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A Fuzzy Logic Approach to The Evaluation of Health Risks Associated with Obesity

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***Abstract*—Excessive body weight, especially in the form of the so-called abdominal obesity (AO) is an important factor of the cardio-metabolic risks (CMR). The paper presents a fuzzy model of AO and CMR assessments based on such key indicators of anthropometric measurements as body mass index (BMI as a measure of the global adiposity) as well as waist circumference (WC) and waist-to-height ratio (WHtR) as AO indicators. For the construction of a membership function (MF) the Zadeh's Extension Principle (EP) and mapping of the BMI fuzzy sets into adequate AO fuzzy sets using different transformation functions have been applied. Taking advantage of the results of a screening study, the AO membership functions for adult population of Lodz (WHO-CINDI project) are presented. MF design based on the EP theory is a useful methodology for assessing the AO and, consequently for a better assessment of CMR.**

I. Introduction

OBESITY is an important risk factor for cardiovascular diseases, and a primary public health problem in many countries of the world [1]. The trend in obesity is especially alarming among children and adolescents [2].

Pol-MONICA (Multinational Monitoring of Trends and Determinants in Cardiovascular Diseases) study has shown that overweight is exhibited by about 67% of the Polish population, while approximately 30% of women and 20% of men suffer from obesity [3].

As far as obesity is concerned, its most disadvantageous form is known as abdominal obesity (AO) also called visceral or central obesity [4]. An excess of visceral fat surrounding abdominal organs substantially increases a risk of life-threatening diseases such as type 2 diabetes and heart diseases [5]. These diseases are the most common cause of death and have the greatest impact on the financial burden of both individual and public health [6].

AO evaluation based on exact measurements of visceral fat is very difficult and it is only possible to be carried out with the help of complex and expensive imaging techniques [7]. In practice, an unfavorable distribution of adipose tissue and a presence of AO are usually estimated by indirect indices such as waist circumference (WC), waist to hip ratio (WHR) or recent the waist-to-height ratio (WHtR) [8], [9], [10].

Current recommendations establish sharp boundaries between terms like overweight, obesity, etc. They are often of a contractual nature of a consensus obtained in the form of recommendation. Issues related to the assessment of the AO belong to such unspecific problems of body composition which could be well approached by a theory of fuzzy sets [11], [12]. The paper presents a concept of fuzzy AO models developed on the basis of BMI, WC and WHtR measurements. Results of the respective studies in Lodz population were used to construct AO membership function (MF) with Zadeh Extension Principle [13], [14].

II. Categorization of Health Risk Using Body Mass Index (BMI) and Waist Circumference (WC)

Both in epidemiological studies and in clinical practice, overweight is most frequently determined on the basis of the BMI value. BMI is a simple index of "weight-for-height" calculated as weight in $[kg]$ divided by squared height in meters $[m^2]$. Clinically individuals with normal weight (NO) are those with BMI is lower than 25 $[kg/m^2]$. Overweight (OW) is defined as BMI of between 25 and 30 $[kg/m^2]$ and obesity (OB) is defined as BMI of 30 $[kg/m^2]$ [1].

Recently, the WC and WHtR indices have been successfully used as effective measures of AO both in adult and in children or adolescent populations. According to WHO and to National Cholesterol Education Program-Adult Treatment Panel (NCEP-ATP III), AO in the adult population refers to: WC higher than 102 cm for men (M) and higher that 88 cm for women (F) [8], [9]. The newest criteria developed by International Diabetes Federation (IDF) are much more demanding and they recommend an identification of AO obesity at lower levels of WC (94 cm for men and 80 cm for women) [10]. For WHtR, its value > 0.5 indicating AO (central fat distribution), regardless of gender and age [8], [11].

Classification based on a combination of BMI and WC is useful in identifying people at increased CMR. Table 1 presents health risk (CMR) classification according to BMI (three stages) and WC (two stages against NCEP-ATP-III) [8].

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TABLE I
HEALTH RISK CLASSIFICATION FOR ADULT MEN (M) AND FEMALE (F) ACCORDING TO BODY MASS INDEX AND WAIST CIRCUMFERENCE [8].

Waist	**Body Mass Index (BMI in $[kg/m^2]$)**		
Circumference (WC in [cm])	Normal (NO) BMI <25	Overweight (OW) $25 \leqslant$ BMI <30	Obese (OB) BMI $\geqslant 30$
<102 cm (M) <88 cm (F)	Least Risk **(LRisk)**	Increased Risk **(IRisk)**	High Risk **(HRisk)**
$\geqslant 102$ cm (M) $\geqslant 88$ cm (F)	Increased Risk **(IRisk)**	High Risk **(HRisk)**	V. High Risk **(VHRisk)**

TABLE II
CARDIO-METABOLIC RISK (CMR) CLASSIFICATION ACCORDING TO BMI AND THREE AREA OF WC (CNO - WITHOUT CENTRAL OBESITY; COW - CENTRAL OVERWEIGHT AND COB - CENTRAL OBESITY).

