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Determining a global mid-upper arm circumference cut-off to assess underweight in adults (men and non-pregnant women)

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ABSTRACT

Objective. To determine if a global mid-upper arm circumference (MUAC) cutoff can be established to classify underweight in adults (men and non-pregnant women).

Design. We conducted an individual participant data meta-analysis (IPDMA) to explore the sensitivity (SENS) and specificity (SPEC) of various MUAC cutoffs for identifying underweight among adults (defined as body mass index (BMI) <18.5 kg/m^2). Measures of diagnostic accuracy were determined every 0.5 cm across MUAC values from 19.0 to 26.5 cm. A bivariate random effects model was used to jointly estimate SENS and SPEC while accounting for heterogeneity between studies. Various subgroup analyses were performed.

Setting. Twenty datasets from Africa, South Asia, Southeast Asia, North America, and South America were included.

Participants. All eligible participants from the original datasets were included.

Results. The total sample size was 13,835. Mean age was 32.6 years and 65% of participants were female. Mean MUAC was 25.7 cm and 28% of all participants had low BMI (<18.5 kg/m^2). The area under the receiver operating characteristic curve (AUROC) for the pooled dataset was 0.91 (range across studies: 0.61-0.98). Results showed that MUAC cutoffs in the range of ≤23.5 cm to ≤25.0 cm could serve as appropriate screening indicators for underweight.

Conclusions. MUAC was highly discriminatory in its ability to distinguish adults with BMI above and below 18.5 kg/m^2. This IPDMA is the first step towards determining a global MUAC cutoff for adults. Validation studies are needed to determine whether the proposed MUAC cutoff of 24 cm is associated with poor functional outcomes.

Keywords: mid-upper arm circumference, MUAC, nutritional screening, underweight, individual participant data meta-analysis, IPDMA, low BMI, cutoff

Introduction

Body mass index (BMI) is a widely used measure of nutritional status in adults. The World Health Organization (WHO) has established global BMI cutoffs for adults over 20 years of age with the range <18.5 kg/m^2 indicating underweight. Although several recent and large pooled and meta-analytic studies show a shift in focus towards examining the adverse health effects of high BMI levels, these studies continue to show elevated morbidity and mortality in the lowest ranges of BMI. [1-5] In many resource-limited or emergency settings, accurate measurements of BMI may be difficult to obtain due to lack of access to properly maintained equipment (weight scales and stadiometers). In addition, health workers must be trained to read relatively complicated charts to convert weight and height measurements to BMI.

Mid-upper arm circumference (MUAC) is a potential alternative measure to BMI to screen for adult underweight. MUAC is a measure of the circumference of the upper arm at the midpoint between the tip of the elbow (olecranon process) and tip of the shoulder blade (acromion process).[6] While MUAC measurements are generally a reflection of both muscle and subcutaneous fat, in undernourished individuals who tend to have smaller amounts of subcutaneous fat, MUAC measurements can reflect chronic energy deficiency.[6] MUAC measurements are linear and can be taken with a simple tape measure. With appropriate MUAC cutoffs, the assessment could be performed by anyone with minimal training using even a simple paper strip that designates the cutoff values using color codes.

In 2013, we completed a systematic review examining low MUAC as an indicator or predictor of nutrition and health outcomes in adults and adolescents.[7] Our review found that MUAC correlates well with BMI in adult populations and that people with low MUAC (variably defined by the original studies) are significantly more likely to have low BMI (<18.5 kg/m^2).[8-11] Low MUAC was also shown to be a significant predictor of short-term mortality.[12-14] Yet globally recognized MUAC cutoffs have not been established to classify underweight among adults. Within the past decade, countries and programs, particularly those working in the fields of human immunodeficiency virus (HIV) and tuberculosis (TB), have tried to establish their own MUAC cutoffs to determine eligibility for program services, but there is limited evidence that these cutoffs are optimal for identifying individuals who are undernourished and who are at higher risk for morbidity or mortality.[15-17]

To date, there is no guidance from the WHO about what MUAC cutoff should trigger further action in adults. However, WHO has recommended a MUAC cutoff of <11.5 cm as a screening tool for acute malnutrition in children 6 to 60 months of age.[18] This cutoff has become a globally recognized standard for the identification and management of severe acute malnutrition in children and is often used to determine eligibility for, and to monitor progress in, facility-based and community-level nutritional interventions.[19] Global MUAC cutoffs for adults could also serve to strengthen and harmonize programming across various sectors, including HIV, TB, and broader community health and nutrition activities.

To determine the potential for developing standardized MUAC cutoffs to identify adults at risk of undernutrition, we undertook an individual participant data meta-analysis (IPDMA) to examine the diagnostic accuracy of various MUAC cutoffs for identifying underweight (BMI<18.5 kg/m^2) among men and non-pregnant women, henceforth referred to simply as "non-pregnant adults." In our systematic review, BMI <18.5 kg/m^2 was the outcome most consistently found to be associated with low MUAC. The decision to conduct meta-analyses using individual-level data rather than study-level (published) data was primarily dictated by the fact that most of the published studies did not examine or provide data on the sensitivity or specificity of various MUAC cutoffs.[7] An original report which included 17 studies was published online in June 2017.[20] The current paper extends the findings of this report by including three additional datasets obtained after the report was finalized.

