Body Density of Japanese Children from Age 10 to 18 Measured by the Underwater Weighing Method

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Children's body density has been reported to differ from that of adults mainly due to the chemical immaturation of fat-free mass. The present study was conducted to fully examine the body density of Japanese children (268 males and 332 females) from 10 years of age (4th grade in primary school) to 18 years of age (3rd grade in high school) in Nagasaki Prefecture, who were categorized by one-year age interval. Their body density was measured by an underwater weighing method to provide the basic data for estimation of body composition.

The following results were obtained:

1. The subjects were taller than the national average at younger ages in both boys (11 years) and girls (10 and 11 years), though no difference was observed in other age groups.
2. The body densities in boys showed proportional relationship with age, whereas those in girls tended to decrease with age.
3. Combining the results of the present study and other reports for Japanese and foreign subjects, body densities in boys increased in a linear fashion with aging and those in girls showed a slight decrement with aging. These tendencies were well explained by increment of fat mass in girls and increment of fat-free mass in boys.
4. A review of literature demonstrated that the equations used in estimation of body composition from density in children and adolescents should differ from those in adults. It is thus suggested that new equations specific to these age groups should be formulated.

Key words: body density, underwater weighing method, children and adolescents, body composition

I Introduction

Body is composed of fat and fat-free mass. Fatness has been the main interest for health-related areas such as nutrition,

school health, physical fitness, preventive medicine, and so on (Behnke and Wilmore, 1974; Lohman, 1989).

To assess body composition, which is generally shown as the proportion of fat to

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Table 1 Physical characteristics and body density for each age in boys

Age Category		10	11	12	13	14	15	16	17	18
N		4	21	47	46	30	35	36	29	20
Age	Mean	10.7	11.7	12.4	13.5	14.4	15.4	16.5	17.5	18.4
	S.D.	0.14	0.22	0.26	0.28	0.27	0.23	0.31	0.36	0.41
Height	Mean	134.9	144.4	148.8	158.6	163.4	166.8	167.1	169.8	169.9
	S.D.	7.0	6.5	6.2	6.7	6.8	5.5	5.8	4.0	5.7
Weight	Mean	30.7	36.4	39.2	45.9	50.5	55.1	56.5	60.7	59.9
	S.D.	4.2	5.9	6.1	6.9	9.2	9.3	9.4	9.3	6.5
BMI	Mean	16.9	17.4	17.6	18.2	18.9	19.8	20.2	21	20.8
	S.D.	1.7	2.0	1.9	1.6	3.0	2.9	3.0	2.9	2.4
Body Density	Mean	1.0581	1.0530	1.0563	1.0637	1.0695	1.0646	1.0644	1.0647	1.0665
	S.D.	0.0108	0.0147	0.0147	0.0121	0.0134	0.0140	0.0168	0.0141	0.0158

Table 2 Physical characteristics and body density for each age in girls

Age Category		10	11	12	13	14	15	16	17	18
N		22	44	40	30	38	52	30	43	33
Age	Mean	10.6	11.7	12.7	13.5	14.7	15.7	16.6	17.7	18.4
	S.D.	0.19	0.18	0.18	0.31	0.14	0.18	0.25	0.22	0.28
Height	Mean	139.1	145.8	150.6	155.7	155.8	157.2	158.4	157.2	157.8
	S.D.	6.5	7.2	5.9	4.4	5.6	5.4	6.0	5.0	5.7
Weight	Mean	31.5	36.8	43.7	46	48.5	48.7	51.9	50.2	52.9
	S.D.	4.5	6.5	6.4	6.8	6.2	5.9	7.2	6.6	6.6
BMI	Mean	16.2	17.2	19.2	18.9	20	19.7	20.7	20.3	21.2
	S.D.	1.3	1.9	3.7	2.2	2.4	2.0	2.4	2.0	2.1
Body Density	Mean	1.0482	1.0518	1.0482	1.0530	1.0466	1.0461	1.0415	1.0423	1.0433
	S.D.	0.0101	0.0129	0.0174	0.0124	0.0137	0.0132	0.0137	0.0104	0.0105

body mass, several equations have been developed. It is well known that Siri's (1956) and Brozek's (1963) formulae are widely accepted for this purpose (Martin and Drinkwater, 1991). The fat portion is calculated from the measured body density and two constants of fat and fat-free densities. Thus, two important processes are required for the study of body composition. One is to assess body density and the other is to formulate the equation from which body composition is estimated.