Waist Circumference (WC)	**Body Mass Index (BMI)**		
	Normal BMI <25	**Overweight** $25 \leqslant$ BMI <30	**Obese** BMI $\geqslant 30$
cNO <94 cm (M) <80 cm (F)	**(LRisk)**	**(IRisk)**	**(HRisk)**
cOW (94 - 102) cm (M) (80 - 88) cm (F)	**(IRisk)**	**(HRisk)**	**(VHRisk)**
cOB $\geqslant 102$ cm (M) $\geqslant 88$ cm (F)	**(HRisk)**	**(VHRisk)**	**(VHRisk)**

In the light of the proposals by Lean et al. [15] as well as the previously mentioned recommendations by NCEP-ATP III and IDF, a more appropriate classification of CMR is based on BMI and two different WC cut-offs, which define three areas of central adiposity: cNO - without central obesity; cOW - central overweight; cOB - central obesity (Table 2). Similar classification of CMR can be made on the basis of BMI and are recommended by some authors of the two levels of WHtR cut-offs (WHtR $>$ 0.5 as a cOW and WHtR $>$ 0.6 as a cOB) [11]. It should be noted that, due to the dichotomous charkter of the analyzed risk factors as well as the problem of their cut-off points, CMR classifications shown in Tables 1 and 2 constitute rather a qualitative description of the cardio-metabolic complications.

III. EVALUATION OF THE HEALTH RISK ASSOCIATED WITH OBESITY USING A FUZZY LOGIC APPROACH

A. Extension Principle theory

The extension method proposed by Zadeh, usually called Extension Principle (EP) only, is one of the basic ideas to process the extansion of the classical mathematical concepts into fuzzy ones [13], [14]. Let us consider two crisp sets X and Y and f a mapping from X to Y, f: X $\rightarrow$ Y.

Let A be a fuzzy subset of X, $A \in X$ (Figure 1). So, the EP allows to built the image of A under the crisp mapping f as a fuzzy set B:

$$B = f(A) = (y, \mu_B(y) \mid y = f(x), x \in X \qquad (1)$$

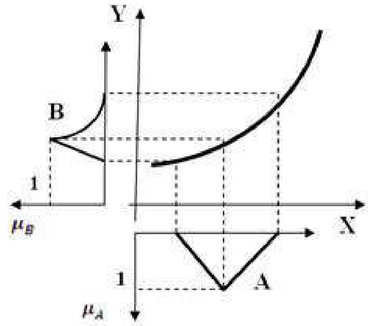

Fig. 1. Illustration of the Extension Principle for a mapping a single variable (explanations in text).

whose, membership function is given by:

$$\mu_B(y) = \begin{cases} sup\ \mu_A(x),\ if\ f^{-1}(y) \neq \emptyset \\ 0,\ if\ f^{-1}(y) = \emptyset \end{cases} \quad for\ all\ y \in Y \qquad (2)$$

where: $f^{-1}(y)$ denotes the set of all points $x \in X$ such that $f(x) = y$.

In the case of X with an infinite number of elements a fuzzy set B induced by the mapping f can be expressed as:

$$B = f(A) = \int_y \frac{\mu_A(x)}{f(x)} \qquad (3)$$

Figure 1 illustrates the EP action considering the mapping $f : X \rightarrow Y$ and A a triangular fuzzy set.

B. Fuzzy models of global and abdominal obesity

The fuzzy model of global fatness was based on BMI that has a defined three fuzzy subsets (NO-normal, OW - overweight and OB - obesity) with the following MF:

$$NO = \begin{cases} 1 & for\ BMI \leq 25 \\ 6 - 0.2BMI & for\ 25 < BMI \leq 30 \\ 0 & for\ BMI > 30 \end{cases} \qquad (4)$$

$$OW = \begin{cases} 0 & for\ BMI \leq 25 \\ 0.2BMI - 5 & for\ 25 < BMI \leq 30 \\ 7 - 0.2BMI & for\ 30 < BMI \leq 35 \\ 0 & for\ BMI > 35 \end{cases} \qquad (5)$$

$$OB = \begin{cases} 0 & for\ BMI \leq 30 \\ 0.2BMI - 6 & for\ 30 < BMI \leq 35 \\ 1 & for\ BMI > 35 \end{cases} \qquad (6)$$

A graphic interpretation of fuzzy subsets of MF for NO, OW and OB is illustrated in Figure 2. Based on the defined BMI fuzzy model and EP theory described in section 3.1, the following transformation functions for men (M) and female (F) in construction of fuzzy AO subsets (cNO, cOW, cOB) have been used:

- f1: WC = f1(BMI); linear equations based on the NCAP-ATP III / IDF criteria [9].

$$f1 : \begin{cases} WC_M = 1.6 * BMI + 54 \\ WC_F = 1.6 * BMI + 40 \end{cases} \qquad (7)$$

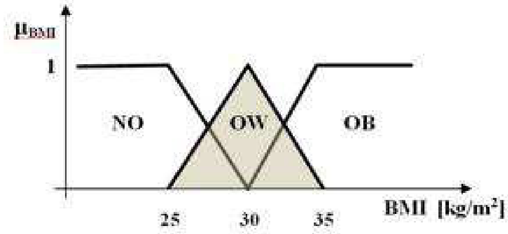

Fig. 2. Illustration of the Extension Principle for a mapping a single variable (explanations in text).