Methods

Prior to seeking datasets, eligibility criteria and an analysis plan were established and approved through our technical advisory group (TAG), which consisted of members from the National Institutes of Health (NIH), the United States Agency for International Development (USAID), and the World Health Organization (WHO). To be eligible for the IPDMA, datasets had to include non-pregnant adults over the age of 18, with a minimum sample size of 100, and be collected on or after the year 2000. We chose the year 2000 because that was the year that antiretroviral therapy for HIV became widely accessible to people living with HIV in low-resource settings. In addition, investigators had to be willing to share participant-level data. The following minimal set of variables was requested: MUAC, height and weight (or BMI), sex, and age.

Of the 13 studies that were included in our systematic review[7], three were not eligible for this IPDMA: one was conducted prior to 2000[8] and two had sample sizes fewer than 100.[21, 22] We attempted to contact researchers from the remaining 10 studies and ultimately received datasets from two of them. One researcher provided two eligible datasets (GUI-HIV and GUI-TBC) and another research group provided six eligible datasets (IND-BKW, IND-FSD, IND-MSD, IND-ORA, IND-SDW, and IND-UNI). We then put out a call for datasets through our technical advisory group (TAG) and updated our literature search. Through these methods, we were able to obtain six additional datasets (BAN, MAL-HNW, MAL-HWW, SAF, VIE-FEM, and ZAM). We also included six eligible datasets from the Tufts team commissioned to conduct the IPDMA (ARG, IND-IDU, NAM, USA-IDU, USA-HIV, and VIE-IDU. Thus, the present analysis includes data from 20 unique datasets. Data from four studies (IND-UNI, MAL-HNW, NAM, and ZAM) were unpublished at the time this manuscript was written. Table 1 provides a brief summary of the studies included in this IPDMA. The twenty studies represent the target populations that would most likely use an established low MUAC cutoff to determine eligibility for limited health and nutrition services, i.e. people living with HIV and/or TB, low-resource and development settings, and individuals at risk of undernutrition (e.g. injection drug users).

Statistical Analyses

All datasets were converted and analyzed using the Stata statistical software (StataCorp, College Station, TX, USA). Each dataset was assessed against published manuscripts or original research protocols to create an overview of the included participants and study procedures. For each dataset, we performed data checks of all variables received, ensuring that units, categories, coding, and labels were consistent across studies. Investigators were contacted to confirm missing data, to check extreme or invalid values, and to obtain clarification of study variables and procedures.

To better understand the data from each individual study and the degree of potential heterogeneity between studies, basic descriptive statistics were calculated for each study. These variables included age, sex, education level, HIV status, MUAC, height, weight, and BMI. The collection of information on education was not consistent across studies. Some studies asked for the number of years of schooling, while others collected data in predetermined categories which were not equivalent between studies. For the purposes of summarizing and comparing education

levels across studies, we created three general categories: no education, education at or up to the primary school level (grades 1 to 8, 1–8 years of schooling, or less than high school), and education at or above the secondary school level (grades 9 to ≥12, ≥9 years of schooling, completion of high school or beyond).

MUAC was measured to the nearest 0.1 cm in all studies except for GUI-TBC, where MUAC was measured to the nearest 0.2 cm. Histograms of MUAC and BMI were constructed to determine the distribution of these measurements for each study separately and for all datasets combined (Supplementary Figures 1 to 4). Scatterplots of BMI by MUAC were examined to determine the association between the two variables, for each study separately and for all datasets combined (Supplementary Figures 5 and 6). Pearson correlation coefficients between MUAC and BMI were calculated for each study separately and for all studies combined. The outcome of low BMI was defined as BMI <18.5 kg/m^2, consistent with the cutoff for underweight recommended by the WHO.[23]

We then examined the diagnostic accuracy of MUAC in predicting low BMI, using MUAC cutoffs in increments of 0.5 cm over the range of 19.0 to 26.5 cm. For each MUAC cutoff, we constructed a 2x2 table showing the cross-tabulation of BMI category (BMI <18.5 vs. BMI ≥18.5) and MUAC (above or below the specified cutoff). We computed sensitivity (SENS), specificity (SPEC), positive predictive value (PPV), and negative predictive value (NPV) over the range of MUAC cutoffs for each of the 20 datasets. We also obtained the area under the receiver operating characteristic curve (AUROC) for each study. Next, we combined the datasets into one pooled dataset and created a unique participant identification number and study identifier variable to identify participants within studies. We estimated SENS, SPEC, and positive and negative Likelihood Ratios (LR+ and LR-) for each MUAC cutoff value using the user-written *metandi* and *midas* commands in Stata.[24, 25] These commands perform a bivariate (or joint) meta-analysis of SENS and SPEC using a two-level mixed-effect logistic regression model with MUAC as the only independent variable predicting low BMI. At the first level, within-study variability is accounted for by modeling the counts of the 2x2 tables within each study. At the second level, the between-study variability (heterogeneity) is accounted for, allowing for the non-independence of SENS and SPEC across studies. We also obtained the AUROC for the pooled dataset.

