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Construction of Lambda, Mu, Sigma Values for Determining Mid-Upper Arm Circumference *z* Scores in U.S. Children Aged 2 Months Through 18 Years

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Abstract

Background: Mid-upper arm circumference (MUAC) has proven highly predictive of morbidity and mortality associated with malnutrition better, in some cases, than other growth indicators, including body mass index (BMI) *z* scores and weight-for-height *z* scores. A recent consensus statement recommended the inclusion of MUAC and MUAC *z* scores in the nutrition assessment of children in the United States; however, the requisite data to permit *z* score calculations for children aged >5 years have not been published. *Objective:* This investigation was designed to generate lambda mu sigma (LMS) values to permit the calculation of MUAC *z* scores in U.S. children 2 months through 18 years of age. *Design:* Anthropometric data from the Centers for Disease Control and Prevention (CDC) National Health and Nutrition Examination Survey (1999–2012) were used for model development (n = 28,995). Smoothed centiles were constructed and compared with previously described CDC percentiles. Independently collected MUAC data from 2 different U.S. studies were used for external validation (n = 1438). *Statistical Analyses:* Goodness-of-fit was assessed visually and statistically by examining detrended quantile-quantile plots, Q statistics, and the distribution of *z* scores. *Results:* The curves generated in this investigation fit the raw data well with no systematic bias and no sacrifice in fit for children aged <12 months. The curves were consistent with those published by the CDC, and the distribution *z* scores approximated 0 ± 1 in all age groups. *Conclusions:* These LMS values derived in this investigation can be used by clinicians to generate MUAC *z* scores for U.S. children. (*Nutr Clin Pract*. 2017;32:68-76)

Keywords

infant; child; adolescent; nutrition assessment; malnutrition; growth curve

In the global healthcare arena, mid-upper arm circumference (MUAC) has been used for years to screen for childhood malnutrition and determine eligibility for feeding programs. In fact, 2017 marks a decade since the United Nations endorsed MUAC as an independent diagnostic criterion for malnutrition.[1] This measure is favored because it requires no complex or costly equipment and can reliably be performed by community health workers and primary caregivers.[2,3] MUAC has also proven to be highly predictive of morbidity and mortality, performing better, in selected settings, than other growth indicators, including body mass index (BMI) and weight-for-height *z* scores.[4–8]

Although much of the focus on the use and performance characteristics of MUAC has emphasized resource-restricted settings, malnutrition has become an increasing concern in developed countries. In the United States, an estimated 14.5% of households experience some difficulty providing enough food for all their members (ie, are classified as "food insecure"). Approximately 5.7% of households experience severe food insecurity where resource limitations have decreased food intake and disrupted normal eating patterns. In 2012, this translated into 3.9 million households that, at times, were unable to provide adequate nutrition for the children who resided therein and an estimated 3.5% of children who were underweight.[9,10] Importantly, the first line of care for these children are acute care settings such as hospitals and clinics where the availability of simplified nutrition assessment tools, including MUAC, also holds value.[11,12]

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Recently, the Academy of Nutrition and Dietetics (AND) and the American Society for Parenteral and Enteral Nutrition (ASPEN) drafted a consensus statement with recommendations for diagnosing and documenting pediatric malnutrition.[13] Among the indicators of malnutrition recommended by the consensus panel was MUAC. The panel acknowledged that "MUAC has been indicated as a more sensitive prognostic indicator for mortality than weight-for-height parameters in malnourished pediatric patients" and proposed that "MUAC measurements should be part of the full anthropometric assessment in all patients." They further explicitly recommend that "z score, decline in z score, and negative z score" be used to classify and document pediatric malnutrition.[13]

In response to this publication, our institution revised its practice guidelines to integrate MUAC measurements into our standard-of-care nutrition assessments. However, published MUAC reference data available for U.S. children exist in 5th percentile increments (eg, 5th, 10th . . . 95th) without the necessary lambda mu sigma (LMS) values to permit calculation of the MUAC *z* scores.[14–18] These values are available for the global pediatric population from the World Health Organization (WHO) but reflect MUAC in optimally growing children aged ≤5 years.[19] The investigators undertook this study to enable the calculation of MUAC *z* scores in U.S. children aged 2 months through 18 years to facilitate implementation and interpretation of the MUAC data that we and others are now collecting as part of routine practice.

Materials and Methods

Data

Anthropometric data for model development were obtained from the Centers for Disease Control and Prevention (CDC) National Health and Nutrition Examination Survey (NHANES).[20] Data from 1999–2012 were downloaded and data sets for children aged 2 months through 18 years extracted into a separate database. Incomplete data sets and those missing the relevant variables were excluded. MUAC outliers that might be the result of measurement error were identified by application of the modified Thompson τ test. Data were segregated by sex, and mean ($\bar{x}$) and standard deviation (σ) MUAC were calculated at each month of age. The absolute deviation for each data point (δ_i) was determined according to $\delta_i = |x_i - \bar{x}|$. The modified Thompson τ value was calculated according to $\tau = [t_{\alpha/2} * (n - 1)]/[\sqrt{n} * \sqrt{(n - 2 + t_{\alpha/2}^2)}]$, where n is the number of data points and $t_{\alpha/2}$ is the Student *t* value based on a highly conservative α value of 0.001 with n − 2 degrees of freedom. The individual sample with the largest δ_i value was rejected when $\delta_i > \tau * \sigma$ if the deviation was inconsistent with that observed for other anthropometric variables in the individual (namely, weight and height). Subsequently, $\bar{x}$ and σ were recalculated, and recursive elimination was used to remove each successive maximum δ_i value until no additional outliers were identified (ie, $\delta_i \leq \tau * \sigma$).

