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Sex-specific cervical vertebral growth in height & depth: A study using computed tomography

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I. OBJECTIVE:

1. Identify the growth trend and type of cervical vertebral body heights and depths during the first two decades of life.
2. Identify if there are sex differences in cervical vertebral growth.

II. INTRODUCTION:

- The neck has a complex growth pattern. Scammon[1] noted its growth to follow both the general/somatic and neural growth types. As seen in Figure 1:
  - Both growth types are accelerated during early childhood, however, by age 6 years neural growth attains most of the adult size, while somatic growth attains only 1/3 of the adult size.
  - During puberty, neural growth is slow and steady while somatic growth is accelerated.

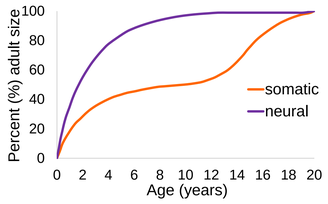

Fig. 1 - Schematic plot of neural and somatic growth types associated with the head and neck[1].

- Cervical Vertebral Maturation Index (CVMI)[2,3] is an important method to qualitatively assess the morphological changes in the cervical vertebral body to determine skeletal maturation and when surgical intervention/treatment should occur in modern populations, as well as assess age-at-death in past populations[4].
  - The six CVMI stages of morphological changes of C2-C6 during puberty[2,3] are depicted in Figure 2.

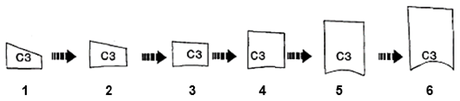

Fig. 2 - Cervical Vertebral Maturation Index stages. Figure modified Hassel et al. (1995)[3] exhibiting the six stages of morphological changes occurring in C3 associated with the pubertal growth spurt.

- CVMI has been found to have poor reproducibility[5] given the qualitative nature of this method.
- Sexual dimorphism in size and shape of cervical vertebral bodies is present during growth[6] as well as in adulthood[7], however CVMI does not account for it[6].

III. MATERIALS:

- **Subject –** 115 medical CT studies (70 males, 45 females) from modern typically developing individuals between the ages of 6 months to 20 years.
- **Image and data acquisition –** Retrospective medical imaging studies were acquired and data collected as specified in Miller et al. (2019)[6], Vorperian et al. (2009[8] and 2011[9]).

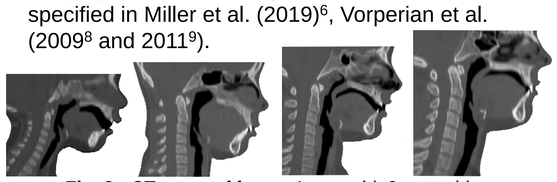

Fig. 3 - CT scans of from a 1 year old, 9 year old, 13 year old and 19 year old sequentially.

IV. METHODS:

- Landmark-based measurements were calculated from 23 landmarks placed in the midsagittal plane of each cervical vertebra[6]. See first panel, Figure 4.
- Using the 23 landmarks the 3D Euclidean distance was calculated for each cervical vertebral body in anterior height, posterior height, superior depth, and inferior depth.

Statistical Analysis

- The height and depth measures were plotted as a function of age for each variable with sex-specific 4th degree polynomial fits.
- Growth type percentages of neural and somatic growth were quantitatively assessed using the composite growth model by Wang et al. (2013)[10].

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V. RESULTS:

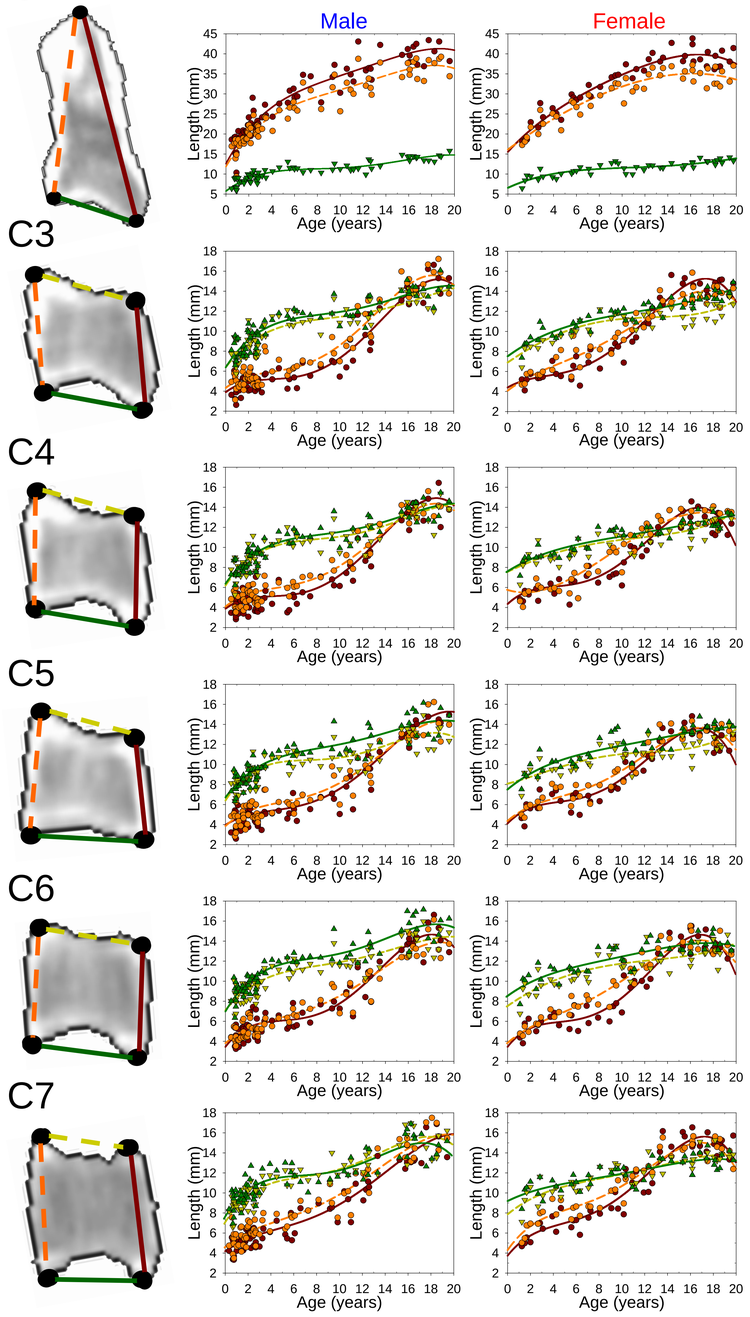

Fig. 4 - C2-C7 landmarks with height & depth measurements.

Fig. 5 - Height & depth growth trend: Male (left) and female (right) growth trends plotted with data for anterior height (maroon, solid/circle), posterior height (orange, dashed/circle), inferior depth (dark green, solid/triangle) and superior depth (light green, dashed/triangle).

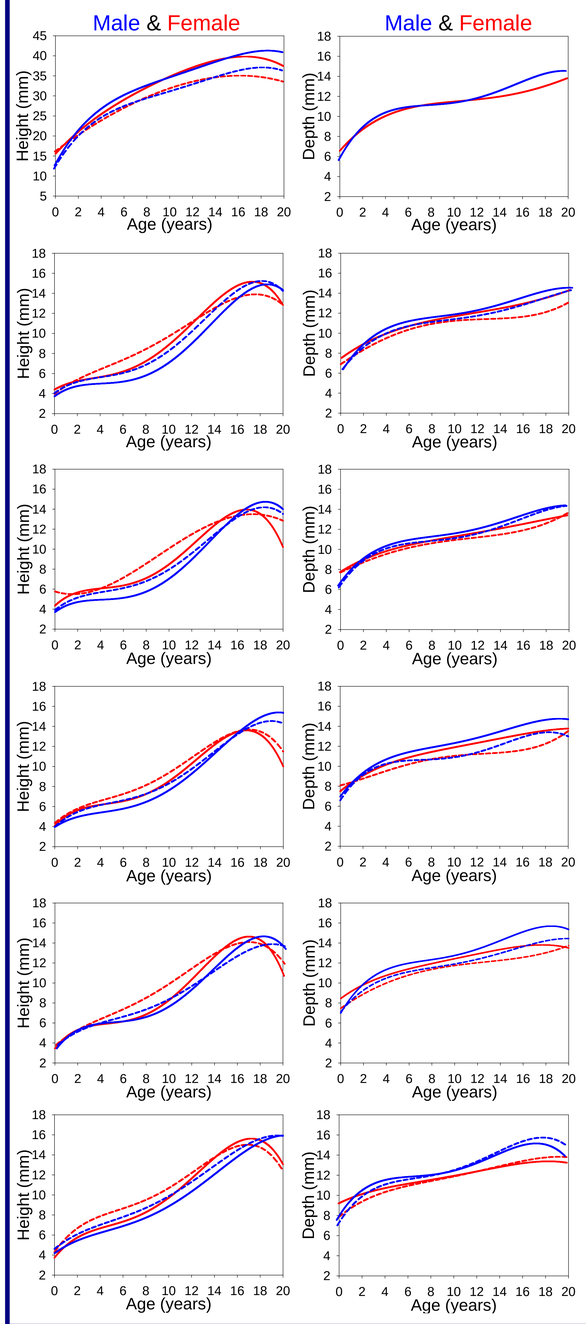

Fig. 6 - Male compared to female height & depth growth trends. Male (blue) and female (red) growth trends are plotted for height (left; superior-dashed and inferior solid) and depth (right; posterior dashed and anterior solid).

- **Growth Types:**
  - Height follows somatic growth type with the exception of C2 while depth follows neural growth type. See Table 1 and Figure 5.
- **Growth Trends:**
  - The posterior height is larger than the anterior height until puberty when they become equal in size. See Figure 6, height panel.
  - The inferior depth is always larger than the superior depth with the exception of C7 between 8-10 years when the depths are equal. See Figure 6, depth panel.
- **Sex Differences:**
  - Height in females is larger than in males until around age 16 where females reach maturity but males continue to grow and become larger than females.
  - Males have more depth than females at all ages.