RESULTS

The number of participants in each study ranged from 182 (ZAM) to 4,926 (VIE-FEM) (Table 1). The VIE-FEM dataset was by far the largest, with nearly five times the number of participants as the second largest dataset (GUI-HIV, with n=1,055).

Table 2 shows the demographic characteristics of the participants, by individual study and for all studies combined. Overall, the mean age was 32.6±12.1 years, with ages ranging from 18 to 91 years. The average age for each study was predominantly in the 30s, with a few exceptions. Three studies targeted slightly younger populations (BAN, IND-UNI, and VIE-FEM), and two studies included slightly older participants (USA-IDU and USA-HIV). One study (SAF) specifically targeted an elderly population and thus had a mean age of 71.5±7.9 years.

Nearly two-thirds of participants in the pooled dataset were female (64.4%). Two studies (IND-FSD and VIE-FEM) included only female participants and five studies (IND-BKW, IND-MSD, IND-ORA, IND-IDU, and VIE-IDU) included only male participants.

Six of the 17 studies did not collect data on education status. Of the remaining 11 studies, education level differed widely between studies. Two studies (IND-BKW and IND-FSD) included a majority of participants that had no schooling. Two studies (ARG and IND-IDU) included a majority of participants with primary school education, and six studies (GUI-TBC, IND-UNI, NAM, USA-HIV, VIE-FEM, and VIE-IDU) included a majority with secondary school education or above.

HIV status was not ascertained in half of the studies. Five studies (GUI-HIV, MAL-HNW, MAL-HWW, USA-HIV, and ZAM) included HIV-positive participants only and the remaining five studies (ARG, IND-IDU, NAM, USA-IDU, and VIE-IDU) included both HIV-positive and HIV-negative participants.

Table 3 shows the MUAC and BMI measurements by individual study and for all studies combined. MUAC measurements ranged from a low of 11.6 cm in GUI-HIV to a high of 57.0 cm in USA-HIV. The average MUAC measurement varied between studies, ranging from 19.7 cm in MAL-HWW to 32.7 cm in SAF. Overall, 28.4% of participants had low BMI (<18.5 kg/m^2). Prevalence of low BMI ranged from approximately 5% or less in six studies (ARG, GUI-TBC, MAL-HNW, SAF, USA-HIV, and USA-IDU) to 89% in two studies (MAL-HWW and ZAM). Supplementary Figures 5 and 6 show the scatterplots of BMI by MUAC for each study separately and combined. Correlations between BMI and MUAC were strong and statistically

significant for all studies, ranging from 0.45 (IND-ORA) to 0.89 (SAF). Fourteen of the 20 studies had correlation coefficients at or above 0.80. For the pooled dataset, the correlation coefficient was 0.85 ($p<.00001$). The ROC curve for the pooled dataset (Figure 1) indicates clear discrimination between the distributions of MUAC measurements among those with low BMI compared to those with normal to high BMI. The ROC curve approaches the upper left-hand corner of the graph, indicating high SENS is achieved with high SPEC. AUROC ranged from 0.61 (ZAM) to 0.98 (ARG and USA-HIV), with 13 of the 20 values being ≥0.90 (Table 3). AUROC for the pooled dataset was 0.91.

Supplementary Tables 2 to 17 compare SENS, SPEC, PPV, and NPV for predicting low BMI across studies for each MUAC cutoff from 19.0 cm to 26.5 cm, in increments of 0.5 cm. As shown, the values of SENS, SPEC, PPV, and NPV at each MUAC cutoff varied widely between studies.

Table 4 shows the summary estimates of SENS, SPEC, positive and negative likelihood ratios (LR+ and LR-) derived from the bivariate random-effects model. SENS and SPEC ranged from 4.9% and 99.7%, respectively, at a MUAC cutoff of 19.0 cm to 98.0% and 51.0%, respectively, at a MUAC cutoff of 26.5 cm. The MUAC cutoff with the highest SENS at or above a SPEC of 70% was 25.0 cm. However, cutoffs with lower (but still acceptable) SENS values and higher SPEC values could extend down to 23.0 cm. For example, a cutoff of 23.0 cm would misclassify 35% of those with BMI <18.5 kg/m^2 as being adequately nourished and 7% of individuals with BMI ≥18.5 kg/m^2 as being undernourished. Based on the likelihood ratios, a person with BMI <18.5 kg/m^2 is 9.7 times more likely to have a MUAC ≤23.0 cm than an individual with BMI ≥18.5 kg/m^2, and a person with BMI <18.5 kg/m^2 is 60% less likely to have a MUAC >23.0 cm than a person with BMI ≥18.5 kg/m^2. A higher cutoff of 25.0 cm would correctly classify 93% of individuals with low BMI as being undernourished but would misclassify approximately 27% of those with BMI ≥18.5 kg/m^2. Based on the likelihood ratios, a person with BMI <18.5 kg/m^2 is 3.5 times more likely to have a MUAC ≤25.0 cm and 90% less likely to have a MUAC >25.0 cm than an individual with BMI ≥18.5 kg/m^2.