The body density is calculated as a proportion of mass to volume. While body mass (body weight) is easily measured, body volume is rather difficult to measure. The underwater weighing method uses Archimedes' principle and is considered to be one of the most accurate and valid techniques for estimating body composition (Katch and Michael, 1963). This method has been virtually synonymous with densitometry, which is the procedure of estimating body composition (Going, 1996).

Fig. 1 Scattergram of body density with aging for boys.

Reviewing the methods of densitometry, Going (1996) pointed out that although density can be estimated with acceptable precision and accuracy in most groups, the assumption of fat-free composition may not be valid for certain individuals and groups. For example, children are reported to be chemically immature and the density of their fat-free mass should be less than that of adult.

If a difference of body density exists between children and adults, the prediction equation for the body composition for adults cannot be used for children. To solve these problems and to provide the basic information on the body density of Japanese children, the present study was conducted by scrutinizing children aged 10–18 from

their individual age groups.

II Methods

Density was measured by the method of underwater weighing for all data in this research.

1) Subjects

A total of 600 children (268 male and 332 female), 10 years of age (4th grader in primary school) to 18 years of age (senior in high school), served as subjects in this research. The number of participants of each sex and age is shown in Table 1. They were all residents in Nagasaki Prefecture. An informed consent form was filled out by their parents and themselves before the experiment.

Prior to under-water immersion, height

Fig. 2 Scattergram of body density with aging for girls.

and weight were measured for each subject.

2) Procedure

The subjects completed their meals at least two hours before the experiment and defecated and urinated immediately before the measurement of body density.

Underwater weighing was conducted in a cylindrical stainless-steel tank with a diameter of 120 cm and a depth of 160 cm. Each subject wore a swimming suit and was instructed to sit on a metal seat in the tank and to exhale completely prior to the immersion of their whole bodies. The seat was suspended from a force transducer (MINEBIA-U3B1-20B). Underwater weight was measured by a recorder (RIKADENKI WE-21) via an amplifier (NIHONKODEN RM-45). Measurements were repeated five

times and the greatest value was determined to be his/her assessment value. The water temperature was recorded for calculation of water density.

Residual volume was calculated from the measurements of tidal volume, inspiratory reserve volume, expiratory reserve volume and functional residual capacity, all of which were obtained by a helium spirometer (FUKUDA COMF100). This measurement was conducted after each underwater trial in the seated position, which is the same posture as was used in water in the next room.

3) Equation

Body density (BD) was assessed by the following formula:

BD

$$= \frac{\text{Body weight in air} - (\text{BW in air} - \text{BW in water})}{\text{Density of water}} - \text{Res. vol.}$$

Table 3 Combined data of present study and other reports on body density in boys

Age	N	Body Density	Researcher
9.9	42	1.049±0.017	Slaughter, et al(1984)
10	95	1.056±0.013	Wilmore et al(1974)
10.1	195	1.0556±0.0101	Ogawa (1985)
10.7	4	1.0581±0.0108	Oresent study
10.7	13	1.047±0.005	Sady et al(1984)
11	15	1.0617±0.0079	Hachisuka et al(1970)
11.2	23	1.0532±0.01439	Sady et al(1982)
11.4	51	1.0467±0.0107	Kitagawa et al(1988)
11.5	47	1.0616±0.0162	Satoh(1978)
11.7	21	1.0530±0.0147	Present study
12	10	1.0580±0.0124	Ikai et al(1969)
12	14	1.0633±0.0060	Hachisuka et al(1970)
12.1	79	1.046±0.018	Harsha et al(1978)
12.4	47	1.0563±0.0147	Present study
12.5	23	1.056±0.019	Slaughter et al(1984)
13	13	1.0607±0.0134	Ikai et al(1969)
13	13	1.0655±0.0068	Hachisuka et al(1970)
13.1	49	1.055±0.020	Harsha et al(1978)
13.5	46	1.0637±0.0121	Present study
14	9	1.0727±0.0050	Ikai et al(1969)
14	7	1.0694±0.0046	Hachisuka et al(1970)
14.4	30	1.0695±0.0134	Present study
15	19	1.0743±0.020	Novak(1963) (median age)
15	10	1.0693±0.0077	Ikai et al(1969)
15	9	1.0719±0.0069	Hachisuka et al(1979)
15.4	35	1.0646±0.0140	Present study
15.5	34	1.061±0.015	Boileau et al(1984) (on white)
15.5	18	1.071±0.015	Boileau et al(1984) (on black)
16	8	1.0677±0.0050	Ikai et al(1969)
16	9	1.0736±0.0071	Hachisuka et al(1970)
16.5	36	1.0644±0.0168	Present study
17	17	1.0743±0.030	Novak(1963) (median age)
17	9	1.0669±0.0109	Ikai et al(1969)
17	9	1.0722±0.0082	Hachisuka et al(1979)
17.5	29	1.0647±0.0141	Present study
18	10	1.0693±0.0077	Ikai et al(1969)
18	10	1.0719±0.0090	Hachisuka et al(1970)
18.4	20	1.0665±0.0158	Present study

