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Continuing Bone Growth Throughout Life: A general phenomenon

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ABSTRACT Cross-sectional data on 2799 subjects from five different populations and longitudinal data on 113 older adults indicate continuing adult bone growth in the second metacarpal. Similar 6-decade increases in the size of the cranium confirm continuing bone growth as a general phenomenon not necessarily related to weight-bearing or flexion stress and representing an increase of approximately 10% in skeletal volume concomitant with the major age-associated decrease in skeletal mass.

In 1964, Smith and Walker provided cross-sectional radiographic evidence for continuing "expansion" of the femur in women aged 45–90. Trotter and Peterson ('67), using skeletalized femora have given confirmation to this trend. Epker, Kelin and Frost ('65) similarly reported an increase in the size of the periosteal envelope through the seventh decade in rib cross sections of subjects of both sexes. Moore ('55) earlier published separate cross-sectional data indicating continuing growth of the cranial vault through late adulthood, thus indicating that weight-bearing, flexion-stressed bones are not unique in the apparent property of continuing growth.

With cross-sectional data from five populations at hand, and having both long-term and short-term longitudinal data from a single ongoing study population, we have been concerned with three aspects of the problem of continuing bone growth. First, there is the question of such adult growth in various bones throughout the body, weight-bearing, flexion-stressed and otherwise. Second, there is the problem of generalization—whether such bone expansion is population-limited or not and sex-specific or not. Third, there is the problem of confirmation of such continuing growth on an individual basis in order to rule out artifacts of sampling and differential survival.

It is the purpose of the present study to explore continuing bone growth in two populations from the United States and three Central American populations, using longitudinal data to further test for individual trends. It is the additional purpose of this study to investigate adult bone growth in both weight-bearing bone and in bone not subject to compression or flexion stress in order to determine whether such mechanical factors play a necessary role in continuing bone growth.

METHODS AND MATERIALS

This study is based upon vernier caliper measurements of the second metacarpal on postero-anterior hand radiographs from five different population samples, one skeletal and four living. 2799 subjects are represented in the cross-sectional study. A second part of the data analysis is purely longitudinal.

Subject material includes 121 skeletalized adults from the Terry Collection of Washington University, 677 adult participants in studies of growth and aging at the Fels Research Institute and 2001 adult participants in nutritional surveys in Guatemala, El Salvador and Nicaragua. Radiographic techniques were standardized within each study, and the measurements were taken as previously described by us (Garn, Rohmann and Nolan, '64; Garn, Pao and Rihl, '64; Garn et al., '64, '66a, '66b; Garn and Hull, '66; Garn, Rohmann and Guzman, '66). The measuring techniques reasonably follow those of Barnett and Nordin ('61) and Smith and Walker ('64).

The measurements can be shown to have both short-term and long-term interfilm reliability in excess of 0.98 (Garn et al., '66a), to be free from systematic left-right asymmetry bias and not notably affected by occupation. Bias in subject selection was minimized by the experimental design and the caliper measurements were made by workers unaware of the specific hypothesis here tested.

In the preliminary data analysis, six decade groupings were employed: 25–34, 35–44, 45–54, 55–64, 65–74 and 75–84. Subjects below age 25 were excluded in view of late epiphyseal union observed in some of the subjects from Central America. Later, for convenience in presentation, the data were regrouped into three-decade groupings, 25–54 and 55–84, with mid-points at 40 and 70 years respectively. Student's *t* tests were then applied to the three-decade sex-specific groupings for each population, with a minimum of 20 and a maximum of 397 subjects in each age-sex-population category. Data for the purely longitudinal analysis of long-term bone changes in adults and short-term metacarpal increases in the aged were restricted to the basic information on continuing bone growth through advanced age. *t* tests were again used to test the significance of individual changes.

While biological generalization from a single study is ordinarily hazardous, the degree of agreement shown by all ten sex and population-specific groupings indicates that the present findings do have broad applicability.

