The timing and duration of adolescent growth

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The adolescent growth of 212 randomly selected Swedish urban children has been investigated by using a graphical analysis of unsmoothed increments of height. The adolescent growth period has been divided into the pubertal spurt and the postpubertal period. On average, the pubertal spurt began at 10.0 years in girls, and 12.1 years in boys and ended at 14.8 years and 17.1 years, respectively. In both sexes peak height velocity occurred two years after the onset of the spurt (12.0 years and 14.1 years). Growth terminated at 17.5 years in girls and 19.2 years in boys. The standard deviation of the age at the occurrence of the various growth events is about one year in both sexes. The duration of the spurt did not differ between the sexes but the postpubertal period was significantly longer in girls. To include the total range of adolescent growth variability, the age range 6 – 20 years in girls and 9 – 23 years in boys must be considered in a Swedish population.

Key-words: Pubertal spurt; postpubertal period; orthodontics

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The adolescent period starts with a marked increase in the general growth rate and ends with the termination of growth. Every muscular and skeletal dimension seems to be involved in this growth spurt (16). Many studies have shown a high degree of association between the peak of facial growth and peak height velocity (2, 3, 11, 26). However, the findings concerning correlation between the termination of facial and height growth have been less consistent (3,11). The adolescent growth spurt in facial dimensions is of importance in orthodontic treatment especially when depending on residual growth capacity (3, 8, 9). Owing to the close association between the growth spurt in facial dimensions and height Björk (3) has proposed that longitudinal growth records of height can be used as a mean in orthodontic treatment planning.

The adolescent spurt occurs in all individuals but there are great individual variations in the onset, the duration and the rate of growth during this period of life (16). Thus it is essential in treatment planning to assess which stage of maturity an individual has reached (3).

The aims of this paper, the first in a series on adolescent growth and maturation in Swedish boys and girls, are:

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- to determine the beginning, the peak and the end of adolescent growth in height
- to determine the duration of adolescent growth.

This information will be applied in a system in which data on linear growth and dental, pubertal and skeletal development are used as means in the timing of various orthodontic measures.

SUBJECTS AND METHODS

Data on somatic development have been collected from 212 randomly selected Swedish urban children (122 boys and 90 girls) as part of a prospective longitudinal study of growth and development from birth to adulthood (13, 14). The children are born between 1955 and 1958. This study is coordinated with four other European longitudinal studies (in Brussels, London, Paris and Zürich) by the International Children's Centre in Paris (6). The selection and representativeness of the sample have been discussed in previous reports (13, 14). At five, ten, fifteen and twenty years of age 95, 92, 84 and 70 % respectively of the original sample remained in the study. The percentage of withdrawals was approximately the same in both sexes.

During the age period covered in this paper the subjects have been examined once a year up to the age of 18 years according to a schedule comprising various body measurements, pubertal development, tooth emergence and radiograms of the hand and wrist, among other variables. The subjects have also been examined at the age of 20–22 years. From 10 years onwards height has been recorded every three month, but only measurements of height taken at even ages have been analysed in this report. Height has been measured with the stretching up

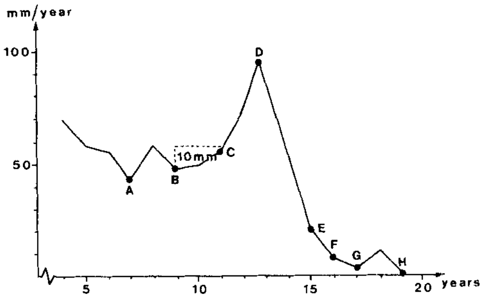

Fig. 1. Various events during adolescent growth in height.

