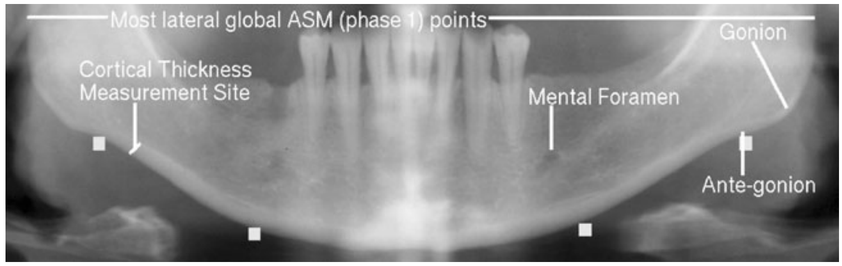


Fig. 1 Typical dental panoramic tomogram, with labelled anatomical points. The rectangles show the lateral positions of the 4 points used if employing a manual initialisation of the Active Shape Model (ASM). The full extent of the phase 1 global ASM beyond the Gonion is also indicated

the training set of Allen et al. [4]. However, when run on the more challenging dataset of Devlin et al. [6], there were partial search failures (convergence to incorrect locations) in about 10% of cases. Therefore, we devised an automatic diagnostic for incorrect convergence [8] based on:

1. The residual sum of squares (RSS) of the fit of the AAM texture model to the image (fits with low residuals are more reliable) and
2. A symmetry measure between the left and right halves (reliable fits should be similar on both halves of the mandible).

Thresholds on both measures were derived from calculating the median μ and a robust estimate of standard deviation σ from an independent dataset [6], but using solutions derived from the four-point manual initialisation. We examined images where either failure criterion exceeded $\mu+\alpha\sigma$. With $\alpha=5$, the vast majority of searches classified as failures were indeed failures, whereas only 5% of detected failures between $\alpha=3$ and $\alpha=4$ were genuine. We therefore set a threshold at $\alpha=3$, above which the search result was checked visually and if necessary subjected to a four-point manual initialisation to reach a reliable fit. This was applied to 1,273 images; in the remaining 3,676 cases, the superior and inferior edges were located using the fully automated ASM/AAM hybrid search.

Extraction of cortical width measurement

It was previously found that the correlation between mandibular cortical width and BMD at other skeletal sites varies depending on the position along the mandible at which the measurement is made, with a peak occurring at roughly three quarters of the distance from the sub-mental foramen point to the antegonion [4]. We found similarly that a position sited 67% of the distance from the sub-mental foramen point to the antegonion (Fig. 1) gave the best area under a receiver operating characteristic curve, for diagnosing osteoporosis from extracted width of the cortex. Defining this distance as L, the extracted width was smoothed over $\pm 0.1L$ from this point using a Gaussian kernel. Thus, the inevitable imprecision in the automatic lateral positioning of the extraction point is mitigated by the smoothing window. The final measurement is the mean of the width measured at this position in the left and right halves.

Statistical analysis

This is a cross-sectional observational study. The response variable is mandibular cortical width, and the predictor is the patients' age. We used nonparametric regression and parametric linear and nonlinear regression to estimate the mean cortical width as a function of age for males and females.

The basic model is $y=f(x)+\varepsilon$, where y is cortical width, x is age, and ε is an error term that follows a normal distribution with mean 0 and some unknown variance σ^2. Independence between observations is assumed, and a different mean cortical width function $f(x)$ is allowed for each gender group. This model is for nonparametric regression where no specific form of $f(x)$ is given a priori, it is only assumed to be a smooth function. Nonparametric regression can be used on its own to estimate $f(x)$ and can also help to derive a parametric form for $f(x)$.

We consider the age variable x as continuous even though the recorded age was integer valued, for example, someone who had had a 50th birthday, but not the 51st, was recorded as aged 50, but the exact age can be anywhere between 50 and 51. For this reason, we added 0.5 to the recorded age to give the centre of the interval. The large sample size (n=4,949) makes it less of an issue not to have exact age in the data. The sample mean cortical width for each age x available contains all the information about $f(x)$, and a confidence interval can be obtained. Plotting them together for all x provides a clearer indication to the shape of the function $f(x)$ than the original data.

Nonparametric analysis

The methodology of nonparametric estimation and hypothesis testing was entirely from Bowman and Azzalini [10], and their R package 'sm' was used. The mean cortical width function $f(x)$ was estimated for males and females using nonparametric regression by locally fitting linear functions of age to the data. There were as many linear regressions as values of x in the calculations. The data points(x_i,y_i) were weighted using a Gaussian kernel according to how far x_i was from x relative to a smoothing parameter h—a larger (smaller) value of h means more (less) smoothing. There are various methods of selecting h, including cross validation which minimises the 'leave-one-out' mean square error and the default 'df' method in sm which tries to achieve a certain degree of freedom (default=6). After fitting a linear regression line like this to the data near x, it is used at x to estimate $f(x)$. This approach to the regression problem is nonparametric because a formula for $f(x)$ is not required.

