

Patterns of bioelectrical impedance vector distribution by body mass index and age: implications for body-composition analysis¹⁻³

Anja Bosy-Westphal, Sandra Danielzik, Ralf-Peter Dörhöfer, Antonio Piccoli, and Manfred J Müller

ABSTRACT

Background: Bioelectrical impedance analysis (BIA) gives resistance (R) and reactance (Xc). R and Xc normalized for body height (H) can be plotted as a bivariate vector (H^2/Xc versus H^2/R). Vector BIA is useful for studying the determinants of BIA results.

Objective: We investigated the effect of age on BIA results and its relevance to body-composition analysis in a large database of impedance vector distributions stratified by age, sex, and body mass index (BMI).

Design: Mean bivariate vector distribution patterns (95% confidence ellipses) were examined in a German population of 15 605 children and adolescents and 213 294 adults. Children and adolescents were divided into 3 age groups with up to 5 BMI categories. In adults, 5 BMI categories were stratified into 7 age groups.

Results: Mean impedance vectors were shorter in children than in adults. The vector distribution pattern was influenced by sex, BMI, and age, with shorter vectors in females than in males and longer vectors with increasing BMI. Consistent with a decrease in body cell mass with increasing age, there was a downward slope in the mean vector with age as a result of a decrease in the H^2/Xc vector component. By contrast, there was no age-dependent increase in the H^2/R vector component. In women of the same BMI at different ages, H^2/R and percentage fat mass tended to decrease with age.

Conclusions: The lack of an age-dependent increase in the H^2/R vector component renders conventional BIA unsuitable for an examination of the age-related increase in body fat mass. By contrast, the increase in the H^2/Xc vector component with advancing age suggests the potential of BIA to depict the age-related decrease in body cell mass. *Am J Clin Nutr* 2005;82:60–8.

KEY WORDS Bioelectrical impedance analysis, resistance, reactance, body mass index, children, adolescents, adults, aging

INTRODUCTION

Vector bioelectrical impedance analysis (BIA, RXc-graph method) is a pattern analysis of direct impedance measurements (resistance, R , and reactance, Xc) plotted as a bivariate vector standardized by the subject's height (ie, expressing R/H and Xc/H in Ω/m). This method was described as a useful tool for monitoring hydration status in renal (1–3) and critical care (4) patients, in the follow-up of obese subjects during weight loss (3), and in infants (5–7). In the clinical setting, the advantages of vector BIA are convincing: no algorithms for conversion of raw impedance data into body-composition compartments are required. Results are therefore not biased by the choice of regression equation, the

accuracy of the criterion method, or the selection criteria of the reference population. Because vector distribution patterns differ between men and women and by race or ethnicity and are dependent on body mass index (BMI) and age, national reference distributions for R and Xc used for body-composition analysis have been stratified accordingly (8, 9).

Vector distribution patterns reveal the determinants of BIA results; ie, the sex- and BMI-dependency of BIA results indicate that equations used for the prediction of body composition from impedance measurements need to be validated separately by sex and BMI classes (9). The age-dependency of vector distribution has not yet been critically viewed with regard to its relevance to body-composition analysis.

The present work aimed to investigate vector distribution patterns according to sex, BMI, and age in a large database of white children and adolescents ($n = 16\,237$) and adults ($n = 214\,294$). We used a modified version of the RXc-graph with the vector components H^2/R and H^2/Xc to analyze the relevance of age-related changes in vector BIA components for the description of age-related changes in body composition.

SUBJECTS AND METHODS

Subjects were recruited from 524 Precon-centers (commercial weight-management facilities) and the Kiel Obesity Prevention Study (KOPS) in Germany. Informed consent was obtained from all volunteers before participation. In case of children, parents provided written informed consent. Data comprising 10 127 girls ($\bar{x} \pm SD$ age: 11.5 ± 3.9 y; range: 6–17 y), 6110 boys (9.5 ± 3.2 y; 6–17 y), 183 982 women (42.5 ± 13.2 y; 18–102 y), and 30 750 men (44.6 ± 13.5 y; 18–100 y) were collected over a period of 14 y from June 1990 to August 2003. Data from 420 girls and 212 boys were omitted because the children's BMI (in

¹ From the Institut für Humanernährung und Lebensmittelkunde, Christian-Albrechts-Universität zu Kiel, Kiel, Germany (AB-W, SD, and MJM); Data Input Company, Darmstadt, Germany (R-PD); and the Department of Medical and Surgical Sciences, University of Padova, Padova, Italy (AP).

² Supported by a grant from Precon, Darmstadt, Germany.

³ Reprints not available. Address correspondence to MJ Müller, Institut für Humanernährung und Lebensmittelkunde, Christian-Albrechts-Universität zu Kiel, Düsternbroker Weg 17, D-24105 Kiel, Germany. E-mail: mmueller@nutrfoodsc.uni-kiel.de.

Received September 14, 2004.

Accepted for publication February 23, 2005.

