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Letter to the Editor

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3-D printing open-source click-MUAC bands for identification of malnutrition

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Nearly half of all deaths in children under 5 years old are attributed to undernutrition, which equates to 3 million deaths annually[1]. Nutrition programmes have been shown to be effective in reversing life-threatening cases of malnutrition, but are capitally intensive[2]. An effective criterion for the diagnosis of severe acute malnutrition and admission into a feeding programme is the measurement of mid-upper arm circumference (MUAC)[3]. Several studies have shown that MUAC measurements correlate with weight-for-height measurements and are an accurate predictor of malnutrition wasting[4–7]. In a study including anthropometric measurements on 450 000 children in thirty-one countries, the prevalence of severe acute malnutrition defined by weight-for-height below 3 SD of the median of the WHO standards and by an MUAC cut-off of 115 mm were very similar: 3·22 % and 3·27 %, respectively[8]. MUAC measurements below 115 mm have also been shown to be a reliable diagnostic criterion for elevated risk of death due to malnutrition[9,10]. These findings were supported by in-hospital studies that concluded MUAC measurements were a significant predictor of death ($P = 0·001$) and both more accurate and precise as a nutritional assessment tool than both BMI[11] and weight-for-height Z-scores[12].

Current methods for measure MUAC in pre-hospital settings is through the use of measuring tape indicators, such as the four-coloured MUAC tapes. These tapes require users to be trained in how to read the device properly. This represents a challenge to using MUAC in many developing-world contexts, as it has been shown that the largest source of error is introduced by human error during measurements[13]. Commercial indicators sell at prices ranging from $US 0·39 to $US 1·19 per indicator for quantities under twenty-five[14,15].

Open-source three-dimensional (3-D) printable click-MUAC bands are designed to overcome the challenges with conventional MUAC tapes and can be digitally distributed and manufactured in hospitals or field offices anywhere in the world. This new model of production enables those investing in medical research to maximize their return on investment[16] and follows the current paradigm shift underway in scientific hardware[17–19]. Click-MUAC bands have been designed using an open-source computer-aided design package (OpenSCAD[20]; Fig. 1(a)) to minimize material costs, print time and embodied energy[21], while ensuring that they can be easily printed on a standard fused filament fabrication (FFF)-based desktop 3-D printer. The click-MUAC bands are parametrically designed to have a specific inner circumference of 115 mm (one dimple), 125 mm (two dimples) or 135 mm (three dimples), and feature a dimple coding to minimize human error during printing. The free and open-source designs are made available under a GNU General Public License (GPL) 3.0[22]. They can be elastically deformed and wrapped around the mid-upper arm of a child. If the clasp clicks closed while the band is around the middle upper arm, the child's MUAC will be known to be less than the given inner circumference. The click-MUAC bands will require minimal training to use due to the binary nature of the test. Consistent reproducibility is imperative, which is solved with the design. The separation between the clasps in the design is minimized as well as the attachment points for the clasps to ensure any distributed manufacturer's 3-D printer is properly calibrated to print the bands. If under-extruding, the clasp will not print whole and if over-extruding, it will fuse the clasp together in a solid ring. Thus the design ensures that if the band 3-D prints correctly on any device the measurements should be accurate enough to use as a medical diagnostic tool.

Experimental verification on the click-MUAC design is as follows. First, the .stl files were sliced with an open-source slicing program, Cura[23]. The click-MUAC bands were printed with 50 % infill on a delta-style RepRap[24] running free and open-source Franklin control software[25] with 1·75 mm poly(lactic acid) (PLA) filament (Hatchbox) and standard printer settings for PLA material[26]. The click-MUAC also successfully demonstrated cross-platform reproducibility as tested on a Cartesian-style FFF-based TAZ 6 3-D printer (Aleph Objects). Each click-MUAC band's diameter was measured three times using a digital micrometer calliper (±0·01 mm) and averaged. Each band was weighed on an electric digital scale (±0·01 g). Failure testing subjected the bands to elastic deformation to a greater extent than would be expected in the application of a band to a patient's arm. The material cost of each band was calculated using PLA cost per gram ($US 19·99/kg; Amazon); previous work has shown that the electrical consumption costs are not needed[27].