The hypotheses of linearity and constancy were tested separately for males and females over various intervals of age, which were chosen based on inspections of the nonparametric regression plots. Here, linearity means the function is linear over a specific age interval and constancy means it does not change with age over this range.

Parametric analysis

We used piecewise linear regression which is like straight line linear regression, except that the line is allowed to bend at one or more places, resulting in a different equation for each section of the data. It can be fitted as a linear model with suitably constructed predictors. By estimating the equations simultaneously, the line segments will join perfectly. The bends can also be estimated using nonlinear regression together with the model coefficients, and we can allow a smooth quadratic transition at each bend. We did all these for the male and female data and were able to simplify the female model using a quadratic piece.

For parametric linear and nonlinear regression using the R functions 'lm' and 'nls', we refer to Venables and Ripley [11]. The programming was done in R, and we found the code provided by Lindstrom [12] useful when extending the hockey model [13].

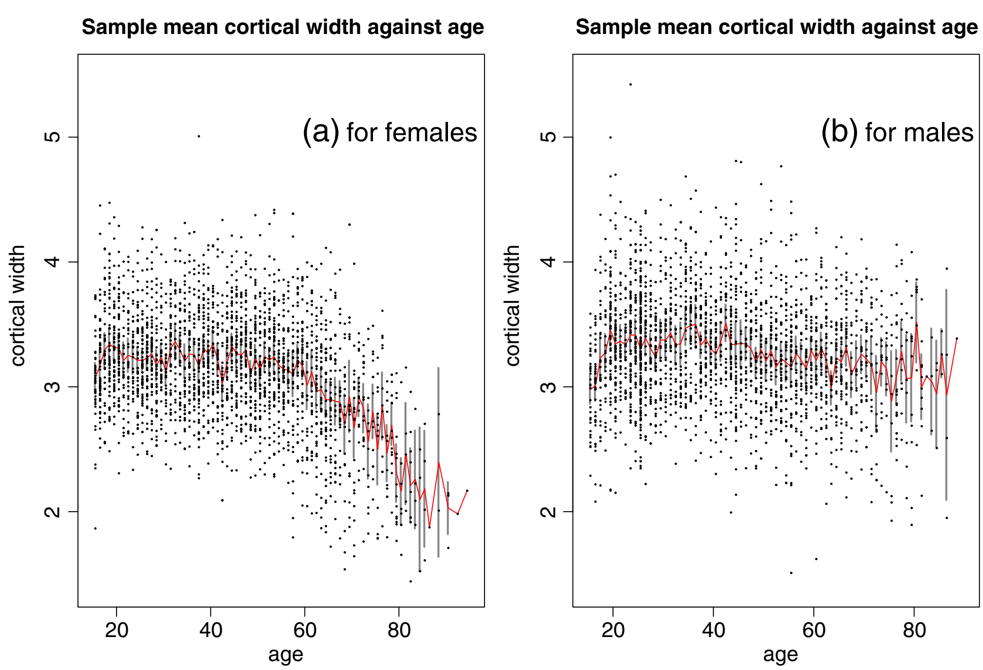
Results

Of the 4,949 dental panoramic images, 2,563 were of women (51.8%). The mean age of the females was 44.25 years (sd=17.50) and of males was 43.09 years (sd=17.83). The mean mandibular cortical width was 3.21 mm (sd=0.46) overall, 3.14 mm (sd=0.46) for the females and 3.29 mm (sd=0.45) for the males.

Considering only those subjects below the age of 50 years, there was a statistically significant difference (0.1 mm) in mean mandibular cortical width between the males and females (3.34 mm for males and 3.24 mm for females, t=6.45, P<0.001). For subjects aged 50 or over, the difference of 0.2 mm between males (3.20 mm, sd=0.44) and females (2.98 mm, sd=0.52) was also statistically significant (P<0.001).

We calculated the sample mean cortical width for each age represented in the data separately for males and females. A crude estimate of the mean cortical width function $f(x)$ of age x can be obtained by simply joining the sample means, see the jagged red lines in Fig. 2a, b for females and males, respectively. The vertical lines in blue represent 95% confidence intervals for $f(x)$ for each x individually. There was obviously a need for smoothing to

Fig. 2 Sample mean cortical width against age **a** for females and **b** for males



get better estimates of $f(x)$, as we only expect a gradual change from 1 year to another.

Nonparametric analysis

The curves in Fig. 3a, b represent smoothed estimates of $f(x)$ for females and males, respectively, obtained by fitting linear regressions locally as described earlier. The smoothing parameters $h=3.01$ for females and 2.58 for males were chosen by cross validation and used for data with age <25 to bring out more details, after which more smoothing was applied by using the values $h=6.99$ (females) and 6.42 (males), as determined by the degrees of freedom method (‘df’ in the R package ‘sm’). The dotted lines in each graph provide a variation band that allows twice the standard errors of the estimates above and below. The circles represent sample means with varying sizes reflecting how many individuals were included at each age. The mean functions are different for males and females, and a nonparametric test of equality gave highly significant ($P<0.001$) evidence against it.