To avoid introducing imprecision with smaller than recommended sample sizes,[21] selected age groups were pooled in a similar fashion to the groupings used by the CDC in the construction of their growth charts.[22] Data for children aged ≥1 year were pooled in 6-month intervals. Data from children 2–11 months of age were retained in 10 distinct age groups and weighted to limit bias in fitting toward the older age groups. Although the sample sizes were smaller for this infant population, estimates of skewness and kurtosis confirmed a near-normal distribution. Independently collected data from 2 different U.S. studies were used for validation.[23,24] These investigations were reviewed and approved by the Institutional Review Board at Children's Mercy Hospital. Comparisons were also made to earlier published MUAC centiles from the 1971–2010 U.S. surveys along with the 1997–2003 WHO survey.[14–18,25]

Curve Construction

Sex-specific growth curves were created using the LMS method described by Cole and Green[26] and executed with LMSchartmaker Pro v2.54 (Harlow Pronting Limited, Tyne & Wear, UK). The distribution of MUAC values was summarized for each age group using age-specific Box-Cox power transformation of skewness (L), median (M), and coefficient of variation (S). This method transforms the anthropometric data so that they are approximately normally distributed and generates age-specific estimates of LMS as cubic smoothing splines by nonlinear regression. Maximum penalized likelihood estimation was used to optimize the effective degrees of freedom (edf) for M followed by L and then S. Goodness of fit was assessed by examining (1) plots of the fitted centiles overlaid on the empirical centiles; (2) the detrended quantile-quantile (Q-Q) plots of the *z* scores with their corresponding worm plots[27]; (3) the Q statistics for L, M, S, and kurtosis[28]; and (4) the mean and standard deviation of *z* scores at each age group.

Validation

Internal validation was performed by comparing the growth curves generated in our models with the centile data published by the CDC to ensure that the reference curves aligned. External validation was performed with MUAC data obtained as part of a larger anthropometric survey. The newly created LMS values were applied to data from each child in the external validation cohort. Sex- and age-specific

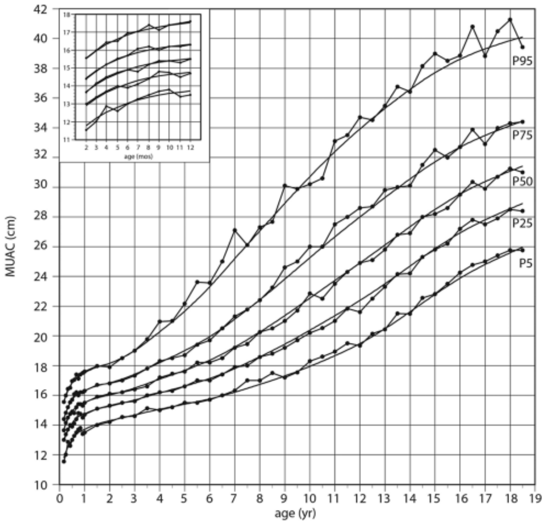

Figure 1. Fitted centiles overlaid on raw centiles for boys aged 2 months through 18 years. The inset provides enhanced resolution for children aged <12 months. MUAC, mid-upper arm circumference.

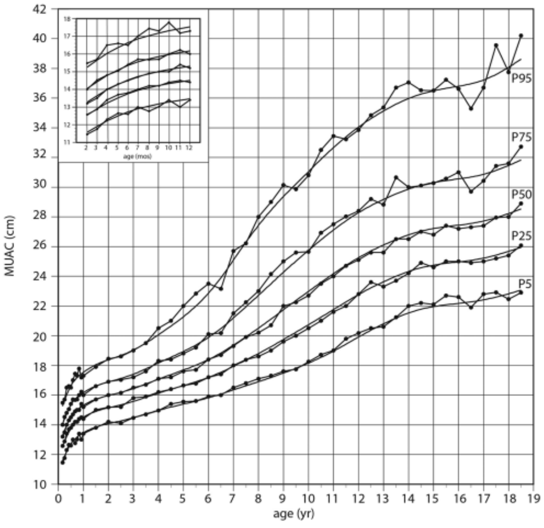

Figure 2. Fitted centiles overlaid on raw centiles for girls aged 2 months through 18 years. The inset provides enhanced resolution for children aged <12 months. MUAC, mid-upper arm circumference.

z scores were calculated according to $z_i = \{[(x_i / M)^L] - 1\}/(LS)$, where z_i represents the individual *z* score, x_i the individual MUAC value, and LMS the lambda, mu, and sigma values, respectively. For cases where L = 0, *z* score was calculated according to $z_i = \ln(x_i / M) / S$. The data were stratified into groups of sufficient sample size, and the mean and standard deviation of *z* scores at each age group were examined as described above. The distribution of weight-for-age *z* scores was also examined for concordance with MUAC *z* scores. Finally, the growth curves were compared with an international data set to contrast U.S. and global norms. All comparisons were performed in SPSS version 23 (SPSS, Inc, an IBM Company, Chicago, IL).