A MINIMUM:	The smallest annual increment before peak height velocity (PHV).
B START:	The smallest annual increment from which there is a continuous increase in the growth rate to PHV.
C ONSET:	The smallest annual increment from which there is a marked continuous increase in the growth rate to PHV. ONSET is found on the incremental curve by locating START. The curve is then followed towards PHV until growth rate has accelerated 10 mm. ONSET will be represented by the increment which is next below or coincides with this growth rate.
D PHV:	Peak height velocity – the greatest annual increment during puberty.
E D-20:	The first annual increment below 20 mm after PHV.
F D-10:	The first annual increment belov 10 mm after PHV.
G D-5:	The first annual increment below 5 mm after PHV.
H D-zero:	The first of three consecutive annual increments each being below 5 mm

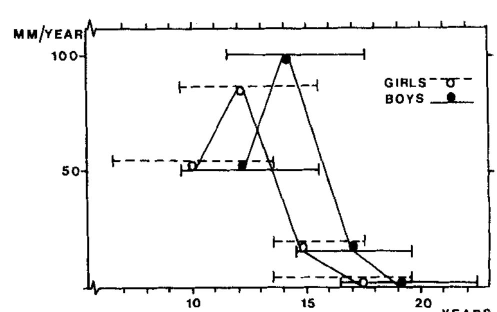

Fig. 2. Mean and range at the beginning, peak and end of the pubertal growth spurt and the termination of growth in height.

Table 1. *Probit analysis of the age (in years) at the occurrence of various growth events during adolescent growth in height*

Growth event	Sex	Mean	S.D.	Adjustment of probit line Chi²ᵃ	df	Range	Sex difference[b]
MINIMUM	G B	8.96 10.59	1.42 1.46	5.08 9.66	8 8	4.5 - 12.5 7.5 - 15.5	1.63^{xxx}
START	G B	9.49 11.55	1.25 1.37	7.10 3.86	7 7	6.5 - 13.5 8.5 - 15.5	2.06^{xxx}
ONSET	G B	10.04 12.08	1.26 1.20	3.03 3.83	7 6	6.5 - 13.5 9.5 - 15.5	2.04^{xxx}
PHV	G B	11.98 14.07	1.02 1.08	9.41 2.53	6 6	9.5 - 15.5 11.5 - 17.5	2.09^{xxx}
D-20	G B	14.82 17.05	0.88 0.98	1.19 1.32	5 5	13.5 - 17.5 14.5 - 19.5	2.23^{xxx}
D-10	G B	15.79 17.90	0.98 1.02	4.04 4.45	5 5	13.5 - 17.5 15.5 - 20.5	2.11^{xxx}
D-5	G B	16.66 18.81	1.16 1.08	0.78 1.04	6 5	13.5 - 19.5 16.5 - 21.5	2.15^{xxx}
D-zero	G B	17.49 19.18	1.18 1.01	2.80 1.39	5 5	13.5 - 19.5 16.5 - 22.5	1.69^{xxx}

[a]No value of Chi² is statistically significant ($p > 0{,}10$)
[b] Significance of the value marked $^{xxx}p < 0.001$

technique (gentle pressure under the mastoid process), as proposed by Tanner (27). About 80% of the measurements have been made in the morning between 8 and 10 a.m. and two examiners performed over 90% of the measurements.

Increments of height have been calculated by means of measurements taken at even ages. Each measurement has been adjusted to exactly specified target ages (e.g. 9.00, 10.00 and so on) according to a subroutine in our data-processing system (14). The incremental curve of height has been analysed graphically without any smoothing of the curve, since this method can be used in clinical routine work.

After visual inspection of the individuals incremental curves eight events of adolescent growth have been defined (Figure 1). Three events represent various definitions of the beginning of the spurt. The smallest annual increment before the peak height velocity (PHV) has been termed MINIMUM. However, in some subjects there was a break in the increase of the growth rate from MINIMUM up to PHV. Because of this another growth event has been defined (START) representing the first increment, after which there has been a continuous increase of the growth rate up to PHV. Since the incremental curve can be rather flat during this phase of growth, it may be difficult to determine the occurrence of START accurately in many subjects. Therefore, a third event during the beginning of the spurt has been defined (ONSET) representing the first increment, after which there was a marked continuous increase of the growth rate up to PHV. A detailed definition of ONSET is given in Fig. 1. According to the definition, MINIMUM, START and ONSET may be represented by the same or separate increments. After PHV four events (D-20, D-10, D-5 and D-zero) have been de-

Table 2. *Cumulative percentage of girls and boys having attained various events of adolescent growth in height at the end of each age interval*