The sample means and smoothed values are given in Table 1 for females and Table 2 for males. From Fig. 3a and Table 1, the mean cortical width for females seems to increase with age before 19, remains more or less constant till about age 42 and then decreases in a nonlinear fashion afterwards but not by more than 0.1 mm before age 55. There is a slight hint of a bend at about age 75. The curve in Fig. 3b for males suggests a similar but almost linear pattern after age 40 with possible bends at 20, 40, 53 and 66. We conducted nonparametric tests and found no significant evidence ($P>0.10$) against linearity for males or females, over the 5 age intervals delineated by vertical lines in each of the two graphs in Fig. 3. There was significant evidence against linearity for females over 42 ($P<0.01$) but not significant evidence ($P=0.37$) against linearity with respect to $(\text{age}-42)^2$ over this interval. Further tests gave no significant evidence against constancy for females from age 19 to 42 ($P=0.39$) and males from 20 to 40 ($P=0.62$).

Parametric regression

Three parametric models of increasing complexity were used to fit the data.

1. A piecewise linear model with a single breakpoint at age 20 for males and age 55 for females
2. A piecewise linear model with breakpoints at 20 and 40 years for males and 19 and 55 years for females, allowing in each case a constant central segment
3. A combined linear and quadratic model for females, with a breakpoint between linear segments at age 19 and a quadratic segment of the form $a-b(x-42)^2$ starting at age 42

The breakpoints were initially specified by inspection of the nonparametric regression curve, but were later estimated along with other model parameters using nonlinear regression. A smooth quadratic transition of 12 months duration was allowed between adjacent linear sections to maintain a continuous first derivative. The fitted parametric curves for females and males are shown in Figs. 4 and 5, respectively.