Findings

As shown in table 1, there is a small but completely systematic three-decade gain in metacarpal width at mid-shaft in both sexes and all five populations sampled. This is true of the very well nourished Ohio sample (primarily of Northwest European ancestry), the skeletalized St. Louis Colored sample and the comprehensive nationwide samples of mixed ancestry from Guatemala, El Salvador and Nicaragua. In view of the internal consistency of the data, ten gains and no losses as compared to the 5:5 (chance) distribution, chance may be therefore ruled out at any reasonable level of probability. Further, with radiography accomplished at many different villages and towns, and in the St. Louis sample entirely on isolated

TABLE 1

Continuing metacarpal growth in five populations

Age group	St. Louis			Ohio			Guatemala			El Salvador			Nicaragua		
	N	$\bar{X}$	σ	N	$\bar{X}$	σ	N	$\bar{X}$	σ	N	$\bar{X}$	σ	N	$\bar{X}$	σ
Women															
25–54	43	8.19*	0.68	299	7.96	0.73	397	7.39	0.67	252	7.47	0.59	266	7.86	0.82
55–84	31	8.22	0.73	94	8.21	0.61	106	7.63	0.59	85	7.61	0.61	98	8.00	0.55
d		+0.03			+0.25			+0.24			+0.14			+0.14	
t		0.20			3.42			3.64			1.43			1.47	
Men															
25–54	27	9.25	0.67	214	9.38	0.77	243	8.48	0.75	125	8.64	0.76	238	8.93	0.59
55–84	20	9.50	0.71	70	9.50	0.74	77	8.64	0.93	54	8.74	0.68	60	9.02	0.79
d		+0.25			+0.12			+0.16			+0.10			+0.09	
t		1.22			1.16			1.48			0.87			0.82	

* mm.

skeletalized matacarpals, systematic age-associated positioning errors remain an unlikely explanation.[1]

Expressing the changes from midpoint 40 to midpoint 70 on a percentage basis, the 3-decade gain in metacarpal width approximates 2.0% in females and 1.6% in males. The full 6-decade gains (pooling all 5 populations) thus equals 4.0% in the women and 3.2% in the males. The percentage gains in cross-sectional area are, of course, larger. Assuming circularity of cross section at mid-shaft, the gains in cross section approximate 12% in women and 6% in men over the entire 6-decade period for which data are available. The small but consistent increases in absolute metacarpal width thus delineate sizeable percentage increases in total cross-sectional area of bone, more so in women with smaller cross-sectional areas to begin with.

Though unlikely to be due to chance or systematic positioning errors, selective survival rather than continuing bone expansion could be the explanation for the apparent gain in metacarpal width. To test this possibility we have made use of purely longitudinal radiographic data on older adult participants in the Fels Institute studies of growth and aging. As shown in table 2, 34 males show a significant average gain in total metacarpal width after a period of 15 years, using Student's t test to test the significance of the mean difference. The same experimental design reveals a statistically-significant gain in the metacarpal widths of 53 women similarly followed in true longitudinal fashion for an average of 24 years. Together the long-term gains shown by 174 serial radiographs on 87 adult subjects confirm the cross-sectional multi-national studies and exclude selective survival as an explanation.

As a further and even more severe test of continuing bone expansion on an individual basis, we compared "before" and "after" postero-anterior hand radiographs of 26 Senior Citizens averaging 73–74 years in age, and followed for an average of 1.3 years (table 3). In this study, employing a fixed-position radiographic installation, the mean difference again revealed a metacarpal gain, exceeding the RMS measuring error, and significant by the two-tailed t test. Expansion of the second metacarpal continuing even into the eighth decade thus appears to be a true individual property.

It is further relevant to report both cross-sectional and longitudinal confirmation of continuing bone expansion in the skull. For 340 of the Ohio participants in the studies of growth and aging, there was a long-term gain of approximately 5 mm in the radiogrammetrically-determined skull

[1] Radiographs were made in a total of 106 locations in Central America under the direction of Fidencio Pérez and in St. Louis by Henry Breier.

TABLE 2

Long-term gains in metacarpal diameter in 87 adults

No.	Sex	Mean age Earlier	Mean age Later	Metacarpal width Earlier	Metacarpal width Later	Mean change	se	t
		years	*years*	*mm*	*mm*	*mm*		
34	Males	33	57	9.41	9.56	0.15	0.06	2.6 [1]
53	Females	40	55	7.83	7.94	0.11	0.02	5.0 [2]

[1] $0.02 > p$.
[2] $0.001 > p$ (cf. Fisher, '58, table IV).

TABLE 3

Short-term changes in metacarpal diameter in 26 senior citizens

No.	Mean age Earlier	Mean age Later	Metacarpal width Earlier	Metacarpal width Later	Mean change	se	t
	years	*years*	*mm*	*mm*	*mm*		
26	73.1	74.5	8.54	8.63	0.08	0.036	2.25 [1]

[1] $0.03 > p$ for two-tailed test.

lengths in both sexes, as ascertained by Dr. Harry Israel. This increase (amounting to 3% overall) also proved to be significant on an individual basis and for a number of selected skull thickness measurements. The lateral-skull views are thus in accord with the longitudinal evidence from approximately 3000 individuals of both sexes from five populations. It is therefore reasonable to summarize these findings by saying that bone growth continues through the eighth decade, that it is not population-specific or sex-limited, and that it appears to be a general phenomenon in man.