Age interval in years	MINIMUM		START		ONSET		PHV		D-20		D-10		D-5		D-zero	
	G	B	G	B	G	B	G	B	G	B	G	B	G	B	G	B
4 – 5	1.2															
5 – 6	2.4															
6 – 7	8.5		1.2		1.2											
7 – 8	19.5	4.3	8.5		3.7											
8 – 9	53.1	11.4	40.7	1.8	21.0											
9 – 10	75.3	38.4	67.9	15.2	49.4	5.3	1.2									
10 – 11	93.8	61.5	90.1	33.9	79.0	14.7	19.8									
11 – 12	98.8	80.7	96.3	64.2	95.0	51.4	46.9	1.9								
12 – 13	100.0	97.2	98.8	87.9	97.5	79.4	88.8	15.9	1.2							
13 – 14		99.1	100.0	94.3	100.0	92.5	97.5	51.4	17.3		6.2		1.2			
14 – 15		99.1		99.1		99.1	98.7	79.8	61.7	1.0	18.8		8.7		1.3	
15 – 16		100.0		100.0		100.0	100.0	96.2	90.1	15.2	53.8	1.9	26.0		12.0	
16 – 17								99.0	98.8	50.5	92.5	21.9	63.3	4.9	35.9	1.0
17 – 18								100.0	100.0	81.9	98.8	51.5	87.3	23.0	62.3	12.0
18 – 19										97.1	100.0	89.2	97.5	57.6	88.5	45.7
19 – 20										100.0		96.2	100.0	87.0	100.0	78.9
20 – 21												100.0		97.1		95.0
21 – 22														100.0		99.0
22 – 23																100.0

fined representing different absolute growth rates (20, 10, 5 and «zero» mm per year; see Fig. 1) during the adolescent deceleration period. According to the definition, these events may occur in the same or separate intervals.

Statistical methods

The individual age of reaching an event has been recorded midway through the examination interval, during which the criteria for the event have been attained. When more than one event occured during an interval, the interval was divided into appropriate parts. These individual ages have been used when analyzing the relationship in time between the various growth events.

Mean age at the occurrence of the various events has been calculated by probit analysis (7). In these analysis maximum information has been extracted from the sample according to principles described earlier (25) which will give an unbiased estimate of the mean values (23). This method gives maximum likelihood estimates of the population mean and standard deviation. It makes use of information not only from subjects in whom the annual interval of the occurrence of a certain event is known, but also from subjects with missing examinations and from those who have been examined only before or after the occurrence of a certain event.

The cumulative percentages have been calculated from the raw figures of the probit analysis (Table 2).

RESULTS

The timing of various events of growth in height

The means and ranges of the ages at the occurrence of the various events of adolescent growth are given in Table 1 and Fig. 2. The cumulative percentage of children who have attained a certain event in each age interval is given in Table 2. All the events occurred later in boys, the difference between the sexes being between 1.6 and 2.2. years.

The beginning of the pubertal spurt

A marked continuous rise in growth rate from MINIMUM up to PHV (i.e. MINIMUM, START and ONSET coincided) was recorded in 42 out of 81 girls (51.9 %) and 23 out of 103 boys (22.3 %), the difference between the sexes in coinciding events being statistically significant ($chi^2 = 15.96$, $p < 0.001$). In 19 out of 81 girls (23.5 %) and 41 out of 103 boys (39.8 %) there was a break in the increase of growth rate after the MINIMUM. This difference between the sexes is also statistically significant ($chi^2 = 5.52$, $p < 0.025$). The difference in time between the occurrence of MINIMUM and ONSET was up to five years in both sexes, while the corresponding difference between START and ONSET was up to three years in boys and two years in girls.

Late adolescent growth

In 58 out of 70 girls (82.9 %) and 77 out of 88 boys (86.5 %) linear growth continued after the interval, when the annual increment was less than 10 mm for the first time, i.e. D-10 and D-zero did not coincide in these subjects. In 23 out of 70 girls (32.9 %) and 16 out of 89 boys (18.0) the growth rate increased again after the annual growth rate of less than 5 mm was recorded for the first time, i.e. D-5 and D-zero did not coincide in these subjects. The latter sex difference is statistically significant ($chi^2 = 4.69$, $p < 0.05$).