Table 5 compares the results obtained from various sensitivity and subgroup analyses that we conducted. Nine studies had either a low prevalence (<10%) of individuals with BMI <18.5 or a low prevalence (<11%) of individuals with normal to high BMI, resulting in less stable estimates of SENS and SPEC. We conducted a sensitivity analysis excluding these nine studies

and found that, compared to the full dataset, SENS increased and SPEC decreased across all MUAC cutoffs. We obtained very similar results when excluding five upper middle or high-income countries (ARG, NAM, SAF, USA-HIV, AND USA-IDU) from the analyses. Subgroup analyses by sex and HIV status found that SENS was higher and SPEC lower in females and people living with HIV than their male or HIV-negative counterparts.

Discussion

The purpose of this IPDMA was to determine whether a global MUAC cutoff could be recommended as a screening tool to assess underweight in nonpregnant adults. Currently, the screening tool most commonly used to determine underweight is low BMI (<18.5 kg/m^2). However, the measurement of BMI requires equipment (weight scales and stadiometers) that needs to be properly set-up and maintained, and skilled individuals to measure the height and weight and calculate the BMI. For these reasons, in settings where obtaining accurate measurements of BMI is not feasible, a simple identification of low MUAC could serve as a surrogate for low BMI. Using 20 compiled datasets from various parts of the world, we found that MUAC has an excellent ability to discriminate between those with low BMI (<18.5 kg/m^2) and those with normal to high BMI (≥18.5 kg/m^2). The results remained robust across the various sensitivity and subgroup analyses we performed. We found that, although individual measures of SENS and SPEC at each of the MUAC cutoffs varied between studies, the diagnostic accuracy of MUAC for identifying adults with low BMI was consistently high. AUROCs ranged from 0.61 to 0.98 for individual studies, with most studies having values ≥0.90. The AUROC was 0.91 for all studies combined, which is considered to be in the "excellent" range based on general interpretations for the AUROC.[26] Results of the meta-analysis showed that MUAC cutoffs in the range of 23.5 cm to 25.0 cm could potentially serve as appropriate indicators for low BMI, with acceptable levels of SENS and SPEC at each of these cutoffs for the purpose of initial screening for underweight in the community or in a clinical setting. MUAC cutoffs in the range of 24.0 cm to 25.0 cm provided optimal levels of SENS and SPEC for many of the subgroups analyzed.

The selection of the optimal MUAC cutoff for identifying moderate and severe undernutrition in non-pregnant adults must take into consideration the tradeoff between failing to capture the entire population in need of services (false negative rate) and referring too many

individuals who are not in need of services to the health care system or program (false positive rate). At a MUAC cutoff of 24.0 cm, SENS was 84% and SPEC was 83%. At this cutoff, the false negative and false positive rates would be 16% and 17%, respectively. Lowering the MUAC cutoff to 23.5 cm would increase the false negative rate to 25% and decrease the false positive rate to 11%. At a MUAC cutoff of 25.0 cm, SENS increased to 93% and SPEC decreased to 73%, lowering the false negative rate to 7%, but increasing the false positive rate to 27%.

The recommendation for a MUAC cutoff (or a range of cutoffs) based on this IPDMA is only a first step towards determining a standardized and global MUAC cutoff to identify undernutrition among nonpregnant adults. While many countries and programs currently use low MUAC as a tool for assessing nutritional status and determining eligibility for limited nutrition interventions, the lack of a standardized cutoff makes it difficult to compare studies internationally and to evaluate the effect of nutritional interventions in larger contexts. The widespread collection and reporting of outcomes based on a single standardized MUAC cutoff would facilitate better understanding of the effectiveness of MUAC as a screening tool for adult underweight in various contexts and settings. It is important to note that the purpose of nutrition assessment is to identify individuals who are at risk of malnutrition and who would benefit from nutrition and/or clinical intervention. WHO defines malnutrition as "deficiencies, excesses or imbalances in a person's intake of energy and/or nutrients".[27] Others have defined malnutrition as "a subacute or chronic state of nutrition in which a combination of varying degrees of over- or under-nutrition and inflammatory activity have led to a change in body composition and diminished function".[28] A comprehensive nutrition assessment therefore requires several elements, including: 1) evaluation of an individual's history and clinical diagnoses; 2) physical examination for signs of malnutrition (e.g., edema or specific nutrient deficiencies) and/or clinical indicators of inflammation (fever, hypothermia, tachycardia); 3) anthropometric data, such as weight, BMI, skinfolds, or circumferences; 4) evaluation of usual dietary intake; 5) laboratory indicators if available (e.g., C-reactive protein, white blood cell count, glucose); and 6) functional outcomes, such as strength and mobility.[29] As it is not feasible to conduct a complete nutrition assessment on every individual in a community, or even on every individual who enters a health care facility, valid screening tools that are simple, quick, acceptable, and inexpensive are needed. Ideally, low MUAC would be used as a screening tool in community

and clinic settings to accurately identify individuals who are at highest risk of undernutrition leading to impaired function and poor clinical outcomes, and for whom intervention would improve their nutritional status and clinical outcomes and restore function. It is important to keep in mind that no one screening tool is optimal for all individuals in all situations. Each has its strengths and limitations in different contexts, and each can be affected by an individual's clinical status. Therefore, screening tools such as low MUAC should only be used as an initial step that triggers further and more detailed nutrition assessment, followed by intervention if appropriate. Although programs and policymakers will need to consider available resources when deciding on the optimal MUAC cutoff, we propose that in the context of initial screening under ideal situations, a high SENS (low false negative rate) is more critical than a high SPEC (low false positive rate).