Results

Data from a total of 28,995 children (14,702 males, 14,293 females) were used to develop these models with data from an additional 1438 children (699 males, 739 females) used for external validation. A power transformation was used to define the curve for boys with edf for L/M/S of 7/13/10 (power, 0.6; offset, 0). A rescale option was used to describe the curve for girls with edf values of 7/11/8 for L/M/S. Figures 1 and 2 depict the fitted 5th, 25th, 50th, 75th, and 95th centiles overlaid on the raw centiles. For both sexes, the data fit reasonably well with no sacrifice in fit for children aged <12 months. For nearly all age groups, the detrended Q-Q plots satisfy the desired criteria. The worms pass through the origin, the slope approximates 0, and the curve is not parabolic in shape. However, some curves reflect a bit of residual kurtosis which could not be minimized with the applied fitting strategy. Nevertheless, the distribution of *z* scores highlights a mean near 0 and a standard deviation close to 1 for all age groups. The resulting LMS values for this model are detailed in Table 1.

When the LMS values were applied to the external validation set, the distribution of *z* scores reflected a reasonable fit for all but the youngest age group where the mean ± standard deviation *z* score was −0.97 ± 1.23. Notably, this group of infants was enrolled from our institution's "Ready Set Grow" clinic, which manages undernourished and failure-to-thrive children. An examination of the weight-for age (−0.75 ± 1.41) and length-for-age (−0.63 ± 2.05) *z* score distributions in these infants confirms that these children were, in fact, smaller than average, which explains the observed deviation in MUAC *z* score. The remainder of children represented a mix of hospitalized and nonhospitalized children, which may explain the slight variations observed in the *z* score distributions.

Compared with the empiric centiles reported for the 1971–2007 surveys, MUAC values in both sexes have trended up over the past 4 decades (Figure 3). The changes have occurred primarily in school-aged children and are most pronounced at the upper extreme of MUAC values (ie,

Table 1. Lambda (L), Mu (M), Sigma (S) Values for *z* Score Calculation in Children Aged 2 Months Through 18 Years.