However it should be observed that after the age of eighteen years the examinations were not made annually. Because of this the occurrence of the events during the adolescent deceleration could not be established strictly according to the definitions given in Figure 1 in all subjects (Table 3). When making the inter- and extrapolations additional information

Table 3. *Number and percentage of inter- and extrapolated events during the adolescent deceleration of growth in height in girls and boys*

Growth event	Sex	Total number	Interpolated		Extrapolated	
			n	%	n	%
D-20	G	80	0	0.0	3	3.8
	B	103	8	7.7	7	6.8
D-10	G	77	0	0.0	2	2.6
	B	93	25	26.9	4	4.3
D-5	G	75	3	4.0	4	5.3
	B	90	45	50.0	9	10.0
D-zero	G	70	14	20.0	1	1.4
	B	89	52	58.4	10	11.2

Table 4. *The duration of various periods of adolescent growth*

Growth period	Sex	Number	Mean	S.D	Skew-ness[a]	Kurto-sis[a]	Range	Sex-diff.[b]
Adolescent period (ONSET - D-zero)	G	70	7.62	1.23	0.42	3.39	5.0 – 11.0	0.43*
	B	89	7.19	1.04	0.79	3.27	5.3 – 10.0	
Pubertal spurt (ONSET - D-20)	G	80	4.73	0.95	0.21	2.82	2.8 – 7.0	-0.18
	B	103	4.91	0.82	0.09	3.03	2.8 – 8.0	
Acceleration period of the spurt (ONSET - PHV)	G	81	1.94	0.83	0.65	2.95	1.0 – 4.0	-0.02
	B	104	1.96	0.76	0.86	4.69	1.0 – 5.0	
Deceleration period of the spurt (PHV - D-20)	G	80	2.78	0.64	0.08	3.62	1.0 – 4.8	-0.16
	B	103	2.94	0.58	-0.07	2.73	1.8 – 4.0	
Postpubertal period (D-20 – D-zero)	G	70	2.84	1.12	0.22	2.35	0.5 – 5.2	0.58***
	B	89	2.26	0.76	0.05	2.48	0.5 – 4.0	

a The values of skewness should be within ± 0.6 and of kurtosis within 2.2 – 4.4 for $p > 0.01$
b Significance of the value marked *$p < 0.05$; *** $p < 0.001$

were taken from the growth curves of other body measurements as well as from the skeletal and pubertal development.

The duration of adolescent growth

The period of adolescent growth was abritrarily divided into three parts (Table 4):

1. The acceleration period of the pubertal spurt
2. The deceleration period of the pubertal spurt
3. The postpubertal period.

Owing to methodological considerations which will be further discussed below (see Discussion), ONSET was defined as the beginning of the pubertal spurt. PHV will represent the inflection point between acceleration and deceleration. In all subjects except four girls and four boys there was a continous marked decrease in growth rate from PHV to at least an annual increment of 20 mm (= D-20). Below this level of growth rate there was a varying individual pattern in the incremental curve. Due to this finding D-20 was chosen to represent the end of the pubertal spurt and consequently also the beginning of the postpubertal period.

Table 5. *The timing of the pubertal spurt in height in different investigations*

	Age at the beginning of the spurt	Age at peak height velocity	Age at the end of the spurt
Girls			
Present study	10.04	11.98	14.82
Bowden (4)	9.99	11.67	12.88
Hunter (11)	10.41	11.80	13.04
Largo et al. (15)	9.6	12.2	13.5
Preece and Baines (17)	8.96	11.87	–
Tanner et al. (24)	10.30	11.89	–
Boys			
Present study	12.08	14.07	17.05
Bowden (4)	12.00	13.91	15.42
Hunter (11)	12.79	14.11	15.45
Largo et al. (15)	11.0	13.9	15.5
Preece and Baines (17)	10.71	14.17	–
Tanner et al. (24)	12.05	13.91	–

The end of the postpubertal period was represented by D-zero.

The mean duration of the adolescent period (ONSET - D-zero) was 7.6 years in girls and 7.2 years in boys (Table 4). The duration of the adolescent period was significantly longer in girls, owing to a longer post-pubertal period (D-20 - D-zero). This period was 2.3 years and 2.8 years in boys and girls, respectively. There was no significant difference between the sexes in the duration of the pubertal spurt (ONSET - D-20), being 4.7 years in girls and 4.9 years in boys.