This study had some limitations. Our initial systematic review identified 10 potentially eligible datasets of which we were only able to obtain two for the IPDMA. The remaining datasets in this analysis were obtained from our own research studies, through referrals from our TAG, and through further solicitation of studies in the literature that included MUAC as a continuous measure (our systematic review included only studies that analyzed MUAC as a binary/categorical variable). Therefore, in the end, we were not able to use a formal systematic process for identifying all the datasets included in this analysis. In addition, although a large variety of geographical regions and settings were represented in this analysis, the datasets we obtained may not be representative of those regions or settings. Unfortunately, national nutrition surveys that would be representative of our target population, such as the Demographic Health Surveys, do not routinely collect MUAC in adults. Furthermore, readers should use caution when interpreting the results, which may be affected by confounders, both measured and unmeasured. For example, the presence of edema, which was not measured in most datasets, is a likely confounder in the association between MUAC and BMI.

We posited that the applicability of our IPDMA results may be limited due to heterogeneity in population characteristics, specifically the wide variability in prevalence of low BMI. Leeflang et al. have proposed several contexts in which SENS and SPEC can vary with disease prevalence (contrary to what is commonly taught in epidemiology courses), including the use of an imperfect reference standard, such as low BMI.[30, 31] We used meta-regression techniques to explore the extent to which this may have occurred in our IPDMA using MUAC

cutoffs of 24.0 and 25.0 cm as examples. For both cutoffs, we found that very little of the variability in SENS was due to the variation in prevalence of low BMI (Adjusted R^2=5.3% for MUAC ≤24.0 and 1.9% for MUAC ≤25.0 (Supplemental Figure 7)). However, nearly one-third to one-half of the variation in SPEC was due to the variation in low BMI prevalence (Adjusted R^2=48.3% for MUAC ≤24.0 and 31.9% for MUAC ≤25.0). In sensitivity analyses removing the nine studies with low prevalence of BMI <18.5 kg/m^2 or BMI≥18.5 kg/m^2, the proportion of variability in SPEC due to the variation in low BMI prevalence was reduced to 0% for both MUAC cutoffs (Supplemental Figure 8). The remaining variability, which is larger for SPEC than for SENS, is due to unknown factors.

One of the unknown factors contributing to this variability could be ethnicity. Much of the literature examining ethnic differences in body composition has focused on the associations between BMI, adiposity, and health risks associated with overweight and obesity.[32-35] Ethnic differences in the effect of undernutrition on the relative loss of fat from the limbs and trunk is largely unknown. To our knowledge, very little is published on ethnic differences in MUAC measurements, particularly among undernourished adults. In children 6 to 60 months of age, one study suggests that the association between MUAC<11.5 cm and mortality may be modified by ethnicity.[36] It is quite possible that the association between MUAC cutoffs and low BMI differs by ethnicity; however our dataset was not robust enough to examine this. Readers can examine differences by countries and geographic regions in the supplementary tables provided, but we were not able to compare different ethnicities within or across datasets. Large scale studies in each population or country would be required to determine whether a low MUAC cutoff might differ by ethnicity. In addition, further consideration should be given to the implications of establishing different cutoffs for different subgroups (whether it be by ethnicity, age, or disease group) as this would hinder comparisons across countries and would be impractical for community-level screening.

Based on our results, we propose that a MUAC cutoff of 24.0 cm meets the criterion for optimizing SENS and SPEC across various subpopulations when assessed against low BMI. A meaningful MUAC cutoff would be one below which function and clinical outcomes deteriorate. Whether a MUAC cutoff of 24.0 cm fits this criterion needs to be tested and validated in future longitudinal studies. Comparisons of MUAC against measures such as lean body mass or grip strength would provide further evidence that a global MUAC cutoff could be valuable as a

screening tool for undernutrition. As a valid and reliable screening tool, the use of MUAC in place of BMI would reduce the amount of time and technical skill required for nutrition screening in community settings, resulting in a larger number of individuals who would benefit from further nutrition assessment and intervention. We stress that the proposed MUAC cutoff is currently only intended for use as a screening tool to trigger referral for further assessment; it is not recommended to be used for diagnosis or as an entry criterion into food or nutrition supplementation programs until further validation studies with clinical outcomes have been conducted.

Finally, although the focus of this report is on adult underweight, we do acknowledge the growing global burden of overweight and obesity at both the individual and population level, and the need for screening tools to help prioritize the limited services that are available in low-resource settings. Therefore, future studies should also explore MUAC as a potential screening tool for overweight and obesity.