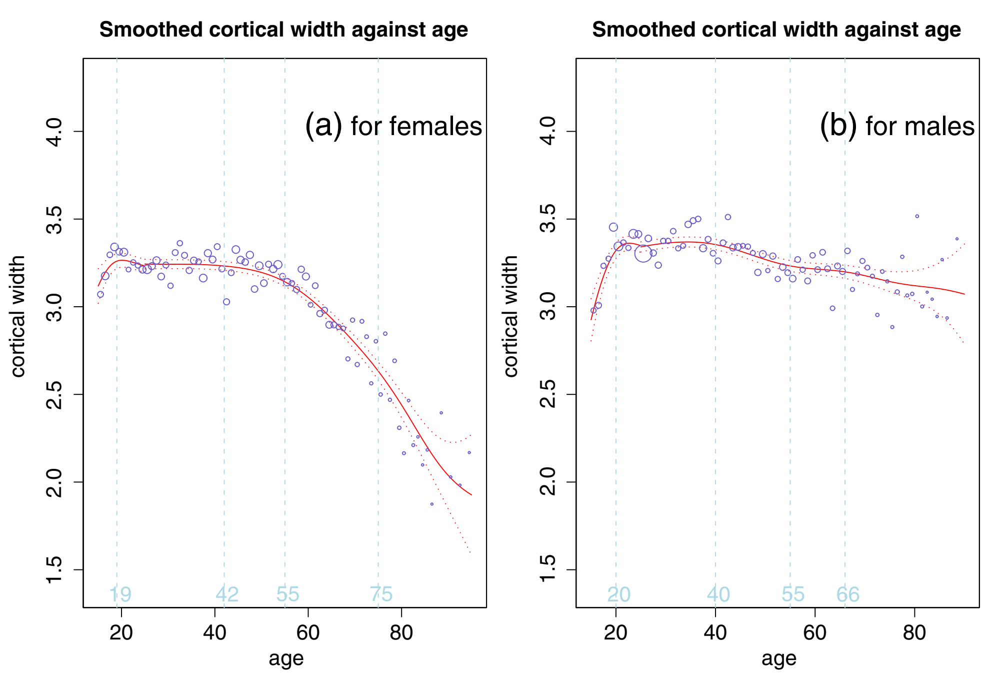


Fig. 3 Smoothed cortical width against age **a** for females and **b** for males

Table 1 Female age, sample means and smoothed cortical widths

Age (years)	15.5	16.5	17.5	18.5	19.5	20.5	21.5	22.5	23.5	24.5	25.5	26.5	27.5	28.5	29.5	30.5	31.5	32.5	33.5
Sample mean (mm)	3.07	3.18	3.30	3.34	3.31	3.31	3.21	3.25	3.24	3.21	3.21	3.23	3.26	3.17	3.24	3.12	3.31	3.36	3.29
Smoothed width (mm)	3.15	3.19	3.23	3.25	3.26	3.26	3.26	3.25	3.24	3.24	3.24	3.24	3.24	3.24	3.24	3.24	3.24	3.24	3.24
Age (years)	34.5	35.5	36.5	37.5	38.5	39.5	40.5	41.5	42.5	43.5	44.5	45.5	46.5	47.5	48.5	49.5	50.5	51.5	52.5
Sample mean (mm)	3.21	3.26	3.26	3.16	3.31	3.27	3.34	3.22	3.03	3.19	3.33	3.27	3.25	3.30	3.10	3.23	3.13	3.24	3.22
Smoothed width (mm)	3.24	3.24	3.24	3.24	3.24	3.24	3.24	3.23	3.23	3.23	3.22	3.22	3.22	3.21	3.21	3.20	3.19	3.18	3.17
Age (years)	53.5	54.5	55.5	56.5	57.5	58.5	59.5	60.5	61.5	62.5	63.5	64.5	65.5	66.5	67.5	68.5	69.5	70.5	71.5
Sample mean (mm)	3.24	3.17	3.14	3.13	3.10	3.21	3.17	3.01	3.12	2.96	2.98	2.90	2.90	2.88	2.88	2.70	2.92	2.67	2.92
Smoothed width (mm)	3.16	3.15	3.13	3.12	3.10	3.08	3.06	3.04	3.02	3.00	2.97	2.95	2.92	2.89	2.86	2.84	2.81	2.78	2.75
Age (years)	72.5	73.5	74.5	75.5	76.5	77.5	78.5	79.5	80.5	81.5	82.5	83.5	84.5	85.5	86.5	88.5	90.5	92.5	94.5
Sample mean (mm)	2.83	2.56	2.80	2.50	2.85	2.47	2.69	2.31	2.16	2.47	2.21	2.26	2.10	2.18	1.87	2.39	2.03	1.98	2.17
Smoothed width (mm)	2.72	2.68	2.65	2.62	2.58	2.54	2.50	2.46	2.42	2.37	2.33	2.29	2.24	2.20	2.16	2.09	2.02	1.97	1.94

Table 2 Male age, sample means and smoothed cortical widths

Age (years)	15.5	16.5	17.5	18.5	19.5	20.5	21.5	22.5	23.5	24.5	25.5	26.5	27.5	28.5	29.5	30.5	31.5	32.5	33.5
Sample mean (mm)	2.98	3.01	3.23	3.27	3.45	3.34	3.37	3.34	3.42	3.41	3.30	3.39	3.31	3.24	3.38	3.37	3.43	3.33	3.35
Smoothed width (mm)	2.98	3.09	3.17	3.25	3.30	3.34	3.36	3.36	3.36	3.35	3.34	3.35	3.35	3.36	3.36	3.36	3.37	3.37	3.37
Age (years)	34.5	35.5	36.5	37.5	38.5	39.5	40.5	41.5	42.5	43.5	44.5	45.5	46.5	47.5	48.5	49.5	50.5	51.5	52.5
Sample mean (mm)	3.47	3.49	3.50	3.33	3.38	3.30	3.26	3.36	3.51	3.34	3.34	3.35	3.34	3.31	3.20	3.30	3.21	3.29	3.16
Smoothed width (mm)	3.37	3.37	3.37	3.37	3.36	3.36	3.35	3.35	3.34	3.33	3.32	3.31	3.30	3.29	3.28	3.27	3.27	3.26	3.25
Age (years)	53.5	54.5	55.5	56.5	57.5	58.5	59.5	60.5	61.5	62.5	63.5	64.5	65.5	66.5	67.5	68.5	69.5	70.5	71.5
Sample mean (mm)	3.23	3.19	3.16	3.27	3.21	3.15	3.29	3.21	3.31	3.22	2.99	3.23	3.20	3.32	3.10	3.19	3.26	3.22	3.17
Smoothed width (mm)	3.24	3.24	3.23	3.23	3.22	3.22	3.22	3.21	3.21	3.21	3.21	3.20	3.20	3.20	3.19	3.19	3.18	3.17	3.17
Age (years)	72.5	73.5	74.5	75.5	76.5	77.5	78.5	79.5	80.5	81.5	82.5	83.5	84.5	85.5	86.5	88.5			
Sample mean (mm)	2.95	3.20	3.14	2.88	3.08	3.28	3.06	3.07	3.52	3.00	3.08	3.04	2.94	3.27	2.94	3.39			
Smoothed width (mm)	3.16	3.15	3.15	3.14	3.13	3.13	3.13	3.12	3.12	3.12	3.11	3.11	3.10	3.10	3.10	3.08			