TABLE 1
Impedance vector components in 183 176 women by BMI and age classes¹

	<i>n</i>	Height	<i>R</i>	<i>Xc</i>	<i>H</i> ² / <i>R</i>	<i>H</i> ² / <i>Xc</i>	<i>r</i>
		<i>m</i>	Ω	Ω	cm^2/Ω	cm^2/Ω	
BMI 18.5–25							
18–19 y	1052	1.68 ± 0.06	624.4 ± 61.7	64.7 ± 8.6	45.71 ± 5.65	444.6 ± 69.4	0.69
20–29 y	8307	1.68 ± 0.06	616.0 ± 60.9	64.3 ± 8.7	46.26 ± 5.64	447.0 ± 71.8	0.71
30–39 y	10162	1.67 ± 0.06	606.1 ± 61.9	63.9 ± 8.5	46.71 ± 5.77	446.9 ± 70.5	0.72
40–49 y	6691	1.66 ± 0.06	601.0 ± 61.2	62.6 ± 8.6	46.21 ± 5.76	447.8 ± 72.8	0.72
50–59 y	3408	1.65 ± 0.06	600.4 ± 60.2	60.2 ± 8.5	45.87 ± 5.59	462.6 ± 76.1	0.69
60–69 y	1106	1.64 ± 0.06	602.0 ± 62.6	57.9 ± 9.3	45.35 ± 5.90	478.1 ± 85.4	0.64
>70 y	276	1.62 ± 0.06	597.3 ± 65.7	53.4 ± 9.9	44.46 ± 6.50	508.1 ± 105.1	0.59
BMI >25–30							
18–19 y	1129	1.67 ± 0.07	577.8 ± 57.8	61.5 ± 8.5	48.92 ± 5.99	464.5 ± 76.3	0.73
20–29 y	11117	1.67 ± 0.06	578.1 ± 56.5	61.6 ± 8.0	48.92 ± 5.98	462.7 ± 73.7	0.72
30–39 y	18824	1.67 ± 0.06	568.3 ± 56.2	61.3 ± 8.0	49.43 ± 6.04	461.8 ± 73.4	0.73
40–49 y	17090	1.65 ± 0.06	562.4 ± 55.3	59.9 ± 8.0	48.91 ± 5.93	463.2 ± 73.5	0.72
50–59 y	13137	1.64 ± 0.06	560.5 ± 55.6	57.5 ± 8.1	48.65 ± 5.96	479.2 ± 78.5	0.70
60–69 y	5649	1.64 ± 0.06	562.4 ± 55.8	55.0 ± 8.2	48.10 ± 5.98	498.4 ± 84.9	0.67
>70 y	1124	1.61 ± 0.06	558.4 ± 60.4	51.3 ± 9.1	47.28 ± 6.50	524.3 ± 102.1	0.69
BMI >30–35							
18–19 y	582	1.67 ± 0.06	544.9 ± 53.2	58.1 ± 7.5	51.95 ± 6.34	491.1 ± 74.4	0.72
20–29 y	6507	1.67 ± 0.07	541.7 ± 53.3	58.5 ± 7.5	51.99 ± 6.61	485.4 ± 80.2	0.73
30–39 y	11506	1.66 ± 0.06	529.9 ± 52.4	57.9 ± 7.6	52.78 ± 6.55	486.8 ± 77.7	0.74
40–49 y	12495	1.65 ± 0.06	521.8 ± 52.7	56.3 ± 7.7	52.47 ± 6.60	491.0 ± 79.7	0.72
50–59 y	11817	1.64 ± 0.06	520.5 ± 53.0	53.8 ± 7.7	52.08 ± 6.59	509.7 ± 86.0	0.71
60–69 y	6305	1.62 ± 0.06	522.4 ± 53.7	51.3 ± 7.8	51.09 ± 6.61	527.4 ± 94.1	0.68
>70 y	1419	1.61 ± 0.06	518.5 ± 58.5	47.9 ± 8.6	50.47 ± 7.20	557.3 ± 111.4	0.73
BMI >35–40							
18–19 y	239	1.68 ± 0.07	506.5 ± 50.1	54.2 ± 7.9	56.11 ± 7.66	530.9 ± 100.6	0.75
20–29 y	2857	1.67 ± 0.07	506.1 ± 52.4	54.9 ± 7.1	55.66 ± 7.39	517.0 ± 86.1	0.75
30–39 y	5064	1.66 ± 0.06	493.2 ± 50.9	53.8 ± 7.1	56.63 ± 7.21	523.6 ± 87.5	0.75
40–49 y	5462	1.64 ± 0.06	484.4 ± 49.2	52.2 ± 7.3	56.33 ± 7.17	528.4 ± 88.9	0.73
50–59 y	5178	1.63 ± 0.07	483.8 ± 50.9	49.8 ± 7.4	55.69 ± 7.43	547.7 ± 97.8	0.72
60–69 y	3090	1.62 ± 0.06	484.2 ± 52.0	47.1 ± 7.8	54.60 ± 7.38	570.6 ± 108.7	0.70
>70 y	685	1.59 ± 0.06	479.0 ± 53.1	44.0 ± 8.3	53.86 ± 7.44	598.9 ± 120.0	0.66
BMI >40–50							
18–19 y	95	1.67 ± 0.07	469.6 ± 47.2	49.7 ± 6.7	60.15 ± 8.04	572.8 ± 97.9	0.80
20–29 y	1306	1.67 ± 0.07	470.5 ± 49.8	50.6 ± 6.7	59.84 ± 7.89	561.4 ± 94.7	0.74
30–39 y	2537	1.66 ± 0.07	456.0 ± 50.7	49.3 ± 7.0	61.33 ± 8.16	572.5 ± 98.3	0.75
40–49 y	2709	1.64 ± 0.07	443.7 ± 50.0	47.2 ± 7.3	61.61 ± 8.79	586.5 ± 110.1	0.76
50–59 y	2280	1.62 ± 0.06	443.4 ± 49.8	45.1 ± 7.3	60.42 ± 8.56	603.1 ± 117.4	0.77
60–69 y	1274	1.61 ± 0.06	440.5 ± 50.7	42.3 ± 7.3	59.60 ± 8.65	631.4 ± 128.6	0.73
>70 y	243	1.58 ± 0.06	443.3 ± 51.0	39.4 ± 7.4	57.21 ± 7.92	659.6 ± 142.4	0.70

¹ BMI is in kg/m². *R*, resistance; *Xc*, reactance; *H*, height; *r*, correlation coefficient between *H*²/*R* and *H*²/*Xc*. ANOVA showed significant interactions between age and BMI categories for both vector components (*H*²/*R* and *H*²/*Xc*).

kg/m²) exceeded the highest age-dependent BMI category. Likewise, we excluded 499 women and 62 men because of underweight (BMI < 18.5) and 761 women and 119 men because of severe obesity (BMI > 50). Thus, the final study population consisted of 15 605 children and adolescents (age range: 6–17 y) and 213 294 adults (age range: 18–102 y) who were examined by a total of 530 trained observers. Training of the investigators followed the same manual. All subjects were white, nonpregnant and nonlactating, and healthy (defined as the absence of a clinical condition that could influence fluid balance, eg, renal, endocrine, or myocardial disease, as ascertained by participant questionnaire). There were no further selection criteria.

Data were acquired between 0700 and 1200. In the case of adults, all subjects were instructed on the importance of fasting overnight before measurement. Fasting was not a precondition for study participation by children. Body weight was measured to

the nearest 0.1 kg and standing height to the nearest 0.5 cm with the subject in underwear and without shoes. BMI (kg/m²) was calculated with weight (kg) and height (m) measurements. A single tetrapolar BIA measurement of resistance (*R*) and reactance (*Xc*) was taken at a fixed frequency of 50 kHz between the right wrist and ankle (standard placement of surface electrodes) with a body impedance analyzer (BIA 2000-S; Data Input, Frankfurt, Germany) while the subjects were in a supine position on a nonconductive surface. (See reference 10 for a detailed description of the measurement procedure.) Mean CVs for within-day and between-day intraindividual measurements by the same observer were <2% for *R* and <3.5% for *Xc* and <1.5% for *R* and <5% for *Xc*, respectively. The study was approved by the Ethical Committee of the Christian-Albrechts-University of Kiel.