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Table 1. Brief description of studies Included in the individual participant data meta-analysis (IPDMA)

Study Abbreviation	Country	Year(s) of Study	Brief Study Description	Sample Size[b]
ARG[37]	Argentina	2005–2006	HIV-positive and HIV-negative drug users in Buenos Aires, Argentina	204
BAN[38]	Bangladesh	2012	Patients of the Dhaka Hospital of the International Centre for Diarrheal Disease Research, Bangladesh	650
GUI-HIV[13]	Guinea-Bissau	2007–2009	Antiretroviral therapy (ART)-naïve, HIV-infected patients in Guinea-Bissau	1,055
GUI-TBC[39]	Guinea-Bissau	2014	Healthy controls and household contacts of tuberculosis (TB) patients in Guinea-Bissau	769
IND-BKW[40]	India	2014-2016	Adult male brick-kiln workers in Murishdabad district, West Bengal, India	501
IND-FSD[9]	India	2006	Female slum dwellers in Midnapore Town, West Bengal, India	333
IND-IDU[41]	India	2007	Current and former male injection drug users (IDUs) in Chennai, Tamil Nadu, India	374
IND-MSD[10]	India	2003–2004	Male slum dwellers in Kolkata, India	474
IND-ORA[42]	India	2007	Oraon men of Gumla District, Jharkhand, India	205
IND-SDW[43]	India	2015-2017	Male and female slum dwellers in Midnapore Town, Paschim Midnapore, West Bengal, India	992
IND-UNI[a]	India	2013–2014	University students in Midnapore Town, West Bengal, India	599
MAL-HNW[a]	Malawi	2008–2010	ART-naïve, HIV-infected adults without wasting in three districts in Malawi (Lilongwe, Mzuzu, and Kasungu)	329
MAL-HWW[44]	Malawi	2006–2007	ART-naïve, HIV-infected adults with wasting and MUAC <22.0 cm in Mangochi, Malawi	186
NAM[a]	Namibia	2014	Adults recruited from bar district in Windhoek, Namibia	407
SAF[45]	South Africa	2002	Free-living and institutionalized elderly black South Africans in Cape Town, South Africa	283
USA-HIV[46]	USA	2001–2013	HIV-infected adults in the Greater Boston area, United States	553
USA-IDU[47]	USA	2005–2007	Current and former IDUs in the United States in Boston, MA; Baltimore, MD; and Providence, RI	520
VIE-FEM[48]	Vietnam	2011–2012	Nonpregnant females of reproductive age in Thai Nguyen Province, Vietnam	4,926
VIE-IDU[49]	Vietnam	2006–2008	Current and former male IDUs in Hanoi, Vietnam	297
ZAM[a]	Zambia	2009–2010	HIV-infected adults with wasting in Lusaka, Zambia	182

[a] Study has not been published yet. See Supplementary Table 1 for more complete descriptions of unpublished studies.

[b] This refers to the total number of observations with MUAC measurements. Missing values on individual variables (e.g., BMI) may slightly reduce the numbers for analysis. Total N=13,835.

Table 2. Participant characteristics, by individual study and for all studies combined

STUDY ID	N	Age (years)[a]		Sex[b]		Education[c,d]			HIV(+)[e]
		Min - Max	Mean ± SD	Male N (%)	Female N (%)	None N (%)	Primary N (%)	Secondary N (%)	
ARG	204	18.4-50.6	31 (7.1)	179 (88)	25 (12)	8 (4)	159 (78)	37 (18)	69 (34)
BAN	650	19-60	27.7 (7.4)	260 (40)	390 (60)	171 (26)	194 (30)	285 (44)	Not tested
GUI-HIV	1055	18-76	37.5 (10.9)	313 (30)	742 (70)		No Data		1,055 (100)
GUI-TBC	769	18-90	33.1 (13.8)	335 (44)	434 (56)	101 (13)	240 (31)	428 (56)	Not tested
IND-BKW	501	18-74	36.6 (11.6)	501 (100)	0 (0)	338 (68)	40 (8)	123 (25%)	Not tested
IND-FSD	333	18-80	34.2 (14)	0 (0)	333 (100)	196 (59)	123 (37)	14 (4)	Not tested
IND-IDU	374	22-61	38.7 (7.2)	374 (100)	0 (0)	85 (23)	222 (59)	67 (18)	178 (48)
IND-MSD	474	18-84	37.5 (14.2)	474 (100)	0 (0)	136 (29)	148 (31)	190 (40)	Not tested
IND-ORA	205	18-70	38 (13.4)	205 (100)	0 (0)		No Data		Not tested
IND-SDW	992	18-85	35.9 (14.5)	490 (49)	502 (51)	368 (37)	239 (24)	384 (38)	Not tested
IND-UNI	599	18-28	22.1 (1.6)	228 (38)	371 (62)	0 (0)	0 (0)	599 (100)	Not tested
MAL-HNW	329	18-57	33.9 (8.1)	122 (37)	206 (63)		No Data		329 (100)
MAL-HWW	186	18-58	34.1 (9)	56 (30)	130 (70)		No Data		186 (100)
NAM	407	18-74	29.9 (9.7)	236 (58)	171 (42)	36 (9)	39 (10)	331 (82)	73 (18)
SAF	283	60-91	71.5 (7.9)	53 (19)	230 (81)		No Data		Not tested
USA-HIV	553	24.1-75.4	46.1 (7.9)	372 (67)	181 (33)	0 (0)	6 (1)	547 (99)	553 (100)
USA-IDU	520	22-67.8	43.8 (7.5)	335 (64)	185 (36)	187 (36)	206 (40)	123 (24)	284 (55)
VIE-FEM	4922	18-44.7	26.4 (4.5)	0 (0)	4922 (100)	0 (0)	404 (8)	4516 (92)	Not tested
VIE-IDU	297	19-46.9	31.2 (5.2)	297 (100)	0 (0)	1 (0)	3 (1)	293 (99)	202 (68)
ZAM	182	20-49	33.2 (7.7)	91 (50)	91 (50)		No Data		182 (100)
COMBINED[f]	13,835	18-91	32.6 (12.1)	4921 (36)	8913 (64)	1627 (14)	2023 (18)	7937 (69)	3111 (23)

