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Original Article

Adaptation of the Carter Method to Adjust Lumbar Spine Bone Mineral Content for Age and Body Size: Application to Children Who Were Born Preterm

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Abstract

In adults, the Carter method allows the separation of the lumbar spine bone mineral content (BMC) into its constituents; bone volume (BV) and volumetric density (bone mineral apparent density [BMAD]). However, this method is not widely used in pediatric studies and does not account for the effects of body habitus on bone mass. The aims of this study were to modify the Carter method for use in children by developing an approach that adjusts separately for age and body height, and to test whether lumbar spine bone mass is normal in children born who were born preterm. Twenty-five preterm-born children were matched to a term-born child. Lumbar spine bone mass was measured using dual-energy X-ray absorptiometry. The BV and BMAD were calculated. Z-scores based on age and height were calculated. The preterm group had reduced absolute height, weight, BMC, BV, and BMAD, and reduced height, weight, and BMC for their age. The BMC was appropriate for height. The BV was appropriate for age. The BMAD was reduced for age but appropriate for height. In preterm children, the major abnormality at the lumbar spine is a decrease in volumetric density; however, this decrease is proportional with their reduced stature, and we speculate that there is no reduction in the strength of the lumbar spine.

Key Words: BMAD; body size; bone mass; child; volumetric density.

Introduction

The number of infants surviving preterm delivery is increasing as a result of improved perinatal and neonatal care. However, there are persisting concerns about sequelae of preterm birth, specifically growth and the attainment of peak bone mass (PBM), which occurs during the third decade. The interpretation of bone mass accretion in childhood and adolescence is complicated by the changes in bone dimensions of children that occur during growth *(1–4)*. In addition, the analysis of bone mass in preterm survivors is confounded by the smaller body size of preterm survivors relative to normal children *(5–7)*.

In this article, bone mass refers to bone mineral content (expressed in grams), and density refers to volumetric density (expressed in grams/cm^3). Bone mass is a function of both size and density *(8)*. During prepubertal growth, increases in bone mass are primarily due to an increase in bone size rather than an increase in density *(9)*. Since adult bone mass is limited by the size of the bone envelope, any variation in growth during infancy and childhood may affect the attainment of PBM, and as a consequence this may also affect future fracture risk.

Several approaches are available to adjust bone mass for bone size. However, these methods were not designed to be used at the lumbar spine, e.g., Molgaard et al *(4)* and Warner *(10)*. The Peel and Eastell method *(11)* for adjusting lumbar spine bone mass requires both AP and lateral scans, and has

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not been used in children. At the lumbar spine, bone mass in children has been adjusted for body size previously using multiple regression techniques *(1)*. Using this method, bone mass in preterm survivors has been shown to be both reduced compared with controls *(6,7,12)* and within the normal range *(13,14)*. In a recent study, Fewtrell et al *(5)* demonstrated reduced bone mass, with reduced bone size in preterm children at ages 8 to 12. However, we found problems with colinearity using this approach, in that the predictors (i.e., bone area, height, and weight) were correlated with each other. The Carter method for the adjustment of bone mass for bone size has been widely used in adults *(15–24)*, but there are few studies that assess bone mineral apparent density (BMAD) calculated from dual-energy X-ray absorptiometry (DXA) data in prepubertal children *(25–29)*. In this method, the vertebral body is approximated to a cube, such that the bone volume (BV) is calculated by the formula $BA^{1.5}$. Bone mineral apparent density (BMAD) is then calculated as bone mineral content (BMC)/BV. Although BMAD is not an accurate reflection of the actual volumetric density, the value is relatively size-independent and can be used to compare individuals with each other.

This study was undertaken to test the hypothesis that preterm children may have lower bone mass than their term contemporaries, and that this reduction is due to deficits in both the size and volumetric density (i.e., BMAD) of bones.

Aims

The aims of this study were: (1) to adapt the Carter method for use in children by developing an approach that adjusts BMC, BV, and BMAD separately for age and body height; and (2) to compare prepubertal bone mass in children who were born preterm with children who were born full term.

Materials and Methods

Data Collection

Fifty children were recruited from the South Yorkshire region in the United Kingdom. Twenty-five preterm subjects were recruited from a cohort of children who were studied as part of a neonatal growth study conducted at the Jessop Hospital for Women, Sheffield, United Kingdom (unpublished data). Neonatal data is shown in Table 1.

Each preterm child was individually age-matched (i.e., within 6 mo) and sex-matched to a subject who was born at term. Term subjects were recruited from siblings, neighbors, and children of hospital workers. Subject characteristics are shown in Table 1. No subjects had previous fractures. Informed written consent was obtained from parents, and oral consent from the subjects following permission from the North Sheffield Local Research Ethics Committee. Subjects attended the Osteoporosis Center at the Northern General Hospital, Sheffield, United Kingdom for investigation.

Height was measured to the nearest 1 mm using a wall-mounted stadiometer (Holtain, Crymych, Wales). Weight was assessed using electronic scales (SECA, Hamburg, Germany) to the nearest 0.1 kg. Subjects wore light indoor clothing and no shoes.

Bone area (BA) (cm^2) and BMC (g) were measured at the lumbar spine (L1 to L4) in the posterior-antero (PA) projection using DXA (Hologic QDR4500 Acclaim; Hologic Inc, Bedford, MA) (coefficient of variation, 1.0%). Subjects were positioned lying supine, with the knees bent and the lower legs resting on a support. Version 4.0 of the software was used with the fast array mode (to reduce scan time), with the low-density option. This was to ensure that bone edges were detected consistently across the range of bone densities that occur in a pediatric population.

Table 1
Subject Characteristics

	Preterm	Term
n	25	25
Male:female ratio	16:9	16:9
Post conceptional age at birth (wk)	28.3 (1.8, 24 to 31)	39.7 (1.5, 37 to 42)*
Birth weight (kg)	1.1 (0.3, 0.55 to 1.79)	3.4 (0.4, 2.16 to 4.12)*
Age at study (mo)	58.0 (15.5, 27 to 88)	60.0 (16.8, 35 to 96)
Skeletal maturity (mo)	52.9 (17.6, 18 to 84)	58.1 (18.4, 30 to 96)
Height (cm)	104.9 (8.8, 85.1 to 117.7)	110.4 (9.9, 92.7 to 126.5)*
Weight (kg)	16.5 (2.9, 11.0 to 21.0)	19.4 (4.6, 12.0 to 27.8)*
LS BA (cm^2)	28.0 (4.4, 17.8 to 34.9)	29.5 (4.7, 21.9 to 36.0)**
LS BMC (g)	12.3 (2.9, 6.4 to 16.3)	14.5 (4.2, 7.8 to 21.9)*
LS BV (cm^3)	149.9 (33.9, 74.8, 206.1)	161.3 (37.6, 102.9 to 216.4)**
LS BMAD (g/cm^3)	0.08 (0.01, 0.07 to 0.10)	0.09 (0.01, 0.07 to 0.11)**

Note: Data presented as mean (SD, range).

Abbr: BA, bone area; BMAD, bone mineral apparent density; BMC, bone mineral content; BV, bone volume; LS, lumbar spine; SD, standard deviation.

*$p < 0.01$.

**$p < 0.05$; paired *t*-test.