TABLE 2Impedance vector components in 30 572 men by BMI and age classes¹

	<i>n</i>	Height	<i>R</i>	<i>Xc</i>	<i>H</i> ² / <i>R</i>	<i>H</i> ² / <i>Xc</i>	<i>r</i>
		<i>m</i>	Ω	Ω	cm^2/Ω	cm^2/Ω	
BMI 18.5–25							
18–19 y	115	1.82 ± 0.07	511.3 ± 53.9	61.0 ± 8.4	65.64 ± 8.46	555.8 ± 95.1	0.70
20–29 y	614	1.82 ± 0.07	510.1 ± 54.8	61.4 ± 7.9	65.51 ± 9.04	547.7 ± 91.3	0.75
30–39 y	639	1.81 ± 0.08	513.6 ± 55.3	69.8 ± 7.7	64.74 ± 8.55	560.9 ± 100.1	0.73
40–49 y	464	1.78 ± 0.07	512.2 ± 53.5	57.8 ± 7.2	62.92 ± 8.13	561.1 ± 91.6	0.72
50–59 y	294	1.77 ± 0.07	507.1 ± 53.0	55.4 ± 7.9	62.54 ± 8.74	578.6 ± 103.4	0.80
60–69 y	218	1.76 ± 0.07	509.7 ± 50.5	51.4 ± 8.1	61.52 ± 7.40	621.6 ± 119.6	0.59
>70 y	86	1.73 ± 0.07	524.3 ± 59.9	46.6 ± 7.8	58.13 ± 7.26	666.2 ± 132.8	0.47
BMI >25–30							
18–19 y	138	1.80 ± 0.08	473.4 ± 52.7	58.5 ± 7.6	69.38 ± 9.39	564.4 ± 88.8	0.78
20–29 y	1360	1.81 ± 0.07	475.0 ± 48.7	58.2 ± 7.3	69.70 ± 9.09	572.8 ± 94.0	0.76
30–39 y	2747	1.80 ± 0.07	472.0 ± 46.7	57.1 ± 7.2	69.65 ± 8.56	579.9 ± 92.5	0.59
40–49 y	2494	1.79 ± 0.07	471.4 ± 49.6	55.2 ± 7.3	68.77 ± 8.93	591.9 ± 100.7	0.74
50–59 y	1994	1.77 ± 0.07	468.0 ± 46.7	52.5 ± 7.3	67.66 ± 8.48	610.0 ± 106.3	0.71
60–69 y	1267	1.75 ± 0.06	469.8 ± 50.0	49.4 ± 7.5	66.15 ± 8.78	637.3 ± 116.8	0.71
>70 y	313	1.73 ± 0.06	470.6 ± 53.6	44.7 ± 8.2	64.83 ± 8.60	696.1 ± 138.9	0.68
BMI >30–35							
18–19 y	115	1.82 ± 0.07	445.7 ± 44.2	53.9 ± 7.2	74.89 ± 9.52	629.3 ± 135.0	0.41
20–29 y	1200	1.81 ± 0.07	448.4 ± 45.3	55.1 ± 6.8	73.52 ± 9.55	603.2 ± 99.7	0.76
30–39 y	2682	1.81 ± 0.07	440.6 ± 45.8	53.5 ± 6.8	74.86 ± 9.48	621.6 ± 103.9	0.75
40–49 y	2809	1.78 ± 0.07	434.3 ± 44.9	51.3 ± 6.7	74.12 ± 9.35	633.2 ± 105.7	0.75
50–59 y	2542	1.77 ± 0.07	432.0 ± 43.8	48.6 ± 6.6	73.02 ± 9.17	656.1 ± 111.7	0.74
60–69 y	1643	1.75 ± 0.07	435.2 ± 46.4	45.9 ± 7.1	70.99 ± 9.26	683.5 ± 129.1	0.71
>70 y	381	1.72 ± 0.06	442.6 ± 47.0	42.5 ± 6.9	67.97 ± 8.98	719.4 ± 141.6	0.70
BMI >35–40							
18–19 y	55	1.81 ± 0.09	423.1 ± 39.2	50.3 ± 4.4	78.46 ± 10.24	659.5 ± 86.6	0.73
20–29 y	518	1.81 ± 0.07	423.2 ± 44.2	51.1 ± 6.6	78.04 ± 10.00	651.4 ± 105.6	0.72
30–39 y	1090	1.80 ± 0.07	411.9 ± 45.2	49.5 ± 6.1	80.01 ± 10.84	668.9 ± 107.6	0.76
40–49 y	1187	1.78 ± 0.07	404.9 ± 43.1	47.0 ± 6.6	79.52 ± 10.83	692.2 ± 124.7	0.77
50–59 y	1060	1.76 ± 0.06	403.5 ± 45.5	44.9 ± 6.8	77.80 ± 10.46	708.6 ± 137.3	0.71
60–69 y	643	1.74 ± 0.07	404.9 ± 45.9	42.2 ± 7.5	75.67 ± 10.35	740.2 ± 152.0	0.72
>70 y	89	1.72 ± 0.07	406.6 ± 48.7	38.5 ± 6.3	73.90 ± 10.53	790.7 ± 147.7	0.66
BMI >40–50							
18–19 y	30	1.81 ± 0.07	412.8 ± 31.1	47.3 ± 4.5	80.11 ± 9.00	702.9 ± 102.6	0.77
20–29 y	196	1.81 ± 0.07	392.9 ± 43.6	46.3 ± 6.0	84.08 ± 11.17	719.9 ± 123.0	0.79
30–39 y	444	1.80 ± 0.07	377.9 ± 44.2	44.2 ± 6.7	87.10 ± 12.44	754.5 ± 145.0	0.78
40–49 y	487	1.78 ± 0.07	372.6 ± 44.6	41.9 ± 6.6	86.74 ± 12.56	781.4 ± 149.0	0.76
50–59 y	417	1.76 ± 0.07	369.1 ± 44.8	39.8 ± 6.7	85.34 ± 12.55	804.2 ± 166.9	0.77
60–69 y	212	1.74 ± 0.06	374.9 ± 45.2	37.7 ± 6.9	81.75 ± 11.66	823.0 ± 186.3	0.67
>70 y	29	1.75 ± 0.08	372.7 ± 39.9	32.9 ± 6.7	82.95 ± 11.98	975.8 ± 276.8	0.81

¹ BMI is in kg/m². *R*, resistance; *Xc*, reactance; *H*, height; *r*, correlation coefficient between *H*²/*R* and *H*²/*Xc*. ANOVA showed significant interactions between age and BMI categories for both vector components (*H*²/*R* and *H*²/*Xc*).

All data are given as means ± SDs. Statistical analyses were performed by using SPSS for WINDOWS 8.0 (SPSS Inc, Chicago, IL). Pearson's correlation coefficients were calculated for relations between *H*²/*R* and *H*²/*Xc*. A *P* value < 0.05 was considered as statistically significant. Differences between age or BMI groups were analyzed by ANOVA with Bonferroni post hoc test. Interactions among age and BMI categories were also investigated by ANOVA.