[a] Number of participants missing data on age: MAL-HNW (n=4), MAL-HWW (n=1), SAF (n=5), USA-IDU (n=9), VIE-FEM (n=23), VIE-IDU (n=1).
[b] Number of participants missing data on sex: MAL-HNW (n=1).
[c] Number of participants missing data on education: IND-SDW (n=1), NAM (n=1), USA-IDU (n=4), VIE-FEM (n=2).
[d] For USA-IDU, categories are < High School, Some High School, >High School.
[e] For NAM, HIV status based on self-report; for VIE-IDU, n=1 missing data on HIV status.
[f] Statistics for the combined datasets for the education and HIV-status characteristics exclude studies that did not collect data on these variables.

Table 3. Mid-upper arm circumference (MUAC), body mass index (BMI), Pearson correlation coefficients, and Area under the ROC curve (AUROC), by individual study and for all studies combined

Study ID	MUAC (cm)		BMI (kg/m^2)		BMI <18.5	Correlation coefficient	AUROC
	Min - Max	Mean (SD)	Min - Max	Mean (SD)	N (%)		
ARG	21.3-48.0	28.7 (3.6)	17.6-45.8	24.0 (3.8)	3 (1.5)	0.85	0.98
BAN	18.2-39.0	25.5 (3.1)	14.4-44.7	21.0 (3.7)	190 (29.2)	0.84	0.90
GUI-HIV	11.6-42.2	26.0 (4.4)	11.3-45.7	20.3 (4.3)	391 (37.4)	0.87	0.95
GUI-TBC	20.2-47.2	29.9 (4.3)	16.2-50.9	24.7 (4.8)	31 (4)	0.85	0.91
IND-BKW	19.6-32.6	24.6 (2.1)	14.6-30.3	20.1 (2.4)	123 (24.6)	0.84	0.92
IND-FSD	14.5-37.1	22.7 (3.2)	12.7-32.9	19.6 (3.7)	153 (45.9)	0.80	0.91
IND-IDU	13.1-39.8	24.4 (3.3)	12.8-31.3	18.7 (3.0)	198 (53.2)	0.81	0.92
IND-MSD	13.6-39.4	25.0 (2.9)	11.6-33.5	20.3 (3.3)	156 (32.9)	0.84	0.92
IND-ORA	14.4-27.6	23.5 (2.0)	15.3-25.0	18.0 (1.6)	133 (64.9)	0.45	0.78
IND-SDW	14.5-43.6	23.4 (3.1)	9.0-50.8	21.7 (4.1)	231 (23.3)	0.72	0.89
IND-UNI	14.3-43.7	25.2 (3.3)	8.5-38.6	22.0 (3.7)	90 (15)	0.74	0.86
MAL-HNW	22.4-36.6	26.9 (2.6)	18.1-41.4	22.7 (3.3)	1 (0.3)	0.82	0.95
MAL-HWW	14.0-23.0	19.7 (1.8)	11.1-23.1	16.4 (1.9)	161 (89)	0.68	0.79
NAM	17.0-42.0	27.8 (3.6)	13.8-62.2	23.0 (5.1)	35 (8.7)	0.53	0.79
SAF	18.4-55.6	32.7 (6.4)	14.1-59.4	31.4 (8.2)	15 (5.4)	0.89	0.96
USA-HIV	20.3-57.0	31.8 (5.1)	15.3-57.1	26.5 (5.7)	17 (3.1)	0.86	0.98
USA-IDU	17.6-50.0	31.5 (4.9)	15.2-61.5	27.7 (6.5)	18 (3.5)	0.84	0.95
VIE-FEM	16.0-40.0	24.5 (2.3)	14.5-32.6	19.6 (2.0)	1545 (31.4)	0.84	0.91
VIE-IDU	17.5-34.5	25.5 (2.7)	13.5-31.7	20.2 (2.4)	78 (26.3)	0.80	0.88
ZAM	13.3-25.0	20.6 (1.5)	10.7-22.2	16.9 (1.6)	162 (89)	0.46	0.61
COMBINED	11.6-57.0	25.7 (4.2)	8.5-62.2	21.2 (4.6)	3731 (28.4)	0.85	0.91

[a]Number of participants missing data on BMI: GUI-HIV (n=10), GUI-TBC (n=3), IND-IDU (n=2), MAL-HWW (n=5), NAM (n=3), SAF (n=4), USA-IDU (n=1), VIE-FEM (n=2).