DISCUSSION

The beginning of the pubertal growth spurt (ONSET)

By definition, the adolescent growth period starts when the prepubertal deceleration changes into the adolescent acceleration. Shuttleworth (20) stated that it is difficult to establish this inflection point in time, whereas this can be done with the level of growth from which the acceleration phase is initiated. This is due to the fact that the prepubertal growth curve more or less flattens out in many individuals. Consequently, errors of measurement and/or transient fluctuations of growth rate may make the location in time of the prepubertal minimum point (MINIMUM) less reliable.

In agreement with this a marked continuous increase in growth rate directly from the smallest annual increment up to PHV (coincidence of MINIMUM, START and ONSET) was observed in only half of the girls and one fifth of the boys in the present study. In the other children the lowest increment was registered up to five years before the onset of the pubertal spurt.

Furthermore, in one fourth of the girls and one third of the boys there was

Table 6. *Age at the occurrence of specified growth rates during late adolescent growth*

Growth rate	Sex	Present study	Fels' study (19)
10 mm per year	G	15.8	15.5
	B	17.9	17.5
5 mm per year	G	16.7	–
	B	18.8	–
Zero growth[a]	G	17.5	18.5
	B	19.2	19.5

[a]D-zero in present study and endpoint in the Fels' study

a break in the increase of the growth rate from the smallest recorded annual increment up to PHV (i.e. MINIMUM and START did not coincide). It is therefore probable that in the latter children the recorded minimum point does not represent the theoretical inflection point between the prepubertal deceleration and the pubertal acceleration. In some of these children the break in the increase of growth rate may represent a separate pattern of growth and is not due to errors of measurement or/and transient fluctuations of growth rate. Accordingly, in comparison with the estimation of the prepubertal minimum (MINIMUM) the onset point (ONSET) will give a more reliable estimate of the point of time and the level of growth rate from which the pubertal acceleration is initiated.

Comparison with other investigations

The timing of the pubertal spurt in various studies (4, 11, 15, 17, 24) is compared in Table 5. PHV occurs at about the same age in these studies, the range being 0.5 years in girls and 0.3 years in boys. The range of the reported mean ages of the beginning of the growth spurt is greater, being 1.3 years in girls and 2.1 years in boys.

The onset of the pubertal growth spurt (ONSET)

The mean ages at the beginning of the spurt of the present study are in both sexes about the same as those reported by Bowden (4) who also used a method of visual inspection of the incremental curve to define the beginning of the spurt. Lower ages were reported by Largo et al. (15) and Preece & Baines (17) both of whom used a mathematical approach. Tanner et al. (24) found mean ages of the beginning of the growth spurt similar to those of the present study when making a visual estimation of the "take-off point" in the graphically smoothed velocity curves in their mathematical model. Hunter (11) reported the highest mean ages. This is to be expected, since he used the method of Stolz & Stolz (21) to define the pubertal growth period. In their method the onset of the spurt is defined in relation to the average growth rate during a five-year period around PHV and is not related to the inflection point representing the change from the prepubertal deceleration to the pubertal acceleration. In the methods of Largo et al. (15) and Preece & Baines (17) the onset represents this theoretical inflection point. In our approach we have deliberately chosen a later onset point, since the estimation in time of the theoretical inflection point is less reliable when a graphical approach is used. Furthermore, it may be argued that from a clinical point of view a later onset point may be more relevant in some instances. Certain orthodontic measures may be postponed until the acceleration of growth has definitely begun.

Peak height velocity (PHV)

In 18.5 % (15 out of 81) of the girls and 2.0 % (3 out of 102) of the boys the occurrence of PHV could not be estimated by visual inspection of the incremental curve based on measurements at even ages, owing to the existence of a flat and /or double peak. By using information from the measurements taken every three months, it was possible to establish the age at PHV in all cases. Shuttleworth (20) found that 1.6 % of the children in his study failed to show "a period of maximum growth which is definitely localized in terms of chronological age". Largo et al. (15) reported that the growth rate accelerated less than 20 mm during the acceleration phase of the pubertal period in 33 % of the girls and 2 % of the boys (in the present study 28 % and 3 % respectively) and have stated that such an acceleration is "not discernible clinically" (22).