Confidence ellipses were calculated by using BIVA software (A Piccoli, G Pastori, Department of Medical and Surgical Sciences, University of Padova, Padova, Italy, 2002; available by E-mail: apiccoli@unipd.it). The calculation of confidence limits for mean impedance vectors requires bivariate normal distributions of *H*²/*R* and *H*²/*Xc* and is explained in detail by Piccoli et al (1, 9). Confidence ellipses describe the area in which the mean sex-, BMI-, and age-specific two-dimensional vectors fall within

a 95% probability (1). This implies that graphically nonoverlapping 95% confidence ellipses are significantly different from each other (*P* < 0.05; conterminous with a significant Hotelling's *T*² test; 1).

RESULTS

Study groups were divided into sex, BMI, and age classes as follows: 15 605 children and adolescents were stratified into 3 age groups with up to 5 BMI classes (6–9 y with BMIs of 9–13, >13–15, >15–17, and >17–25; 10–13 y with BMIs of 11–15, >15–20, >20–25, >25–30, and >30–35; and 14–17 y with BMIs of 14–19, >19–25, >25–30, >30–35, and >35–40). In 213 294 adults, 5 BMI categories (normal weight: 18.5–25; overweight: >25–30; and obese: >30–35, >35–40, and >40–50)

TABLE 3
Impedance vector components in 9707 girls and 5898 boys by BMI and age classes¹

	<i>n</i>	Height	<i>R</i>	<i>Xc</i>	H^2/R	H^2/Xc	<i>r</i>
		<i>m</i>	Ω	Ω	cm^2/Ω	cm^2/Ω	
Age 6–9 y							
Girls							
BMI 9–13	72	1.20 ± 0.11	879.4 ± 94.9	78.4 ± 14.9	16.86 ± 4.61	191.5 ± 52.6	0.77
BMI >13–15	853	1.19 ± 0.06	829.5 ± 74.5	74.8 ± 32.1	17.44 ± 2.80	197.2 ± 34.9	0.71
BMI >15–17	1168	1.21 ± 0.08	777.9 ± 71.2	72.0 ± 12.0	19.19 ± 3.60	209.5 ± 40.3	0.65
BMI >17–25	879	1.30 ± 0.14	714.1 ± 79.8	67.8 ± 9.6	24.72 ± 8.02	259.4 ± 75.6	0.91
Boys							
BMI 9–13	39	1.19 ± 0.06	858.2 ± 97.2	72.0 ± 12.7	16.85 ± 2.51	204.1 ± 39.7	0.74
BMI >13–15	860	1.20 ± 0.06	787.8 ± 63.0	69.6 ± 9.4	18.59 ± 2.68	214.4 ± 71.3	0.33
BMI >15–17	1194	1.22 ± 0.07	734.5 ± 66.7	67.1 ± 9.4	20.62 ± 9.35	225.3 ± 44.5	0.27
BMI >17–25	670	1.28 ± 0.11	676.8 ± 70.3	64.5 ± 8.8	25.04 ± 6.55	263.1 ± 62.1	0.84
Age 10–13 y							
Girls							
BMI 11–15	190	1.41 ± 0.07	816.0 ± 78.1	74.4 ± 9.9	24.54 ± 3.57	272.7 ± 55.2	0.74
BMI >15–20	1113	1.44 ± 0.09	733.4 ± 79.1	69.9 ± 9.8	28.86 ± 5.50	304.5 ± 61.5	0.77
BMI >20–25	748	1.53 ± 0.11	653.0 ± 71.5	63.8 ± 8.5	36.64 ± 7.92	376.1 ± 80.7	0.84
BMI >25–30	654	1.59 ± 0.09	586.3 ± 62.8	58.7 ± 7.4	43.92 ± 7.82	439.7 ± 80.4	0.80
BMI >30–35	293	1.63 ± 0.08	538.9 ± 55.1	55.2 ± 7.8	49.75 ± 7.55	490.2 ± 86.6	0.73
Boys							
BMI 11–15	186	1.42 ± 0.06	786.2 ± 72.0	72.1 ± 8.9	25.93 ± 3.84	285.1 ± 51.0	0.78
BMI >15–20	1125	1.44 ± 0.07	701.2 ± 68.0	67.3 ± 8.7	29.91 ± 4.86	313.9 ± 58.0	0.77
BMI >20–25	484	1.51 ± 0.10	636.0 ± 74.2	62.5 ± 7.9	36.60 ± 8.91	372.2 ± 84.9	0.81
BMI >25–30	379	1.57 ± 0.10	576.3 ± 62.0	57.9 ± 6.9	43.61 ± 8.74	433.9 ± 82.6	0.84
BMI >30–35	165	1.63 ± 0.11	527.5 ± 60.8	53.0 ± 6.4	51.27 ± 10.93	508.3 ± 95.0	0.81
Age 14–17 y							
Girls							
BMI 14–19	157	1.68 ± 0.06	697.8 ± 73.4	68.5 ± 10.3	40.78 ± 5.30	420.9 ± 75.3	0.71
BMI >19–25	1138	1.67 ± 0.06	624.4 ± 65.9	64.7 ± 8.5	45.40 ± 5.79	441.3 ± 69.8	0.72
BMI >25–30	1375	1.67 ± 0.06	578.0 ± 57.8	61.3 ± 8.1	48.61 ± 6.15	462.1 ± 73.6	0.71
BMI >30–35	796	1.67 ± 0.07	541.8 ± 53.9	57.1 ± 7.7	52.10 ± 6.55	489.9 ± 79.5	0.73
BMI >35–40	271	1.67 ± 0.07	504.5 ± 54.2	53.7 ± 7.7	55.90 ± 7.94	529.9 ± 92.2	0.75
Boys							
BMI 14–19	34	1.74 ± 0.12	627.4 ± 72.8	62.7 ± 8.1	49.31 ± 9.97	494.1 ± 100.1	0.85
BMI >19–25	167	1.76 ± 0.09	530.6 ± 62.0	59.1 ± 8.5	59.31 ± 10.01	535.7 ± 100.7	0.73
BMI >25–30	252	1.75 ± 0.10	513.8 ± 64.7	55.6 ± 6.8	60.82 ± 12.06	558.8 ± 96.1	0.75
BMI >30–35	249	1.76 ± 0.09	479.4 ± 58.5	52.3 ± 6.9	66.02 ± 11.68	605.0 ± 99.2	0.74
BMI >35–40	94	1.77 ± 0.09	443.6 ± 50.4	48.9 ± 6.4	72.16 ± 11.28	656.0 ± 107.3	0.55

¹ BMI is in kg/m². *R*, resistance; *Xc*, reactance; *H*, height; *r*, correlation coefficient between H^2/R and H^2/Xc . ANOVA showed significant interactions between age and BMI categories for both vector components (H^2/R and H^2/Xc).

were stratified into 7 age groups (18–19, 20–29, 30–39, 40–49, 50–59, 60–69, and >70 y).