Table 4. Summary Estimates of SENS, SPEC, positive likelihood ratio (LR+)[a] and negative likelihood ratio (LR-)[b] at selected MUAC cutoffs for all studies combined

MUAC (cm)	SENS	SPEC	LR+	LR-	# Studies
≤19.0	4.9 (2.2, 10.5)	99.7 (99.2, 99.9)	16.7 (5.7, 48.6)	1.0 (0.9, 1.0)	15
≤19.5	7.9 (4.1, 14.7)	99.6 (99.0, 99.9)	20.8 (9.2, 46.9)	0.9 (0.9, 1.0)	15
≤20.0	11.3 (6.0, 20.2)	99.6 (98.9, 99.9)	31.8 (13.2, 76.4)	0.9 (0.8, 1.0)	16
≤20.5	16.0 (9.4, 26.0)	99.3 (98.3, 99.7)	22.9 (11.6, 45.0)	0.8 (0.8, 0.9)	17
≤21.0	22.8 (13.9, 35.1)	99.0 (97.5, 99.6)	22.1 (12.2, 40.2)	0.8 (0.7, 0.9)	18
≤21.5	31.0 (20.0, 44.7)	98.4 (95.7, 99.4)	19.6 (9.2, 41.8)	0.7 (0.6, 0.8)	19
≤22.0	45.5 (29.9, 62.0)	96.4 (89.7, 98.8)	12.7 (5.8, 27.8)	0.6 (0.4, 0.7)	19
≤22.5	58.1 (37.7, 76.1)	94.7 (85.2, 98.3)	11.1 (5.1, 24.1)	0.4 (0.3, 0.7)	20
≤23.0	64.8 (47.0, 79.3)	93.3 (86.4, 96.9)	9.7 (5.8, 16.4)	0.4 (0.2, 0.6)	19
≤23.5	75.1 (61.2, 85.2)	89.0 (79.4, 94.4)	6.8 (4.0, 11.6)	0.3 (0.2, 0.4)	19
≤24.0	84.1 (74.1, 90.8)	83.2 (71.7, 90.7)	5.0 (3.1, 8.1)	0.2 (0.1, 0.3)	19
≤24.5	89.9 (82.1, 94.6)	77.4 (64.1, 86.8)	4.0 (2.5, 6.3)	0.1 (0.1, 0.2)	19
≤25.0	92.9 (87.7, 96.0)	73.3 (61.8, 82.3)	3.5 (2.4, 5.0)	0.1 (0.1, 0.2)	18
≤25.5	95.7 (92.0, 97.7)	66.7 (53.8, 77.6)	2.9 (2.0, 4.1)	0.1 (0.0, 0.1)	18
≤26.0	97.6 (94.6, 98.9)	58.7 (44.8, 71.3)	2.4 (1.7, 3.2)	0.0 (0.0, 0.1)	18
≤26.5	98.0 (95.7, 99.1)	51.0 (37.3, 64.6)	2.0 (1.5, 2.6)	0.0 (0.0, 0.1)	18

[a] Positive Likelihood Ratio (LR+) = ratio between the probability of MUAC ≤cutoff given BMI <18.5 and the probability of MUAC ≤cutoff given BMI≥18.5 = SENS / (1-SPEC)

[b] Negative Likelihood Ratio (LR-) = ratio between the probability of MUAC >cutoff given BMI <18.5 and the probability of MUAC >cutoff given BMI≥18.5 = (1-SENS) / SPEC

Table 5. Comparing False Negative (FN) and False Positive (FP) Rates between Various Subgroups of Participants and Studies

MUAC cutoff (cm)	All data combined		Low Prevalence Studies Removed[a]		LMIC[b] only		Males		Females		HIV-Negative		HIV-Positive	
	FN[c] %	FP[d] %	FN %	FP %	FN %	FP %	FN %	FP %	FN %	FP %	FN %	FP %	FN %	FP %
23.0	35	7	28	10	28	10	46	5	25	6	58	2	29	6
23.5	25	11	19	16	19	17	36	8	17	10	43	3	22	10
24.0	16	17	12	24	12	24	24	13	12	15	32	7	15	17
24.5	10	23	7	32	8	32	16	19	8	19	24	9	11	22
25.0	7	27	4	43	5	37	11	22	5	26	20	13	9	19
25.5	4	33	2	51	3	45	6	28	3	32	16	16	4	24

[a] Excludes studies with low (<10%) prevalence of individuals with BMI <18.5 (ARG, GUI-TBC, MAL-HNW, NAM, SAF, USA-HIV, and USA-IDU) or a low prevalence (<11%) of individuals with normal to high BMI (MAL-HWW, ZAM)

[b] LMIC = low and middle-income countries only (Excludes the following upper middle and high-income countries: ARG, NAM, SAF, USA-HIV, AND USA-IDU)

[c] FN = percentage of individuals with BMI<18.5 kg/m^2 who are missed using the MUAC cutoff.

[d] FP = percentage of individuals with BMI ≥18.5 kg/m^2 who are referred for further screening.

Figure legend

Figure 1. Receiver operating characteristic curve for all studies included in the individual participant data meta-analysis (IPDMA) combined. Area under ROC curve = 0.91