The end of the pubertal growth spurt (END)

According to Stolz & Stolz (21) whose method Hunter (11) has used (see above) the pubertal spurt ends at the first examination with an increment below the average growth rate during a five-year period centered around PHV. Largo et al. (15) have defined the end of the spurt as the age, after PHV has been attained, when the growth rate has dropped again to the minimum prepubertal velocity. Bowden (4) has calculated the mean velocity during a period from the age of five years to one year before the attainment of PHV and has defined the end as the first examination after the growth rate had dropped below this mean rate.

In the present study the end of the pubertal spurt has been defined as the first annual increment below 20 mm (D-20), since there was a continuous marked decrease in the growth rate until that level in practically all subjects. In comparison with the other investigations (4, 11, 15, 17, 24) this will represent a lower growth rate, thus giving a higher mean age at the end of the spurt (Table 5). However, we believe that in clinical practice the period of intensive growth may be said to continue until that level of growth rate.

The termination of growth (D-10, D-5, D-0)

As the growth rate decreases the assessment of growth events will become more difficult, since the relative influence of measuring errors increases. Accordingly, it will be impossible to determine more precisely when growth in body height ceases (19). The problem will be further enhanched if data collection has not continued into adulthood (i.e. for late maturers up to the age of 20–30 years) or if the examinations have been performed at wide intervals. Various suggestions have been put forward as to how to estimate adult height and the age when it is attained: the height at a certain age (1); the age when the growth rate is less than a given value for the first time (5, 19, 24); the age at the beginning or the end of a fixed period during which increments at each examination have not exceeded a given value (4, 15, 19); and a mathematical approach (19).

In the present study three events during the termination of growth have been defined (D-10, D-5 and D-zero; Figure 1). In Table 6 the timing of these events has been compared with the corresponding findings in the Fels' study (19) in which PHV occurred at about the same ages as in the present study, the age difference being about 0.3 years in both sexes. The attainment of a growth rate of less than 10 mm occurred at similar ages in both studies. A comparison of the age at which growth has terminated (D-zero) is less valid, since different operational criteria have been used. In the present study the occurrence of D-5 and D-zero did not coincide in about one third of the girls and one fifth of the boys. This means that in these individuals the growth rate increased again after an annual growth rate of less than 5 mm had been recorded for the first time (Figure 1), Since the increments are small during this age period, some of the observations may be artefacts due to errors of measurement and/or fluctuations in the growth rate because of illness etc. However, an analysis of the health records of these individuals has not given any indications that concomitant illnesses have influenced the growth rate. Furthermore, in about 10% of both girls and boys the annual growth rate increased from less than 5 mm per year to at least 10 mm per year. This is definitely a significant increase in growth rate. Other investigators have also found a similar late postpubertal growth (10).

As stated above, various definitions of terminated growth have been used in relevant literature. Which definition should be used must depend on the clinical problem to be solved. For example, when predicting adult height it is sufficient to use statistical equations, which have been calculated for "adult height", corresponding to individual body heights attained at growth rates comparable to those of D-10 (less than 10 mm per year for the first time) and D-5 (less than 5 mm per year), at which more than 99 % of the adult height has been attained in most individuals. However, in orthodontics, even a small growth activity, i.e. the residual growth after D-10 and D-5, is of importance (3, 18). When evaluating orthodontic treatment, the chosen endpoint of growth should represent a more definite termination of growth. D-zero will satisfy this requirement.

Sex differences of adolescent growth

The pubertal growth spurt occurs earlier in girls than in boys, but there is no difference between the sexes in the duration of the spurt (Table 4). The sex difference for age at the occurrence of the various events on the incremental curve is about two years with the exception of the prepubertal minimum (MINIMUM) and the termination of growth (D-zero) (Table 1). The difference between the sexes is less for the latter two events. As concerns the age at MINIMUM this is to be expected, since the growth rate did not increase continously from MINIMUM up to PHV in more boys than girls. In such subjects the prepubertal minimum will occur earlier in relation to the theoretical inflection point than in subjects with a continous increase. The smaller sex difference of the age at the termination of growth (D-zero) is due to a longer postpubertal period in girls (Table 4). A diminishing difference between the sexes towards the end of the adolescent period has also been found when analysing the maturation of some bones of the hands and wrists (12). Accordingly, the increase in height during the postpubertal period ougt to be greater in girls than in boys. This has also been found in the present study (unpublished data) and in a Swiss longitudinal growth study (15).

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