Shown in **Tables 1–3** are all the parameters necessary for calculation of the respective confidence or tolerance ellipses in subgroups of women (Table 1), men (Table 2), and children and adolescents (Table 3). The size of the confidence ellipses was influenced by the variability of the vector components and the sample size (smaller ellipses from a greater number of subjects with a similar SD). The shape of both the tolerance and the confidence ellipses was determined by the coefficient of correlation between H^2/R and H^2/Xc (more flat and elongated shape with a higher correlation).

The sex and BMI dependency of the vector distribution patterns within age classes (95% confidence ellipses) for adults is shown in **Figure 1**. Within a BMI and age category, vectors for women were significantly shorter than those for men. With decreasing BMI, there was a progressive shortening of the impedance vectors with a combined decrease of both the H^2/R and the H^2/Xc components, without overlapping of confidence ellipses.

In **Figure 2**, 95% confidence ellipses were plotted for subgroups of children and adolescents. Mean impedance vectors in children were shorter than in adults, and a gradual vector shortening was observed with decreasing age. Sex differences in vector distribution were already apparent in children, although they were less pronounced than in adults. Longer vectors were found in boys than in girls of the same age and BMI group, without a difference in mean vector direction between the sexes.

In **Figure 3**, the age dependency of mean vector placement is apparent as a continuous down-sloping of the mean vector as the result of a decrease in the H^2/Xc component with decreasing age. By contrast, the H^2/R component within each sex and BMI group remained fairly constant with increasing age. In **Figure 4**, 35 795 women were divided into 6 groups of a certain BMI and 6 age ranges. This classification required a large sample size and could therefore not be done in men because of insufficient numbers in individual BMI categories. As shown in Figure 4A, the H^2/R component increased with increasing BMI ($P < 0.05$ for all age groups), whereas there was no consistent change or even a slight

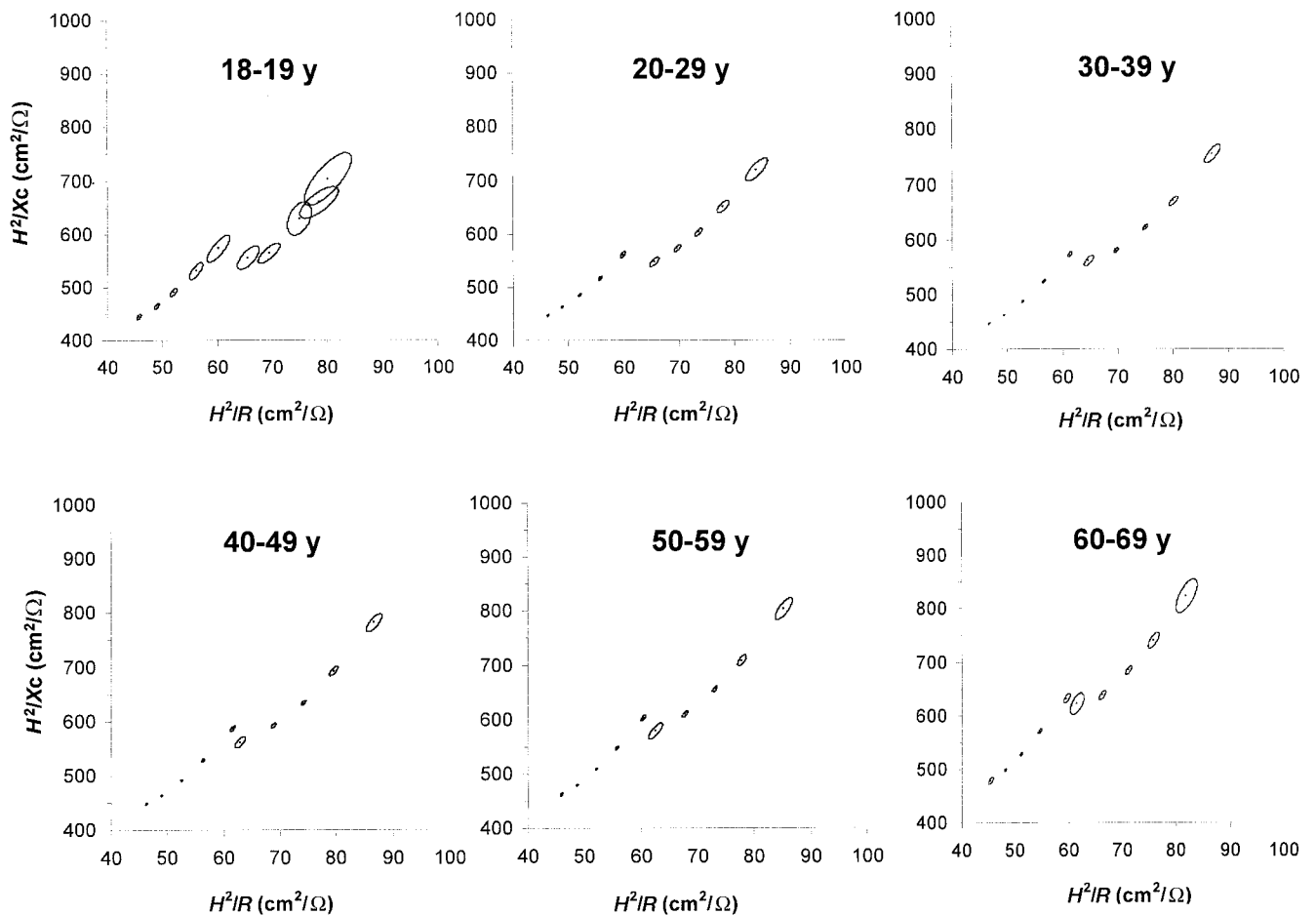


FIGURE 1. Mean impedance vectors with 95% confidence ellipses from subjects stratified by age and BMI groups [BMI (in kg/m²) groups were as follows: 18.5–25, >25–30, >30–35, >35–40, and >40–50]. Within each graph, the ellipse sequence on the left represents women and that on the right represents men. Within each sex, vector shortening is observed with decreasing BMI; ie, the lowest BMI group is represented by the shortest vector and the highest BMI group by the longest vector. *H*, subjects' height; *R*, resistance; *Xc*, reactance. The figure is based on data from 29 674 men and 179 429 women. The numbers of subjects in each BMI and age category are given in Tables 1 and 2. Graphically nonoverlapping 95% confidence ellipses are significantly different from each other, $P < 0.05$ (conterminous with a significant Hotelling's T^2 test).

decrease in the H^2/R component with age. Concomitantly, a prediction equation for body composition that relied on H^2/R , *R*, and weight (11) did not show an age-related increase but rather a slight decrease in percentage fat mass in these women (Figure 4B). By contrast, the H^2/Xc component decreased with increasing BMI and age (Figure 4C), which resulted in a decrease in body cell mass (calculated by the manufacturer's algorithm as total body water/0.732 × phase angle × constant) with age in each BMI group (Figure 4D).