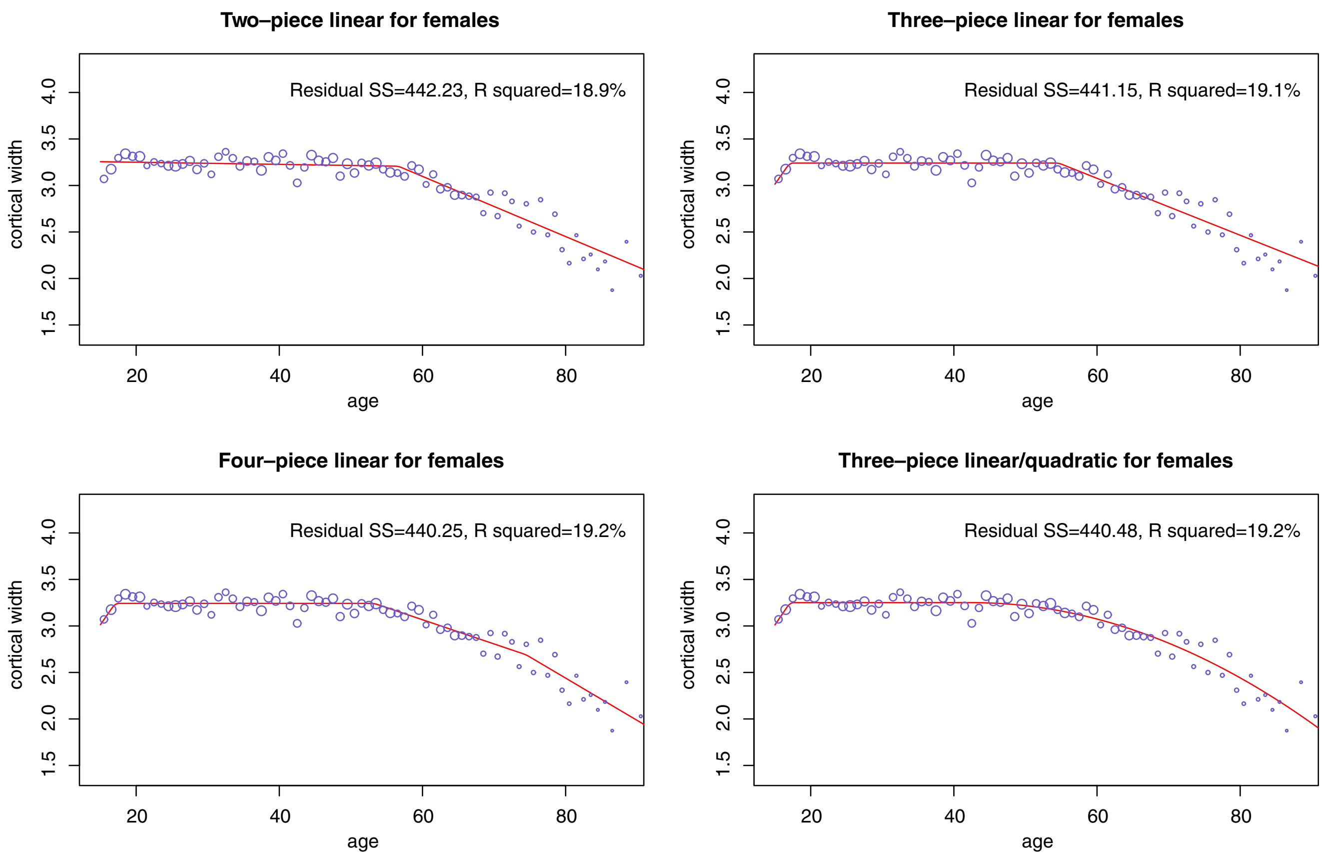


Fig. 4 Two-piece, three-piece and four-piece linear regression models and three-piece linear/quadratic regression model for females

There was a significant difference in RSS between the female two-piece and four-piece models (442.23 vs 440.25, P=0.01), and the improvement from the three-piece to the four-piece model was significant at 10% though not significant at 5% (441.15–440.25, P=0.07) (Fig. 4). The last model with a quadratic piece has a slightly larger RSS than the four-piece. However, it is the preferred model as it has a smaller Akaike's information criterion or AIC value (2,771.9 vs 2,774.5) taking into account its reduced number of parameters. It also looks more natural giving a smooth decay with an increasing rate with age. For the males, the three-piece linear model is preferred, as it provides a significant improvement in RSS from the two-piece (P= 0.01) but adding one or more bends does not do so (P= 0.13, 0.23) (Fig. 5).

The estimated bends in the preferred models are at age 17.12 (se=0.87) and 42.46 (se=1.85) for females and 19.08 (se=0.72) and 36.02 (se=4.40) for males. We set them to 17 and 42.5 for females and 19 and 36 for males and fitted the models for the final time. Details of the final models are given in Table 3 and plotted in Fig. 6 together with nonparametric estimates for comparison. The parametric and nonparametric estimates agree very well.