Table 4 Combined data of present study and other reports on body density in girls

Age	N	Body Density	Researcher
9.9	20	1.036±0.017	Slaughter (1984)
10	172	1.0526±0.0096	Ogawa (1985)
10.6	22	1.0482±0.0101	Present study
11.2	39	1.0408±0.011	Kitagawa (1988)
11.5	49	1.0531±0.0097	Satoh (1978)
11.6	29	1.035±0.017	Slaughter (1984)
11.7	44	1.0518±0.0129	Present study
12.5	64	1.033±0.016	Harsha et al(1978)
12.7	40	1.0482±0.0174	Present study
13.5	30	1.0530±0.0124	Present study
14.7	38	1.0466±0.0137	Present study
15.2	58	1.041±0.013	Slaughter(1984)
15.7	52	1.0461±0.0132	Present study
16.6	30	1.0415±0.0137	Present study
17.7	43	1.0423±0.0104	Present study
18.4	33	1.0433±0.0105	Present study

III Results

The means and standard deviations of height, weight, body mass index (BMI), and body density of the subjects for each age and sex are presented in Table 1 (boys) and Table 2 (girls). The younger subjects in both boys (at 11 yrs of age) and girls (10 and 11 yrs of age) were taller than the national average.

To view the relationship between age and body density, scatter grams for boys (Fig. 1) and girls (Fig. 2) were presented. Regression equations were also presented in each figure. The densities found in the boys from the present study were in direct proportion to their ages, while the densities in the girls slightly decreased with their ages.

To compare the present results with other reports the mean body densities in each age category of the present study and ones

Fig. 3 Relationship between age and body density in boys (Each circle denotes the mean of reported BD. Blackened circles represent BD of present study)

reported elsewhere for subjects in same age range are combined in Table 3 (boys) and Table 4 (girls). all densities are obtained by the underwater weighing method. The relationship between body density and age for each sex presented in Tables 3 and 4 is shown graphically in Fig. 3 (boys) and Fig. 4 (girls). The data in the graphs include those from the present study.

The combined data (Fig. 3 and Fig. 4) also show that the densities in boys were still proportional to their ages, while the densities in girls were shown to decrease slightly by the regression equation.

IV Discussion

The subjects were taller than the national average (Monbushou, 1995) at younger ages

both in boys (at 11 yrs of age) and in girls (at 10 and 11 yrs of age). These results might come from the fact that the measurements were taken in the latter half of their age category.

Chumlea et al (1983) reported that there is little or no change in percent body fat for girls from 10 to 18 years, however, their total fat mass increased at an annual rate of 1.14 kg per year. For boys, the percent body fat are observed to decrease annually by 1.15% across the same age range. The decrease in percent body fat for boys were attributed to an increase in fat-free mass. They also reported that the mean increments of percent body fat did not differ significantly between two genders, but the increments in fat mass were signifi-

Fig. 4 Relationship between age and body density in girls (Each circle denotes the mean of reported BD. Blackened circles represent BD of present study)

cantly greater in girls than in boys. On the other hand, the increments in fat-free mass were significantly greater in boys than in girls. These results could very well explain the outcome of the present study, i.e., the increment of body density according to the aging of the boys 10-18 age range (Fig. 1) and the decrements of body density according to aging of girls for the same age range (Fig. 2). Since density is expressed as the proportion of weight to the volume, it is reasonable to judge that the increase of fat mass for girls according to aging resulted in decrement of the body density, while there was an increment of fat-free mass resulting in an increased in body density for boys.

With respect to the adult body density

Ogawa et al. (1979) reviewed the literature and reported that the body density of male students measured by the underwater weighing method is generally around 1.07. Tahara et al. (1995a) measured body densities of 512 adult female subjects (age of 20 s to 50s) by the underwater weighing method. They used the same equipments and the procedure as those of the present study and reported their average density as 1.04125. On the other hand, the average densities of 257 adult males (age of 20s to 50 s) was reported as 1.05874 (Tahara et al., 1995b). These data indicated that the densities in boys and girls in the present study reached at the level of adults with their later ages.