DISCUSSION

The findings in this extensive study document adult growth at the outer surface of the second metacarpal in five different populations and in both sexes. They add to the growing evidence for continuing bone "expansion" in a variety of bones, weight-bearing and otherwise. Supplementing the large-scale but purely cross-sectional population analyses with truly longitudinal data on over 100 Ohio adult subjects, it is clear that the multi-national adult growth trends revealed in cross-sectional analysis need not be explained solely as the product of selective survival. On an individual basis, continuing bone growth can be demonstrated too, even over a short time period as late as the eighth decade.

Over the full 6-decade period covered in our data analysis, ages 25 through 84 inclusive, the gain in metacarpal width is not quite 4% on a combined-sex, pooled-population basis. Yet the gain in total cross-sectional area due to apposition at the outer surface amounts to approximately 9% during the same time that endosteal resorption makes for cross-sectional bone loss.[2] To some extent these two processes (apposition at the outer surface and resorption at the inner surface) partially cancel. However, the percentage gain in area due to apposition at the outer surface in the second metacarpal appears to be less than that reported for the femur at mid-shaft by Smith and Walker ('64) and for the rib cross section by Epker, Kelin and Frost ('65). Bones may therefore differ in relative gain over the years, though adult remodeling rates undoubtedly also differ at different parts of the same bone as they do prior to epiphyseal union. Our data also suggest a sex difference in percentage gain, with the female gaining relatively more at the outer surface, just as she certainly loses more at the endosteal surface.

While the cross-sectional female findings of Smith and Walker ('64) are consistent with the possibility that "continuing expansion" is a phenomenon of weight-bearing bone, neither the reported changes in rib-section nor in metacarpal width merit this explanation. The possibility that flexion stress is the prime stimulus also seems unlikely in view of our data on continuing skull growth and the data earlier reported by Moore ('55). Nor is it likely that outer bone growth is a compensatory response to inner bone loss, though it is possible that continuing adult growth of different kinds of bones represents responses to differing mechanical and hormonal stimuli.

For certain of the Central American countries where protein-calorie malnutrition (P.C.M.) is common, continuing bone growth in adulthood could represent a delayed form of "catch-up growth." This particular nutritional explanation would not apply to the Ohio population, however, with high intakes of quality protein, exceeding 1.0 gm per kilogram of body weight, as 7-day replicated dietary records show.

In our longitudinal data there is additional intriguing evidence that outer bone growth is greater in tall subjects and less in those short to begin with (Garn and Hull, '66). The method of analysis, using stature in the fourth decade as a point of departure, eliminates vertebral collapse and loss of intervertebral disc height as a potential source of error. However, it does not explain why stature should be related both to long-term gain in outer bone width and to long-term loss of bone endosteally.

Since the second metacarpal is approximately circular at mid-shaft, and the medullary cavity is nearly centered in the tubu-

[2] In the terminology of Frost ('63) this represents an increase in Total Periosteal Volume concomitant with decrease in Absolute Bone Volume. Either of these two processes, and certainly both together, contribute to the age-associated decrease in the weight-to-volume ratio of the skeleton.

lar bone cylinder at that point (Garn et al., '66a, p. 71), calculation of the cross-sectional area is tenable, and the calculated data can then be applied to computing Young's Modulus. Further, by the use of empirical formulae, parallel changes in the more complex femoral and tibial bone sections can be analyzed and the effects of outer bone gain and inner bone loss on breaking strength can be computed for a variety of tubular bones.

Four points bear emphasis here. First, the phenomenon of outer bone gain during adult life now appears to be general with respect to a variety of populations. Second, outer bone gain applies to diverse bones — weight-bearing, flexion-stressed and not. Third, the skeleton gains in volume during adulthood even as it loses in mass. Fourth, outer bone gain compensates — in a mechanical sense — for inner bone loss to some extent, more so in individuals who are tall to begin with. Thus, continuing bone growth during adulthood must be viewed as a general phenomenon, certainly not population-specific, and it must be considered in studies of osteoporosis and osteoporotic bone loss.[3]

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[3] However Trotter et al. ('67a, 67b) now attribute this trend to a cohort effect.