The model for females has a residual sum of squares (RSS) of 440.49, compared to a total sum of squares about the mean of 545.19. The proportion of the variance explained by the age dependence is measured by the pseudo-R^2 value:

$$1 - 440.49/545.19 = 19.20\%.$$

For males, RSS=456.57, but the total sum of squares of 477.51 was lower than for females, resulting in a reduced pseudo-R^2 value for males of:

$$1 - 456.57/477.51 = 4.38\%.$$

This reflects the fact that that the mean cortical width for males varies less with age than for females and changes little after about age 20.

The estimated mean mandibular cortical width of females decreased considerably with age after about 50 years (Fig. 4). The estimated mean cortical width (Table 4) decreased by 4.5% from 3.22 mm at age 50 to 3.07 mm at age 60 years and by a further 8.4% at age 70–2.82 mm. From age 40 to 70, the decrease was 13.4%. The male cortical width decreased by 1.8% from age 50 to 60 years and a further 1.9% from age 60 to 70 years. The reduction in the male cortical width from 3.35 mm at age 40 years to 3.16 mm at age 70 years was 5.4% (Table 4). Taking into account the effect of age, the estimated standard

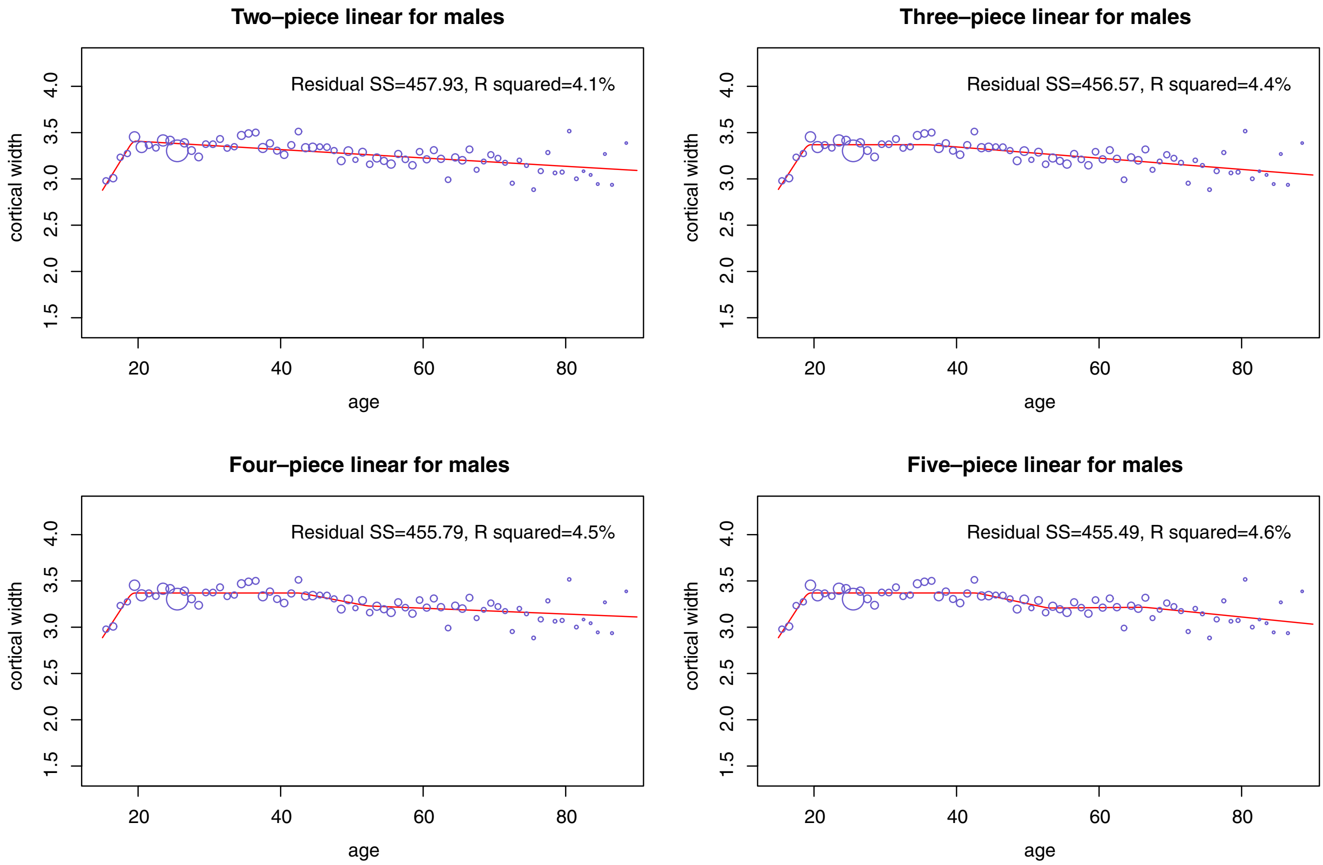


Fig. 5 Two-piece, three-piece, four-piece linear and five-piece linear regression models for males

deviation of cortical width for males was 0.44 and that for females was 0.41 (Table 3).