To obtain the fat component of the body, estimating equations have developed and body density is exclusively used for the formula (Pollock et al., 1975).

Laboratory methods for determining body density have been developed for underwater weighing (hydrostatic method), radiographic analysis, potassium 40, and total body water determination (Lohman, 1989). Although several methods can be used to estimate body density, underwater weighing is known to be reliable and valid. However, the underwater weighing method is still not good for mass testing or for use in field studies. For the purpose of conducting field study, the prediction equations from the selected skinfold fat, girth, and diameter measures are used. They are, in fact, predicting body density. The results calculated from field study measurements were examined for their validity from those obtained by the underwater weighing method. The formula calculating body composition from body density uses Archimedes' principle and is expressed as follows;

$$M/D = (FM/D_f) + (FFM/D_{ffm})$$

The body mass (M) is divided into a fat component of mass (FM) and a fat-free component of mass (FFM), with the density of fat (D_f) and fat-free mass (D_{ffm}). The density of human fat, D_f , is reasonably constant at 0.900 g/ml. Although 1.1 g/ml of the fat-free mass density has been widely used as measured from adult cadavers (Brozek et al., 1963; Buskirk, 1961), some researchers pointed out that D_{ffm} is variable (Martin and Drinkwater, 1991). Based on this assumption, predictive formulas for percent fat are obtained by inserting den-

sities of fat and fat-free mass into the following equations:

Siri's formula:

$$\%Fat = ((4.95/D) - 4.50)100$$

Brozek's formula:

$$\%Fat = ((4.570/D) - 4.142)100$$

While Brozek's formula (Brozek et al., 1963) or Siri's formula (Siri, 1956) are established for adults, the use of the same formula for children and adolescents is suggested to be inappropriate (Lohman, 1981; Lohman et al., 1984; Slaughter et al., 1984). Adult body composition equations tend to overestimate the fat content of children, since prepubescent children are chemically immature (Lohman, 1992). Forbes (1962) reported that major changes in body composition occur during the adolescent period. These changes include a decrease in the water fraction of their free-fat mass. There is also an increase in the calcium content of fat-free mass. It became evident that the largest increase in total body calcium occurred between the ages of 11 and 12 years for girls but later for boys (Christiansen et al., 1975). Garn (1970) and Christiansen et al. (1975) reported that there were markedly larger absolute amounts of calcium for boys than for girls.

These findings suggest that body density cannot automatically be applied for the body fat prediction equations in children and adolescents. For these reasons, percent fat was not calculated in the present study. Instead, only the body density was reported, leaving the prediction equation for further investigation.

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〔原 著〕

水中体重法による日本人児童・生徒（10～18歳）の身体密度について

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体組成を求める算定式に身体密度は不可欠である。しかし算定式が確立しているわけではなく、用いる算定式によって同じ身体密度でも体脂肪率が異なることになる。特に児童、生徒の年齢では、除脂肪組織の比重が成人より小さいという報告もあり、そのまま成人の算定式にあてはめると問題の生じる可能性がある。そこで本研究では身体組成算定の基礎になる身体密度に関する問題を検討するための試みとして身体密度を年齢別にもとめ詳細に検討した。

身体密度の測定は水中秤量法によった。被験者は10歳（小学4年生）から18歳（高校3年生）の男子268名と女子332名の計600名であった。加齢と身体密度の関係をみると男子では年齢が大きくなるにつれ身体密度が大きくなる傾向にあったが、

女子では逆に身体密度は減少する傾向がみられた。この時期の男子では密度の大きい除脂肪量が増加すること、および女子では逆に密度が小さい脂肪量の増加が顕著なことに起因していることが考えられた。

男子の10歳から18歳までの各年齢間で身体密度の平均値を比較すると最小が1.0530g/ml（11歳）で最大が1.0695g/ml（14歳）であった。女子は最小が1.0415g/ml（16歳）で最大が1.0530g/ml（13歳）であった。

小児期では、除脂肪組織の密度が成人とは異なることや脂肪量と除脂肪量の増加の傾向が男女で異なることなどから、この年代について身体組成を求める推定式を明らかにする必要性が示唆された。

キーワード：身体密度，水中秤量法，児童・生徒，身体組成