	Males			Females		
Age, mo	L	M	S	L	M	S
2	1.162	13.680	0.083	−0.096	13.276	0.084
3	1.025	14.081	0.081	−0.119	13.635	0.083
4	0.899	14.419	0.080	−0.142	13.979	0.083
5	0.782	14.688	0.079	−0.166	14.279	0.082
6	0.675	14.903	0.078	−0.192	14.526	0.081
7	0.575	15.078	0.077	−0.223	14.722	0.081
8	0.482	15.218	0.076	−0.257	14.879	0.081
9	0.394	15.323	0.075	−0.295	15.009	0.081
10	0.310	15.401	0.075	−0.335	15.120	0.080
11	0.228	15.464	0.075	−0.377	15.219	0.080
12	0.148	15.524	0.075	−0.419	15.308	0.080
13	0.069	15.581	0.074	−0.460	15.390	0.080
14	−0.010	15.637	0.074	−0.500	15.467	0.080
15	−0.087	15.691	0.074	−0.537	15.538	0.080
16	−0.164	15.741	0.074	−0.572	15.603	0.080
17	−0.240	15.786	0.074	−0.605	15.662	0.080
18	−0.315	15.828	0.073	−0.635	15.716	0.080
19	−0.390	15.864	0.073	−0.664	15.767	0.080
20	−0.465	15.897	0.073	−0.691	15.813	0.080
21	−0.538	15.928	0.073	−0.716	15.856	0.080
22	−0.612	15.958	0.073	−0.739	15.896	0.080
23	−0.684	15.988	0.073	−0.760	15.933	0.081
24	−0.756	16.019	0.073	−0.781	15.969	0.081
25	−0.828	16.051	0.073	−0.802	16.005	0.081
26	−0.899	16.086	0.073	−0.823	16.040	0.081
27	−0.969	16.121	0.073	−0.844	16.075	0.081
28	−1.038	16.158	0.073	−0.865	16.110	0.081
29	−1.105	16.196	0.074	−0.886	16.145	0.081
30	−1.171	16.234	0.074	−0.907	16.181	0.081
31	−1.236	16.273	0.075	−0.931	16.221	0.081
32	−1.298	16.313	0.075	−0.955	16.262	0.082
33	−1.359	16.354	0.076	−0.980	16.304	0.082
34	−1.419	16.397	0.076	−1.006	16.347	0.082
35	−1.477	16.441	0.077	−1.033	16.392	0.082
36	−1.532	16.487	0.078	−1.061	16.438	0.083
37	−1.586	16.534	0.078	−1.091	16.486	0.083
38	−1.639	16.583	0.079	−1.121	16.535	0.083
39	−1.689	16.634	0.080	−1.151	16.586	0.083
40	−1.737	16.684	0.081	−1.183	16.637	0.084
41	−1.784	16.736	0.081	−1.215	16.690	0.084
42	−1.828	16.787	0.082	−1.247	16.743	0.085
43	−1.871	16.838	0.083	−1.280	16.797	0.085
44	−1.912	16.889	0.084	−1.313	16.851	0.086
45	−1.950	16.940	0.085	−1.346	16.905	0.086
46	−1.987	16.990	0.086	−1.379	16.960	0.087
47	−2.022	17.039	0.087	−1.411	17.014	0.087
48	−2.055	17.088	0.088	−1.444	17.068	0.088
49	−2.086	17.137	0.089	−1.475	17.121	0.088
50	−2.115	17.185	0.089	−1.506	17.173	0.089
51	−2.142	17.233	0.090	−1.537	17.225	0.089
52	−2.168	17.280	0.091	−1.567	17.277	0.090
53	−2.191	17.328	0.092	−1.596	17.328	0.091
54	−2.213	17.377	0.093	−1.625	17.379	0.091
55	−2.233	17.425	0.094	−1.653	17.429	0.092
56	−2.251	17.474	0.095	−1.681	17.480	0.093
57	−2.268	17.524	0.096	−1.708	17.530	0.093
58	−2.282	17.574	0.097	−1.735	17.581	0.094
59	−2.294	17.626	0.098	−1.761	17.632	0.095
60	−2.305	17.677	0.099	−1.786	17.683	0.096
61	−2.314	17.730	0.100	−1.811	17.735	0.096
62	−2.321	17.784	0.101	−1.835	17.788	0.097
63	−2.326	17.838	0.102	−1.858	17.841	0.098
64	−2.329	17.893	0.103	−1.881	17.896	0.099
65	−2.330	17.949	0.104	−1.903	17.951	0.100
66	−2.330	18.005	0.105	−1.924	18.009	0.101
67	−2.328	18.062	0.106	−1.944	18.068	0.102
68	−2.324	18.120	0.107	−1.963	18.130	0.103
69	−2.319	18.179	0.108	−1.981	18.193	0.104
70	−2.312	18.239	0.109	−1.998	18.257	0.105
71	−2.304	18.300	0.110	−2.013	18.323	0.106
72	−2.294	18.363	0.112	−2.026	18.391	0.107
73	−2.284	18.427	0.113	−2.038	18.460	0.108
74	−2.271	18.493	0.114	−2.048	18.531	0.109
75	−2.258	18.561	0.115	−2.056	18.604	0.111
76	−2.243	18.631	0.116	−2.062	18.679	0.112
77	−2.227	18.702	0.117	−2.066	18.756	0.113
78	−2.210	18.775	0.119	−2.069	18.835	0.114
79	−2.192	18.849	0.120	−2.068	18.917	0.116
80	−2.173	18.925	0.121	−2.066	19.002	0.117
81	−2.152	19.002	0.122	−2.061	19.088	0.118
82	−2.131	19.080	0.123	−2.054	19.177	0.120
83	−2.109	19.160	0.124	−2.044	19.267	0.121
84	−2.085	19.240	0.125	−2.032	19.358	0.123
85	−2.061	19.322	0.126	−2.017	19.450	0.124
86	−2.036	19.404	0.127	−1.999	19.543	0.125
87	−2.010	19.486	0.129	−1.979	19.636	0.127
88	−1.984	19.570	0.130	−1.957	19.730	0.128
89	−1.956	19.654	0.131	−1.932	19.825	0.130
90	−1.929	19.738	0.132	−1.905	19.920	0.131
91	−1.900	19.824	0.133	−1.877	20.016	0.133
92	−1.872	19.909	0.134	−1.847	20.113	0.134
93	−1.843	19.996	0.135	−1.816	20.209	0.135
94	−1.814	20.083	0.136	−1.783	20.307	0.137
95	−1.785	20.170	0.137	−1.748	20.405	0.138
96	−1.755	20.258	0.138	−1.713	20.504	0.139
97	−1.726	20.347	0.139	−1.676	20.604	0.141
98	−1.697	20.436	0.140	−1.639	20.704	0.142
99	−1.668	20.525	0.141	−1.601	20.806	0.143

(continued)

Table 1. (continued)