DISCUSSION

We established a large database of impedance vector distributions that exceeds current databases with respect to numbers and BMI and the age ranges covered. We used the database to analyze age-related changes in the vector components H^2/R and H^2/Xc with respect to their effects on body-composition analysis. The main result of our study was the insensitivity of conventional BIA to age-related changes in fat mass.

Applications for vector BIA

The RXc graph is a probability chart that relates an individual vector according to the mean value of the reference population

(9). Sex-, BMI-, and age-specific vector distribution patterns 1) contribute to a better understanding of the factors influencing impedance results, 2) may be used as a healthy reference when individual patient data are analyzed, and 3) serve as a quality criterion for BIA results before the application of algorithms to calculate total body water or fat-free mass. The comparison with reference vector distributions allows one to discriminate between impedance values that 1) lie within the normal range (and may therefore reasonably be converted into total body water or fat mass) or 2) lie outside the respective reference range and thus must not be converted into total body water or fat mass. If an individual vector does not match with its sex-, BMI-, and age-specific reference distribution, this is explained by either a measurement error (eg, false placement of electrodes) or increased or decreased hydration fraction of the fat-free mass (eg, in case of edema or dehydration). Vector BIA thus can be used as a measure of quality control to prevent misinterpretation of impedance readings and thus erroneous predictions of body compartments. A comparison of an individual impedance measurement with a reference database is easily achieved by using tolerance ellipses of the RXc graph. Tolerance ellipses are bivariate percentiles indicating the probability that an individual measurement falls at

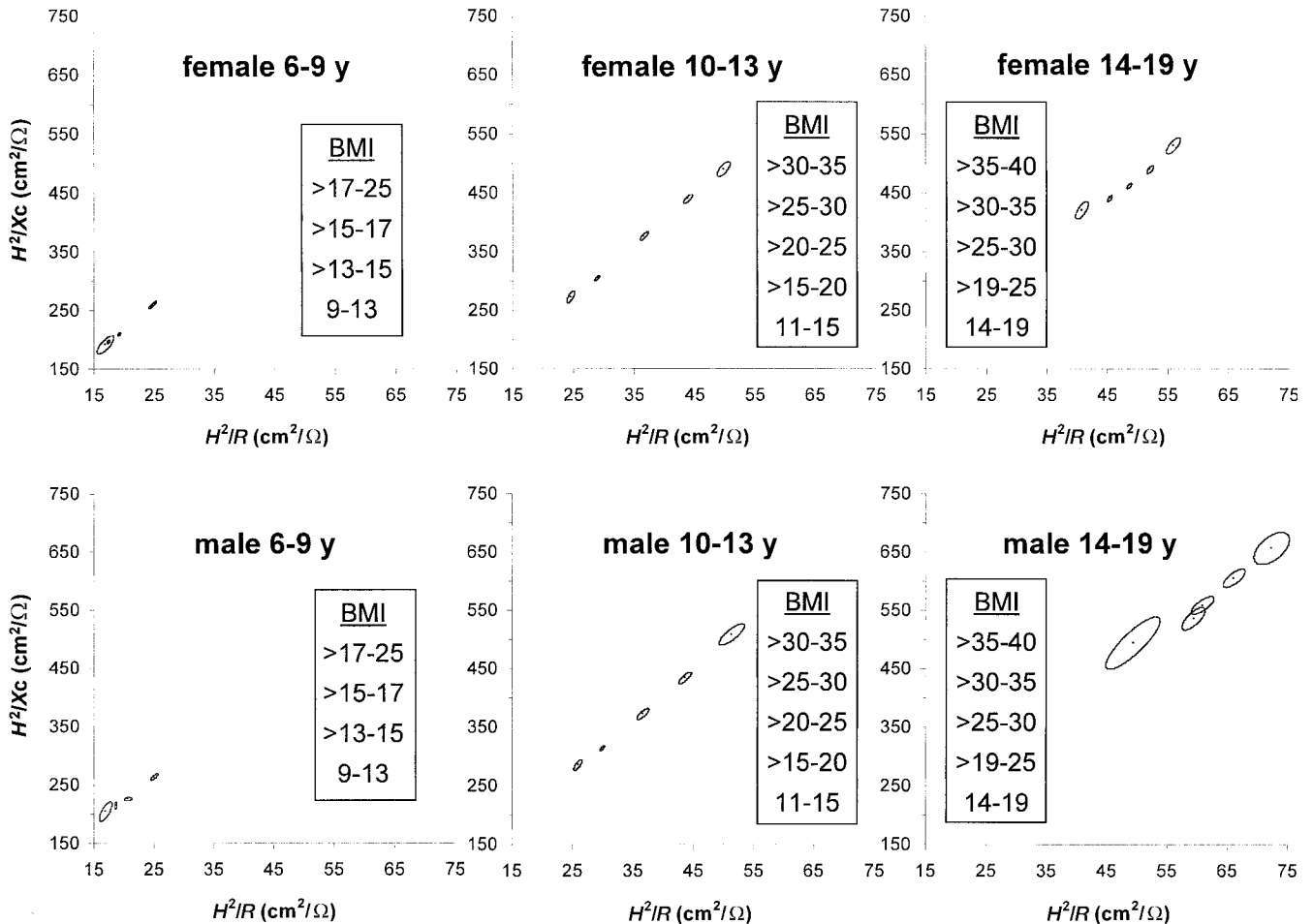


FIGURE 2. Mean impedance vectors with 95% confidence ellipses from children and adolescents (9707 girls and 5898 boys) stratified by sex, age, and BMI groups [BMI groups (in kg/m^2) for each age and sex group are shown on the figure]. The numbers of subjects in each BMI and age category are given in Table 3. H , subjects' height; R , resistance; X_c , reactance. Graphically nonoverlapping 95% confidence ellipses are significantly different from each other, $P < 0.05$ (conterminous with a significant Hotelling's T^2 test).

a given distance from the observed mean vector of the reference population obtained with the same type of impedance analyzer. Tolerance ellipses for the R/H and X_c/H vector components have been reported for sex-specific populations comprising age ranges of 20–69 y and BMI ranges of 19 to <30 (8, 9).

Determinants of vector distribution pattern

Vector length is influenced by the amount of total body water and thus fat-free mass per conductor length. Men and obese subjects had greater fat-free mass per body height along with shorter R/H or longer H^2/R vector components (Figures 1–3; 1–3, 8, 9). By contrast, vector direction (phase angle) is influenced by soft tissue cell mass, which is modified by age in healthy subjects.

Fluid overload and increasing fat mass both lead to progressive vector shortening of the classic R/H and X_c/H vector components (1–3) or vector elongation of our modified vector components H^2/R and H^2/X_c . Discrimination between the 2 conditions is possible, however. With increasing fat mass, the H^2/X_c vector component remains in a fixed sex-dependent relation to the H^2/R component (which is reflected by a constant phase angle with increasing BMI from 25 to 50; Figure 1). By contrast, fluid overload in renal patients was accompanied not only by vector shortening (lowering of the R/H vector component) but also by

vector down-sloping (lowering of phase angle), which could both be reversed after hemodialysis (3). Thus, fluid shifts occur along the major axis of a tolerance ellipse, and the upper and lower poles of the 75% tolerance ellipse represent the biological thresholds for clinically relevant dehydration and fluid overload, respectively (1, 2).