Figure 1(b) shows three click-MUAC bands, colour- and dimple-coded to correspond with the inner circumference of the bands. Using the diameter measurements, the results showed that the click-MUAC bands are dimensionally

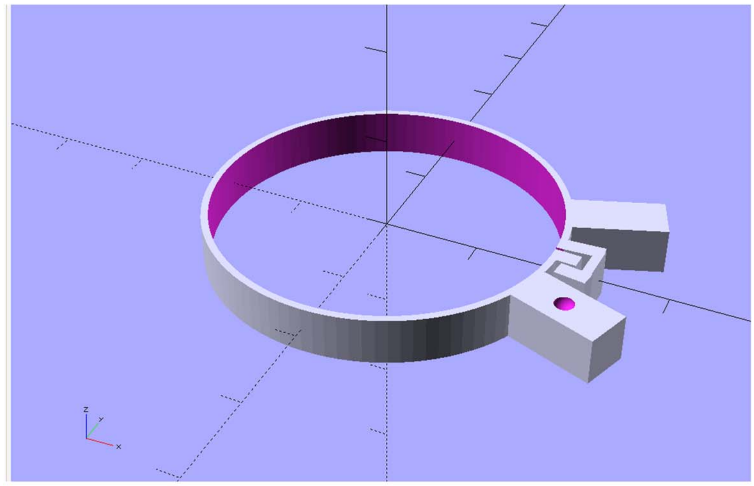
(a)

```
//c=115mm 2 pı r =c
h2=5;
h=10;
b=0.75;
r=18.3;
$fn=100;

difference(){
rotate([0,0,-20])translate([r+r/3.5,0,0])cube([h, h/2, h2], center=true);//left hold
rotate([0,0,-20])translate([r+h/2,0,h2/2]) sphere(r=1);
}
rotate([0,0,20])translate([r+r/3.5,0,0])cube([h, h/2, h2], center=true);//right hold
rotate([0,0,-3])translate([r+r/12,0,0])cube([h/4, h/6, h2], center=true);//left clasp


rotate([0,0,3])translate([r+r/7,0,0])cube([h/2.5, h/6, h2], center=true);//right clasp
rotate([0,0,-8.5])translate([r+r/6,0,0])cube([h/3, h/6, h2], center=true);//right clasp hook
rotate([0,0,-3])translate([r+r/4.5,0,0])cube([h/10, h/2, h2], center=true);//right clasp top of hook

difference(){ //ring
cylinder(r=r+b, h=h2, center=true); //outside
cylinder(r=r, h=h2+1, center=true); //inner diameter to be 115mm
translate([r/2+b+.1,0,0])cube([r, .3, h2+1], center=true);//break in the ring
}
```



(b)

Fig. 1 (a) The OpenSCAD code (left) and solid model (right) of the 115 mm 3-D printable click-MUAC band[24]. (b) Colour-coded 3-D printed click-MUAC bands. From left to right the bands have an inner circumference of 135 mm (green; three dimples), 125 mm (yellow; two dimples) and 115 mm (red; one dimple). (3-D, three dimensional; MUAC, mid-upper arm circumference)

accurate with only an insignificant error of 0·287 % between the average printed inner circumference and the solid model file when printed by a user-assembled RepRap. These are the most accessible and lowest-cost 3-D FFF-based printers in the world, which are capable of producing most of their own parts as well as a long list of appropriate technologies[28–30]. In the failure analysis all bands tested passed a series of 500 deformations without any significant permanent deformation.

Printing at a rate of 5 min per band, the click-MUAC falls into the category of disaster-relief items currently in use by groups like Field Ready, which utilize 3-D printed medical items on demand[31]. The experimental average mass of the click-MUAC bands was 1·15 g for the 115 mm bands, 1·24 g for the 125 mm bands and 1·49 g for the 135 mm bands. This results in a material cost ranging from $US 0·023 (red) to $US 0·030 (green) per click-MUAC band. One of the core advantages of this approach is that the cost of shipping can be reduced. However, even if shipping costs are ignored, the 3-D printable click-MUAC provides a substantial economic saving ranging from 92 to 97 % when compared with commercially available MUAC tapes. To further enhance cost savings, readily available waste plastics can now be used with open-source hardware machines called recyclebots[32] to produce printing filament from discarded plastic waste at a cost of less than $US 0·10/kg[33]. Thus, if recycled plastic is used, $US 0·10 could produce over 800 click-MUAC bands. Distributed digital manufacturing of click-MUAC bands is technically and economically viable.

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