	Males			Females		
Age, mo	L	M	S	L	M	S
100	−1.639	20.615	0.142	−1.562	20.908	0.144
101	−1.611	20.706	0.143	−1.523	21.010	0.145
102	−1.582	20.797	0.144	−1.483	21.114	0.146
103	−1.555	20.889	0.145	−1.443	21.219	0.148
104	−1.527	20.982	0.146	−1.403	21.324	0.149
105	−1.500	21.076	0.147	−1.363	21.429	0.150
106	−1.473	21.170	0.148	−1.323	21.535	0.151
107	−1.447	21.264	0.149	−1.285	21.641	0.151
108	−1.421	21.360	0.150	−1.247	21.746	0.152
109	−1.395	21.456	0.150	−1.210	21.851	0.153
110	−1.370	21.552	0.151	−1.175	21.955	0.154
111	−1.346	21.650	0.152	−1.141	22.059	0.155
112	−1.322	21.747	0.153	−1.109	22.162	0.155
113	−1.298	21.845	0.154	−1.078	22.265	0.156
114	−1.275	21.944	0.154	−1.049	22.368	0.157
115	−1.253	22.043	0.155	−1.022	22.471	0.157
116	−1.231	22.142	0.156	−0.996	22.574	0.158
117	−1.209	22.241	0.156	−0.972	22.676	0.158
118	−1.189	22.340	0.157	−0.950	22.778	0.159
119	−1.168	22.439	0.158	−0.929	22.880	0.159
120	−1.149	22.538	0.158	−0.910	22.982	0.160
121	−1.130	22.637	0.159	−0.893	23.083	0.160
122	−1.111	22.736	0.159	−0.877	23.184	0.161
123	−1.093	22.835	0.160	−0.863	23.285	0.161
124	−1.075	22.933	0.160	−0.850	23.385	0.162
125	−1.058	23.032	0.161	−0.838	23.486	0.162
126	−1.042	23.130	0.161	−0.828	23.585	0.162
127	−1.026	23.229	0.162	−0.819	23.685	0.162
128	−1.010	23.327	0.162	−0.811	23.784	0.163
129	−0.995	23.426	0.163	−0.805	23.882	0.163
130	−0.980	23.524	0.163	−0.799	23.980	0.163
131	−0.966	23.622	0.164	−0.795	24.077	0.163
132	−0.952	23.720	0.164	−0.792	24.174	0.163
133	−0.939	23.818	0.164	−0.791	24.270	0.163
134	−0.927	23.917	0.164	−0.791	24.364	0.163
135	−0.915	24.014	0.165	−0.792	24.458	0.163
136	−0.904	24.112	0.165	−0.794	24.551	0.162
137	−0.893	24.210	0.165	−0.798	24.642	0.162
138	−0.882	24.308	0.165	−0.803	24.733	0.162
139	−0.873	24.406	0.165	−0.809	24.822	0.162
140	−0.864	24.504	0.166	−0.816	24.910	0.162
141	−0.855	24.602	0.166	−0.824	24.996	0.161
142	−0.847	24.700	0.166	−0.834	25.081	0.161
143	−0.840	24.799	0.166	−0.844	25.165	0.161
144	−0.833	24.898	0.166	−0.856	25.246	0.160
145	−0.827	24.997	0.166	−0.868	25.326	0.160
146	−0.821	25.097	0.165	−0.881	25.405	0.160
147	−0.816	25.197	0.165	−0.894	25.482	0.159
148	−0.811	25.297	0.165	−0.908	25.557	0.159
149	−0.807	25.398	0.165	−0.923	25.630	0.158
150	−0.804	25.499	0.165	−0.937	25.702	0.158
151	−0.801	25.600	0.165	−0.952	25.772	0.158
152	−0.798	25.702	0.164	−0.966	25.840	0.157
153	−0.796	25.804	0.164	−0.981	25.907	0.157
154	−0.795	25.906	0.164	−0.995	25.973	0.156
155	−0.794	26.008	0.163	−1.010	26.038	0.156
156	−0.793	26.111	0.163	−1.024	26.102	0.156
157	−0.793	26.214	0.163	−1.038	26.166	0.155
158	−0.794	26.316	0.162	−1.052	26.229	0.155
159	−0.794	26.419	0.162	−1.066	26.291	0.155
160	−0.796	26.521	0.161	−1.079	26.352	0.154
161	−0.797	26.624	0.161	−1.092	26.412	0.154
162	−0.799	26.726	0.160	−1.105	26.471	0.153
163	−0.801	26.829	0.160	−1.117	26.528	0.153
164	−0.804	26.931	0.159	−1.128	26.583	0.153
165	−0.807	27.032	0.159	−1.139	26.637	0.152
166	−0.811	27.134	0.158	−1.149	26.690	0.152
167	−0.814	27.235	0.158	−1.159	26.740	0.152
168	−0.819	27.336	0.157	−1.168	26.789	0.152
169	−0.823	27.437	0.157	−1.177	26.835	0.151
170	−0.828	27.537	0.156	−1.185	26.879	0.151
171	−0.833	27.637	0.156	−1.192	26.921	0.151
172	−0.838	27.736	0.155	−1.199	26.961	0.151
173	−0.844	27.835	0.155	−1.205	26.999	0.150
174	−0.849	27.933	0.154	−1.211	27.035	0.150
175	−0.855	28.030	0.154	−1.216	27.069	0.150
176	−0.862	28.127	0.153	−1.221	27.101	0.150
177	−0.868	28.222	0.152	−1.226	27.131	0.150
178	−0.874	28.317	0.152	−1.230	27.159	0.150
179	−0.881	28.410	0.151	−1.234	27.186	0.150
180	−0.887	28.503	0.151	−1.238	27.212	0.149
181	−0.894	28.594	0.150	−1.241	27.236	0.149
182	−0.901	28.685	0.149	−1.245	27.259	0.149
183	−0.908	28.775	0.149	−1.248	27.280	0.149
184	−0.915	28.863	0.148	−1.251	27.301	0.149
185	−0.922	28.950	0.148	−1.253	27.321	0.149
186	−0.929	29.037	0.147	−1.256	27.339	0.149
187	−0.936	29.122	0.146	−1.258	27.357	0.149
188	−0.943	29.206	0.146	−1.261	27.374	0.149
189	−0.949	29.289	0.145	−1.263	27.391	0.149
190	−0.956	29.370	0.145	−1.265	27.408	0.149
191	−0.963	29.450	0.144	−1.267	27.424	0.149
192	−0.970	29.529	0.143	−1.269	27.441	0.149
193	−0.977	29.607	0.143	−1.271	27.458	0.149
194	−0.984	29.683	0.142	−1.273	27.475	0.149
195	−0.990	29.757	0.142	−1.276	27.493	0.149
196	−0.997	29.831	0.141	−1.278	27.512	0.149
197	−1.004	29.902	0.141	−1.280	27.532	0.149