Table 1: Percentages of somatic versus neural growth: Anterior height (upper left), posterior height (lower left), superior depth (upper right), and inferior depth (lower right) percentages of somatic versus neural growth were calculated. Growth type was designated when the percentage was > 60% otherwise denoted as somatic/neural.

Anterior Height	Sex	Somatic (%)	Neural (%)	Growth Type
C2A	Male	7	93	Neural
	Female	32	68	Neural
C3A	Male	97	3	Somatic
	Female	94	6	Somatic
C4A	Male	97	3	Somatic
	Female	91	9	Somatic
C5A	Male	99	1	Somatic
	Female	93	7	Somatic
C6A	Male	100	0	Somatic
	Female	92	8	Somatic
C7A	Male	100	0	Somatic
	Female	98	2	Somatic

Superior Depth	Sex	Somatic (%)	Neural (%)	Growth Type
C3S	Male	16	84	Neural
	Female	7	93	Neural
C4S	Male	27	73	Neural
	Female	1	99	Neural
C5S	Male	25	75	Neural
	Female	0	100	Neural
C6S	Male	25	75	Neural
	Female	1	99	Neural
C7S	Male	48	52	Somatic/ Neural
	Female	20	80	Neural

Posterior Height	Sex	Somatic (%)	Neural (%)	Growth Type
C2P	Male	6	94	Neural
	Female	17	83	Neural
C3P	Male	99	1	Somatic
	Female	99	1	Somatic
C4P	Male	100	0	Somatic
	Female	98	2	Somatic
C5P	Male	100	0	Somatic
	Female	99	1	Somatic
C6P	Male	98	2	Somatic
	Female	100	0	Somatic
C7P	Male	98	2	Somatic
	Female	100	0	Somatic

Inferior Depth	Sex	Somatic (%)	Neural (%)	Growth Type
C2I	Male	8	92	Neural
	Female	4	96	Neural
C3I	Male	11	89	Neural
	Female	4	96	Neural
C4I	Male	17	83	Neural
	Female	11	89	Neural
C5I	Male	19	81	Neural
	Female	4	96	Neural
C6I	Male	21	79	Neural
	Female	19	81	Neural
C7I	Male	30	70	Neural
	Female	64	36	Somatic

VI. DISCUSSION:

This study quantified sex-specific growth of the cervical vertebral bodies in height and depth during the first two decades of life. Findings reveal that:

- In general, the growth type is related to the plane of growth. Specifically, growth in the vertical plane follows a somatic growth type while growth in the horizontal plane follows a neural growth type[8].
  - The accelerated growth in height during puberty based on previous studies revealed an increase in height of an average of 6 mm[11,12]. This study found similar results for the anterior cervical vertebral body heights (female=6.5mm, male=6.2mm). However, the posterior height increased by an average of 5 mm (female=4.9 mm, male=5.5).
  - Depth growth trends for all cervical vertebrae had neural growth where the majority of the growth is achieved (about 75%) by early childhood.
- The height and depth findings in this study quantify the six stages of CVMI changes in shape.
  - Heights have accelerated growth during the period associated with CVMI, whereas depths have attained most of the adult size before the CVMI stages. Therefore, shape changes of CVMI are likely due to growth in height rather than depth.
  - The slow and steady growth in depth suggest the changes in the inferior border of cervical vertebral bodies during CVMI stages 3-6 occur more due to concavity than growth in depth.
- Sexual dimorphism is present in height and depth growth trends even though both males and females follow a somatic growth type in height and neural growth type in depth.
  - As seen in Figure 5, the intersection of the height and depth growth trends reflect equivalent lengths and imply a square shape.
    - This intersection occurs at around 13 – 15 years in females, supporting Altan et al. (2011)[12] quantitative findings and Lamparski[13] CVMI stage association with chronological age, while occurring in males around 16 – 18 years.
    - The difference in age between the sexes when height and depth intersect, suggests females progress through the CVMI stages earlier than males[6].
  - As seen in Figure 6, larger depths in males at all ages support previous research findings of sex differences in shape[6].
- The poor reproducibility and reliability of CVMI is likely due to sexual dimorphism as evidenced by timing differences in growth/maturation between males and females as seen as Figure 5, and sex differences in height and depth as seen in Figure 6.

VII. CONCLUSION:

- Cervical vertebral body (C3-C7) growth in height and depth follow different growth types, somatic and neural respectively. C2 growth in height and depth are both neural.
- Sex differences are present as evidenced by differences in age of maturation with females maturing sooner than males; also, the cervical vertebrae depth is greater in males than females at all ages.
- Based on the strong evidence of sexual dimorphism, reassessment of the CVMI stages accounting for sex differences is needed to improve determination of skeletal maturation and better serve for clinical guidance.

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