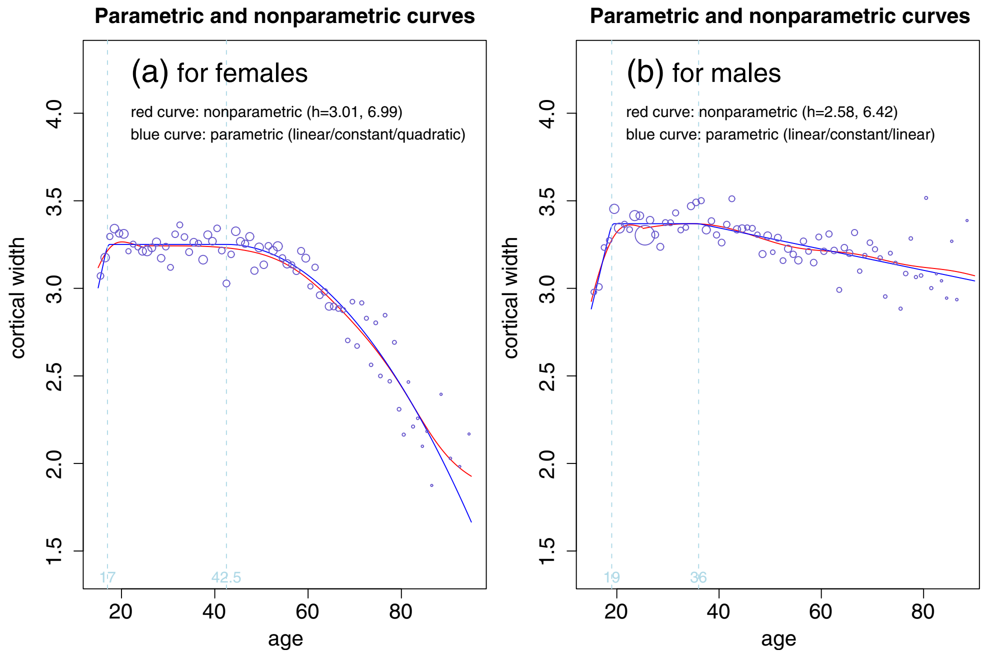
Discussion

Mandibular cortical width has been proposed as an opportunistic method of detecting osteoporosis in women despite some variation about the sample mean. In our sample, the estimated standard deviation in the cortical widths of females was 0.41 mm, which takes account of age. Potential sources of variability include errors in patient positioning in the radiography machine, inaccuracies in the accurate location of the mandibular measurement site, variable anisotropic scaling at different locations in the dental panoramic tomogram, measurement error in the software detection of the endosteal bone margins and inherent variation in the population. Our estimated standard deviation of 0.41 is less than the value of 1.2 obtained by Ledgerton et al. [2] using manual methods. To summarize, we have found a nonparametric estimate and a precise formula for the expected cortical width at any age after 15 years and a better estimate of the standard deviation. The improved estimate of the age-related variation in cortical

Table 3 Details of final fitted parametric models for females and males

	Females		Males	
f(x)	$a+c(x-17)$	$x<16.5$	$a+c(x-19)$	$x<18.5$
	$a-0.35c(x-17.5)^2$	$16.5\leq x7.5$	$a-0.5c(x-19.50)^2$	$18.5\leq x<19.5$
	a	$17.5\leq x<42.5$	a	$19.5\leq x<35.5$
	$a-\mathrm{b}(x-42.5)^2$	$x\geq 42.5$	$a-0.5\mathrm{b}(x-35.5)^2$	$35.5\leq x<36.5$
			$a-b(x-36)$,	$x\geq 36.5$
Estimates	a=3.25(se=0.01)	b=0.000575 (se=0.000023)	a=3.37(se=0.01)	b=0.0061 (se=0.0007)
	c=0.12(se−0.01)	σ=0.41	c=0.12(se=0.02)	σ=0.44

Fig. 6 Parametric and nonparametric curves **a** for females and **b** for males



width allows us to estimate referral rates implied by the application of various width thresholds, on which referral decisions might be made.

We observed that accelerated cortical thinning in women occurs after about 42.5 years of age. A number of other studies have produced results with which this observation may be compared. Morita et al. [14] measured the mandibular cortical width in 80-year-old men and women. They found that the prevalence of severe mandibular cortical erosions was ten times higher in the female sample than in the males (58.8% vs 5.9%). Figure 2 shows that this is where the differences in mean values of cortical thickness between sexes would be large. The accelerated decline in cortical width of women after the age of 50 years has been observed at various anatomical sites. Riggs et al. [15] showed that cortical thinning accelerated in the radius only after the age of 50 years in normal women, whereas men were little affected. Hyldstrup and Nielsen [16] used the "metacarpal index" (the ratio of the radiographic cortical thickness of the metacarpal bone to the total mid-metacarpal diameter) as a measure of osteoporosis. Using thickness measurements on digital radiographs, the index was maximal in the third decade and declined with age [16]. However, it needs to be taken into account that the metacarpal index is reduced by periosteal apposition, as well as endosteal cortical resorption [17].