(continued)

Table 1. (continued)

	Males			Females		
Age, mo	L	M	S	L	M	S
198	−1.010	29.973	0.140	−1.283	27.553	0.149
199	−1.016	30.042	0.140	−1.286	27.577	0.149
200	−1.023	30.110	0.139	−1.289	27.602	0.149
201	−1.029	30.176	0.139	−1.292	27.628	0.149
202	−1.035	30.242	0.138	−1.295	27.656	0.149
203	−1.041	30.306	0.138	−1.298	27.686	0.149
204	−1.047	30.369	0.137	−1.302	27.718	0.149
205	−1.053	30.432	0.137	−1.305	27.751	0.149
206	−1.059	30.494	0.136	−1.309	27.787	0.149
207	−1.065	30.555	0.136	−1.313	27.824	0.149
208	−1.071	30.615	0.136	−1.317	27.863	0.149
209	−1.076	30.675	0.135	−1.321	27.903	0.149
210	−1.082	30.734	0.135	−1.325	27.945	0.149
211	−1.088	30.793	0.134	−1.329	27.988	0.149
212	−1.093	30.851	0.134	−1.334	28.032	0.149
213	−1.099	30.909	0.133	−1.338	28.078	0.149
214	−1.105	30.966	0.133	−1.342	28.125	0.149
215	−1.110	31.023	0.133	−1.346	28.173	0.150
216	−1.116	31.079	0.132	−1.351	28.222	0.150
217	−1.121	31.135	0.132	−1.355	28.273	0.150
218	−1.126	31.190	0.131	−1.360	28.325	0.150
219	−1.131	31.245	0.131	−1.365	28.377	0.150
220	−1.136	31.300	0.130	−1.369	28.429	0.150
221	−1.142	31.355	0.130	−1.374	28.481	0.150
222	−1.147	31.409	0.130	−1.378	28.533	0.150

90th percentile). Predictably, this change in MUAC parallels the change in weight reported over a similar time frame.[29] Compared with the most recent WHO data for children aged ≤5 years, MUAC values in U.S. children were higher across all age groups (Table 2). MUAC values at the 50th percentile were 5.8% larger on average (range, 4.3%–8.3%) with the magnitude of difference increasing at the upper extremes of MUAC. Composite centile-based MUAC growth charts for reference use are included in Supplementary Figures S1–S4.

Discussion

Global health organizations continue to rely on MUAC to classify malnutrition; however, the currently defined classification thresholds remain an area of active debate.[7,30–34] Most striking is the application of a fixed threshold to children spanning the range of ages from 6–60 months. Not surprisingly, this leads to overdiagnosis in the youngest children and underdiagnosis in children at the upper extreme of the age, effectively reducing the sensitivity of this measure. This practice arose from the argument that MUAC is independent of age in children aged <5 years; however, this assertion is widely disputed.[35] In fact, as early as 1993, an expert committee assembled by the WHO concluded that mid-upper arm growth was not age independent and that proper interpretation of this measure requires evaluation against age-specific reference data.[36]

Studies comparing the use of fixed thresholds for MUAC vs thresholds that have been adjusted for patient age or height corroborate that *z* score–based classifications are less likely to discriminate malnutrition between sexes and more likely to distribute malnutrition diagnoses across the spectrum of ages evaluated, thereby enhancing the sensitivity of this measure.[36–38] Coincidentally, no other anthropometric variables examined in children are not framed in the context of a reference measure (eg, weight-for-age, length-for-age, BMI-for-age, weight-for-height). Admittedly, a fixed reference could be considered easier and faster to apply in field settings where a large number of children need to be screened. Yet experts argue that examining MUAC-for-age should be no more difficult than evaluating weight-for-height (another commonly used measure) provided that age can be adequately determined.[39]

The analyses performed in this study provide the necessary LMS parameters to permit MUAC *z* score calculation in children aged 2 months through 18 years. When applied to our external validation cohort, the distribution of *z* scores predictably spanned zero with the exception of the youngest, undernourished cohort of children who were effectively discriminated from the remainder of the population with a mean *z* score approaching −1. In contrast to WHO LMS parameters, which derive from affluent children with no chronic illness who are willing to adhere to feeding recommendations (thus reflecting "optimal" growth), the LMS values presented in this article simply reflect reference data from U.S. children aged 2 months through 18 years at the time of sampling. In no way are they intended to reflect prescriptive standards for growth as is the case with the WHO charts. It is also important to acknowledge that weighting strategy applied by individual NHANES surveys, to account for their complex survey design, was not applied in these analyses in part because the data span multiple surveys. For this reason, we examined our curves against the published empiric percentile from each survey and included an external validation data set to ensure the generalizability of the models that were generated.