Age-dependency of BIA variables

There is evidence that body composition can be accurately estimated with conventional BIA by using sex-specific regression equations validated against a 4-compartment model in the age range of 12–94 y and BMI range of 14–39 (11). However, the lack of increase in the H^2/R component with increasing age at the same BMI (Figure 4A) might explain the insensitivity of H^2/R to age-related changes in body composition (Figure 4B). The use of a prediction equation for body composition that included both H^2/R and X_c (12) also failed to show an increase in percentage fat mass with age at the same BMI (results not shown). With the use of dual-energy X-ray absorptiometry or a 4-compartment model, mean percentages of body fat mass in 60–79-y-old women and men were shown to be 3% and 5% higher than the percentages in 20–39-y-old subjects of the same BMI (13). The inclusion of age as an independent variable in the regression equation might

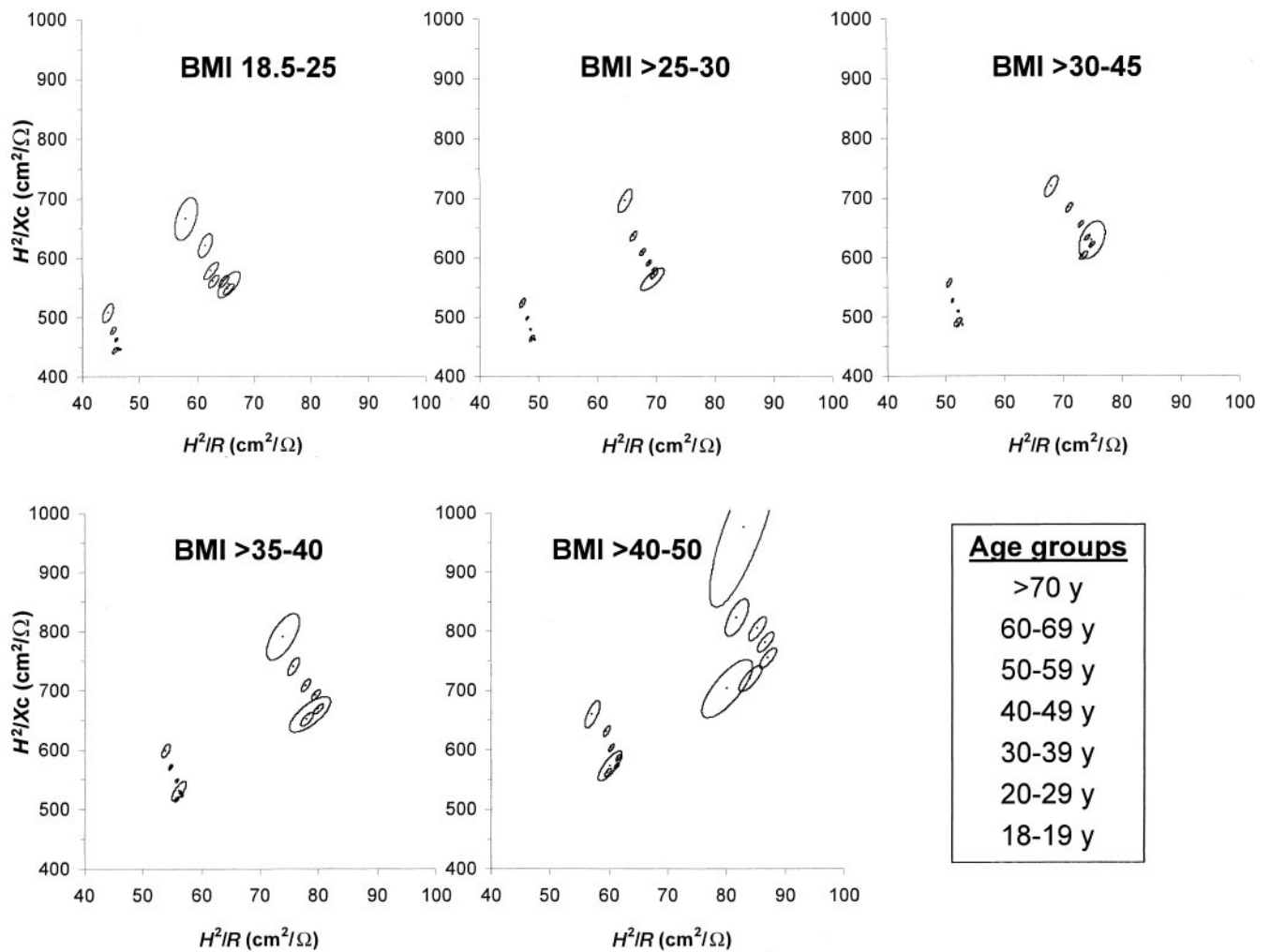


FIGURE 3. Mean impedance vectors with 95% confidence ellipses from subjects (30 572 men and 183 176 women) stratified by BMI (in kg/m²) and age groups. Within each graph, the ellipse sequence on the left represents women and that on the right represents men. Within each sex, vector down-sloping is observed with decreasing age, ie, the youngest group is represented by the shortest vector and the oldest group by the longest vector, respectively. H , subjects' height; R , resistance; Xc , reactance. Graphically nonoverlapping 95% confidence ellipses are significantly different from each other, $P < 0.05$ (conterminous with a significant Hotelling's T^2 test).

therefore be indispensable for a plausible result, ie, an increasing percentage fat mass with age at the same BMI. By contrast, age-related changes in body cell mass might be predictable by conventional BIA by applying prediction equations that include Xc (Figure 4C and D). BIA prediction equations need to be developed and validated in the population under study (14, 15). Some authors suggest that application of BIA to elderly populations requires only uniform validation procedures in the actual study population but not age-specific equations (16).