Table 4 Estimated mean cortical widths at the age of 40, 50, 60 and 70 years together with standard errors for males and females

Age (years)	Estimated mean cortical width: Females (mm)	Males (mm)
40	3.25 (se=0.01)	3.35 (se=0.01)
50	3.22 (se=0.01)	3.28 (se=0.01)
60	3.07 (se=0.01)	3.22 (se=0.01)
70	2.82 (se=0.02)	3.16 (se=0.02)

Thinning of the femoral cortex with age is more rapid than the decline in areal BMD measured at the femoral neck, and it is the precipitous decline in cortical bone width at the hip which is present in hip fracture [18]. We have found a similar pattern of cortical bone loss in the mandible, which raises the intriguing question as to whether the mandibular measurements could be used to predict hip fracture.

We have previously proposed that mandibular cortical thickness measured from dental panoramic radiographs may be used as an opportunistic method for detecting osteoporosis [5]. Our earlier recommendation, based on manual measurements, was that a mandibular cortical width below the mental foramen of less than 3 mm merited referral of women for investigation of osteoporosis. The present study utilised a more lateral measurement site on the mandible (Fig. 1), which had previously been shown to have a better efficacy of detection of skeletal osteoporosis than measurement at the mental foramen [4]. Using this previously published dataset of females, the ASM/AAM method detected osteoporosis at the femoral neck with a sensitivity of 78% and specificity of 80% at a mandibular cortical width threshold value of 2.75 mm. In the analysis of the large dataset reported here, we can calculate where this threshold lies on the age-dependent width distributions. At age 40 years, it lies 1.2 standard deviations below the mean female width, reducing at ages 50, 60 and 70 to 1.1, 0.7 and 0.1 standard deviations, respectively. As osteoporosis is rare before age 40, we estimate that using this threshold as a criterion for referral would result in a false-positive rate of referral of low bone mass of 12% in pre-menopausal women. Law et al. [19] found a similar false-positive rate of 15% when using bone density measurements at the femoral neck as a screening tool for predicting hip fractures, based on a cut off of 1 standard deviation below the mean density of the controls. Our threshold would refer 50% of women at age 71 and 34% at 65 years. The latter figure is around double the estimated National Health and Nutrition Examination Survey (NHANES) III prevalence rate of 15% at 65 [20], although the increase of 22% above our baseline false-positive rate of 12% for 40 years old is closer to the NHANES figure. The previously published prevalence figures for osteopenia in the femoral neck in women aged over 50 years is 50% [20], and we may be detecting a proportion of these. From Table 3, the rate of decrease in mean cortical width is $2b(x-42.5)$ mm/year for females with age x in the 60–80 range, which increases from 0.049σ per year at $x=60$ to 0.105σ per year at $x=80$. This is in line with the published [21] reduction in BMD T-score in the UK, which varied between 0.25 and 1.3 per decade for femoral neck at different centres.

There has been no previous study on what mandibular cortical width threshold should be used for ageing males, and this study does not have BMD data to allow a definitive recommendation. However, given the female threshold, we make the provisional recommendation that males aged over 65 with a mandibular cortical width below the same threshold of 2.75 mm should consider DXA screening. This translates to 1 standard deviation below the male mean at age 65.

Measurement of the mandibular cortical width has been shown to be a poor predictor of fractures in an elderly study group, but this statistically nonsignificant result may be due to the small numbers of patients who developed fractures in some studies [22]. In our previous work, greater sensitivity in osteoporosis detection was introduced by using mandibular cortical width in combination with other clinical risk factors [1], but no other clinical risk factors were available for our sample in the present study.

It was a limitation of our study that definitive absolute scale measurements (e.g. including a ball bearing of known size in the dental panoramic tomogram) were not available relating image distance to anatomical distance. However, the previous study [6] included data using the same scanner, and in that study, absolute scale was measured using a ball bearing of known size that was placed intra-orally and incorporated into the radiographic image. This was used to calibrate for differences in magnification between images. As the images in the current study had been collected for other reasons, no calibration object was used. The standard error on the calculated mean scale (derived by bootstrap resampling of the data in [6]) was 1.2%. The limitations of our study also include a few unusually high or low averages in the cortical widths, e.g. at age 42.5 in both the male and female data.

Many osteopenic or osteoporotic female subjects, aged over 60 years, are likely to have cortical bone loss from both the hip and the mandible. The rate of loss of bone from the hip accelerates exponentially with age and follows a time course which is very similar to that observed for the mandibular bone [23]. The similarities with our results imply a phenomenon that is driving bone loss in older women, but which leaves men relatively unaffected. It is in this age group of women that the automated detection of cortical width will prove to be most useful in osteoporosis diagnosis and prevention of hip fractures.

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Conflicts of interest The authors declare that there are no conflicts of interest.

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