At our institution, we are obtaining MUAC values and MUAC *z* scores along with *z* scores for other anthropometric parameters (eg, length, weight, BMI) in all children being seen by our clinical nutrition staff. We are also conducting ongoing evaluations across our population to examine the relationship between MUAC *z* scores, other anthropometric *z* scores, and practitioner-based nutrition

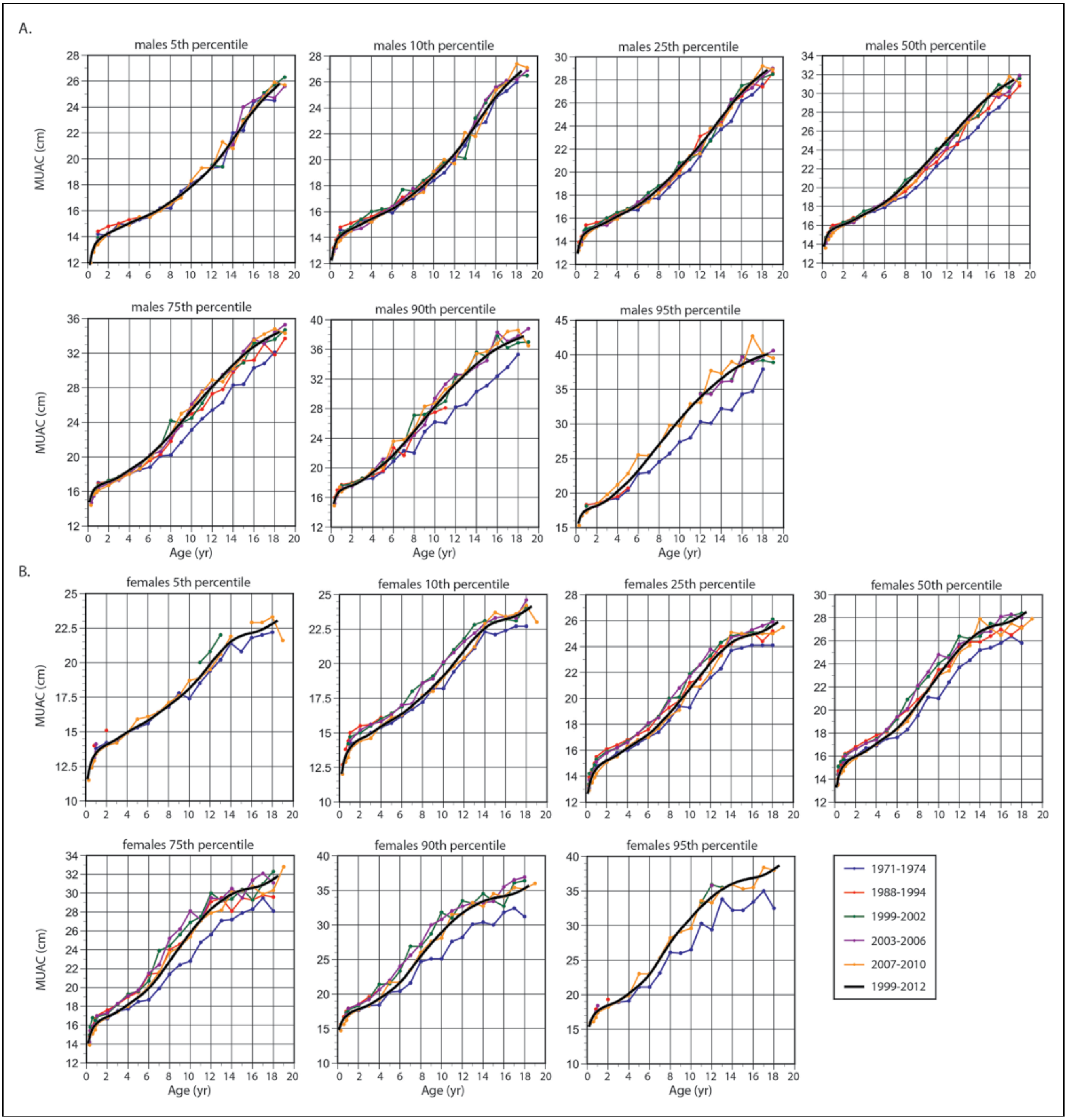

Figure 3. Current fitted centiles overlaid on previously published empiric percentiles reported for (A) males and (B) females from 1971–2010. MUAC, mid-upper arm circumference.

classification. These data may provide some preliminary insight into MUAC *z* score thresholds that are the most predictive of altered nutrition status in the underweight and overweight/obese.