Study limitations

The limitations of our study derive from the selection criteria of the sample (ie, inquiring rather than examining participants' health status). Thus, we cannot exclude disturbances in fluid balance due to mild cardiac or renal insufficiency. However, because of the large sample size, the low variation in results (SD of H^2/R and H^2/Xc), and the 95% CI, the effect of this bias should be negligible. Additionally, our study lacks independent data on

body-composition analysis (eg, measuring total body water by deuterium dilution) to confirm that individual vector placements solely determined by electrical properties of tissue per human conductor length relate to body composition independently of body shape and geometry. Future studies will be needed to examine this issue. Although we collected a huge database from centers located in different regions of Germany, our data cannot be considered to be representative of the German population. Because weight reduction was the main reason for monitoring nutritional status in the Precon centers, our data on overweight and obese subjects exceed the average of age- and sex-specific German population references (17). However, the aim of our study was to examine the patterns of bioelectrical impedance vector distribution by BMI and age. Thus, we only required a reasonable number of cases in each BMI and age group. The lack of representativeness of our study population as a whole is not contrary to the use of our data as a reference for the sex-, age-, and BMI-dependent distributions of H^2/R and H^2/Xc because 1) we

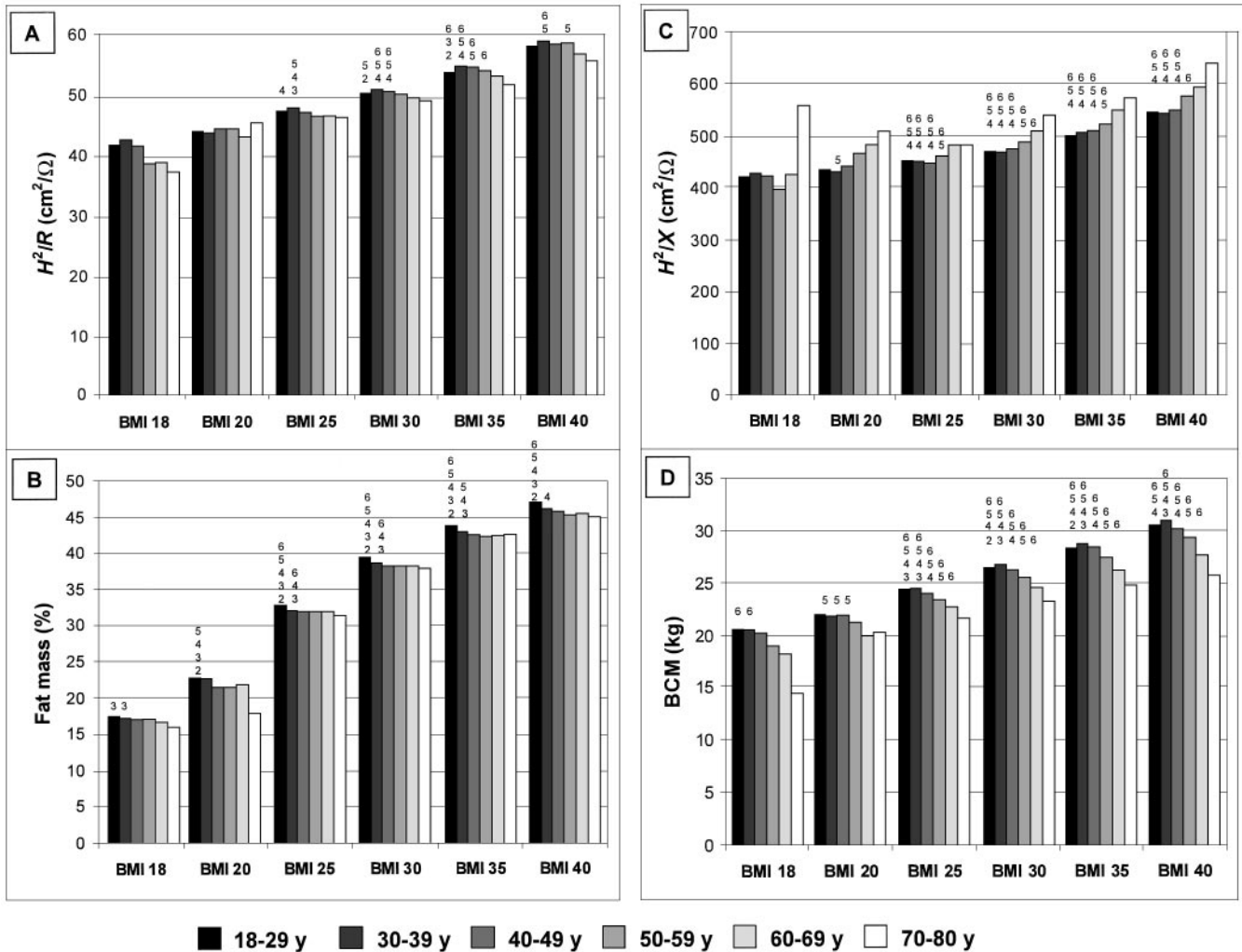


FIGURE 4. (A) Age dependency of the H^2/R vector component at certain BMIs. (B) Age dependency of percentage body fat mass calculated by the formula of Sun et al (11) at certain BMIs. (C) Age dependency of the H^2/Xc vector component at certain BMIs. (D) Age dependency of body cell mass (BCM) calculated by the manufacturer's formula (see Subjects and Methods) at certain BMIs. A total of 35 795 women in 6 BMI (in kg/m^2) categories were divided into 6 age groups as follows: BMI ≥ 17.5 to < 18.5 , $n = 163$ (18–29 y), 67 (30–39 y), 36 (40–49 y), 7 (50–59 y), 8 (60–69 y), and 2 (70–80 y); BMI ≥ 19.5 to < 20.5 , $n = 481$ (18–29 y), 347 (30–39 y), 186 (40–49 y), 75 (50–59 y), 33 (60–69 y), and 5 (70–80 y); BMI ≥ 24.5 to < 25.5 , $n = 2910$ (18–29 y), 3774 (30–39 y), 2770 (40–49 y), 1675 (50–59 y), 580 (60–69 y), and 85 (70–80 y); BMI ≥ 29.5 to < 30.5 , $n = 1881$ (18–29 y), 3219 (30–39 y), 3264 (40–49 y), 2887 (50–59 y), 1428 (60–69 y), and 308 (70–80 y); BMI ≥ 34.5 to < 35.5 , $n = 1004$ (18–29 y), 1519 (30–39 y), 1716 (40–49 y), 1639 (50–59 y), 935 (60–69 y), and 196 (70–80 y); BMI ≥ 39.5 to < 40.5 , $n = 359$ (18–29 y), 596 (30–39 y), 616 (40–49 y), 623 (50–59 y), 330 (60–69 y), and 71 (70–80 y). H , subjects' height; R , resistance; Xc , reactance. ANOVA with Bonferroni post hoc test was used to compare the 6 age groups (1 = 18–29 y, 2 = 30–39 y, 3 = 40–49 y, 4 = 50–59 y, 5 = 60–69 y, and 6 = 70–80 y) within one BMI group. Differences between age groups within BMI groups are indicated by a number ($P < 0.01$). All differences between BMI groups within age groups were significant ($P < 0.05$).

divided our subjects into subgroups according to sex and narrow ranges of BMI and age and 2) each subgroup consisted of a reasonable number of cases.

AB-W and MJM were responsible for the study design; AB-W, SD, and R-PD were responsible for data collection; AB-W and AP were responsible for data analysis; AB-W, AP, and MJM were responsible for discussion of data; and AB-W and MJM were responsible for writing of the manuscript. None of the authors had a conflict of interest.

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