Table 2. Comparison of MUAC Between the U.S. Data and Data Reported by WHO.[25]

	U.S. MUAC, cm							WHO MUAC, cm						
Child, mo	Z − 3	Z − 2	Z − 1	Z0	Z1	Z2	Z3	Z − 3	Z − 2	Z − 1	Z0	Z1	Z2	Z3
Male														
2	10.2	11.4	12.5	13.7	14.8	15.9	17.0	—	—	—	—	—	—	—
4	11.0	12.1	13.3	14.4	15.6	16.7	17.9	10.9	11.8	12.8	13.8	14.9	16.0	17.2
6	11.6	12.6	13.8	14.9	16.1	17.3	18.5	11.3	12.2	13.2	14.2	15.4	16.5	17.8
8	12.0	13.0	14.1	15.2	16.4	17.6	18.9	11.4	12.4	13.4	14.5	15.6	16.8	18.1
10	12.2	13.2	14.3	15.4	16.6	17.8	19.1	11.5	12.5	13.5	14.6	15.7	17.0	18.3
12	12.4	13.4	14.4	15.5	16.7	18.0	19.3	11.6	12.5	13.6	14.6	15.8	17.1	18.4
18	12.8	13.7	14.7	15.8	17.0	18.4	19.9	11.8	12.7	13.7	14.8	16.0	17.3	18.7
24	13.1	14.0	14.9	16.0	17.3	18.7	20.3	12.0	13.0	14.0	15.2	16.4	17.7	19.2
30	13.3	14.2	15.1	16.2	17.5	19.1	21.0	12.3	13.3	14.3	15.5	16.8	18.1	19.7
36	13.5	14.3	15.3	16.5	17.9	19.7	22.0	12.5	13.5	14.5	15.7	17.1	18.5	20.1
42	13.7	14.5	15.5	16.8	18.4	20.4	23.3	12.6	13.6	14.7	15.9	17.3	18.8	20.5
48	13.8	14.7	15.8	17.1	18.8	21.2	24.9	12.7	13.7	14.9	16.1	17.6	19.1	20.9
54	14.0	14.9	16.0	17.4	19.3	22.1	26.8	12.8	13.9	15.0	16.3	17.8	19.4	21.3
60	14.1	15.0	16.2	17.7	19.8	23.0	29.1	12.9	14.0	15.2	16.5	18.0	19.8	21.7
Female														
2	10.4	11.2	12.2	13.3	14.4	15.7	17.1	—	—	—	—	—	—	—
4	11.0	11.9	12.9	14.0	15.2	16.5	18.0	10.5	11.3	12.3	13.4	14.5	15.8	17.2
6	11.4	12.4	13.4	14.5	15.8	17.1	18.7	10.8	11.7	12.7	13.8	15.0	16.3	17.8
8	11.8	12.7	13.7	14.9	16.1	17.6	19.1	11.0	11.9	12.9	14.0	15.2	16.6	18.1
10	12.0	12.9	14.0	15.1	16.4	17.8	19.4	11.1	12.0	13.0	14.1	15.4	16.7	18.2
12	12.2	13.1	14.1	15.3	16.6	18.1	19.7	11.1	12.1	13.1	14.2	15.4	16.8	18.3
18	12.6	13.5	14.5	15.7	17.1	18.6	20.4	11.4	12.3	13.4	14.5	15.7	17.1	18.6
24	12.8	13.7	14.8	16.0	17.4	19.0	20.9	11.7	12.7	13.7	14.9	16.1	17.5	19.1
30	13.0	13.9	15.0	16.2	17.6	19.3	21.3	12.0	13.0	14.1	15.3	16.6	18.1	19.7
36	13.2	14.1	15.2	16.4	17.9	19.7	21.9	12.2	13.3	14.4	15.6	17.0	18.5	20.2
42	13.4	14.4	15.4	16.7	18.3	20.2	22.7	12.4	13.5	14.6	16.0	17.4	19.0	20.8
48	13.7	14.6	15.7	17.1	18.7	20.9	23.8	12.5	13.6	14.9	16.2	17.8	19.4	21.3
54	13.9	14.8	16.0	17.4	19.2	21.6	25.0	12.7	13.8	15.1	16.6	18.1	19.9	21.9
60	14.0	15.0	16.2	17.7	19.6	22.3	26.4	12.8	14.0	15.4	16.9	18.5	20.4	22.5

MUAC, mid-upper arm circumference; WHO, World Health Organization; Z, *z* score; —, values for this age range are not reported by WHO.

Conclusions

The MUAC LMS values generated under this investigation provide clinicians with the data necessary to determine MUAC *z* scores in their population.

Statement of Authorship

S. M. Abdel-Rahman and K. Thaete contributed to the conception and design of the research; S. M. Abdel-Rahman and C. Bi contributed to the acquisition and analysis of the data; S. M. Abdel-Rahman, K. Thaete, and C. Bi contributed to the interpretation of the data; and S. M. Abdel-Rahman drafted the manuscript. All authors critically revised the manuscript, agree to be fully accountable for ensuring the integrity and accuracy of the work, and read and approved the final manuscript.

Supplementary Material

Supplementary Figures S1–S4 are available online at http://journals.sagepub.com/home/ncp.

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