- f2: WC = f2(BMI); linear regression equations defined on the basis of epidemiological studies of the population in Lodz, designed by the WHO-CINDI (Countrywide Integrated Noncommunicable Diseases Intervention Programme: 1264 men and 1330 female aged 18 - 80 y.) [16]:

$$f2: \begin{cases} WC_M = 2.66 * BMI + 22.9 \\ WC_F = 2.27 * BMI + 23.1 \end{cases} \quad (8)$$

- f3: WHtR = f3(BMI); linear equation prepared on the basis on Ashwell recommendations [11]:

$$f3: WHtR_{M/F} = 0.02 * BMI \quad (9)$$

- f4: WHtR = f4 (BMI); regression equations defined on the basis of the WHO-CINDI population of Lodz [15]:

$$f4: \begin{cases} WHtR_M = -16 * 10^{-5} * BMI^2 + 25 * 10^{-3} * \\ \quad * BMI - 0.012 \\ WHtR_F = -12 * 10^{-5} * BMI^2 + 22.7 * 10^{-3} * \\ \quad * BMI + 0.0125 \end{cases} \quad (10)$$

Example: Mapping of the cOW fuzzy subset based on the proposed model and the fuzzy BMI predefined transformation functions f1-f4 ($OW_{BMI} \rightarrow cOW$).

Let:

$$OW_{BMI} = \{\frac{0}{25} + \frac{0.2}{26} + \frac{0.6}{28} + \frac{1}{30} + \frac{0.6}{32} + \frac{0.2}{34} + \frac{0}{35}\} \quad (11)$$

will be selected fuzzy numbers belonging to OW fuzzy set defined by the formula (5). Using the transformation functions f1-f4 (7 - 10) defined for men (M) let us calculate appropriate numbers belonging to a fuzzy subset cOW

- for f1:

$$cOW_{f1} = \{\frac{0}{f(25)} + \frac{0.2}{f(26)} + \frac{0.6}{f(28)} + \frac{1}{f(30)} + \frac{0.6}{f(32)} + \frac{0.2}{f(34)} + \frac{0}{f(35)}\} \quad (12)$$

and after substituting the values we get:

$$cOW_{f1} = \{\frac{0}{94} + \frac{0.2}{95.6} + \frac{0.6}{98.8} + \frac{1}{102} + \frac{0.6}{105.2} + \frac{0.2}{108.4} + \frac{0}{110}\} \quad (13)$$

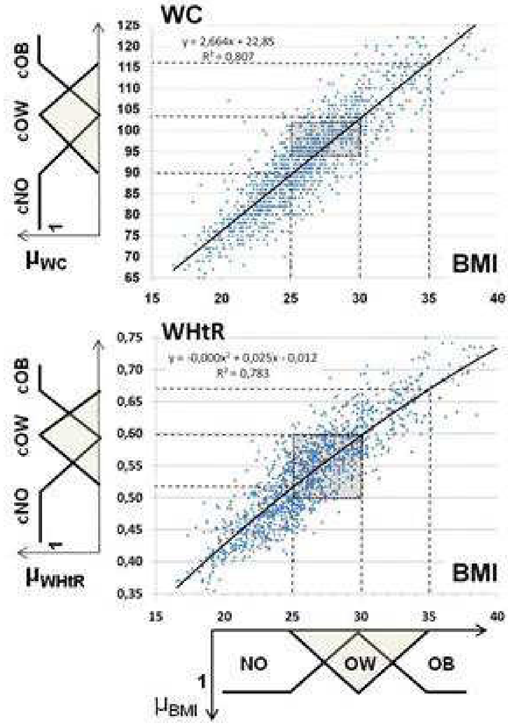

Fig. 3. Example of mapping the WC (top) and WHtR (bottom) fuzzy sets for a men population from Lodz [15]. The regression equations were used as a transformation functions. The gray rectangles - the cOW areas based on the NCEP-ATPIII/IDF recommended classification [8],[9].

- for f2:

$$cOW_{f2} = \{\frac{0}{89.5} + \frac{0.2}{92.1} + \frac{0.6}{97.4} + \frac{1}{102} + \frac{0.6}{105.2} + \frac{0.2}{108.4} + \frac{0}{110}\} \quad (14)$$

- for f3:

$$cOW_{f3} = \{\frac{0}{0.5} + \frac{0.2}{0.52} + \frac{0.6}{0.56} + \frac{1}{0.6} + \frac{0.6}{0.64} + \frac{0.2}{0.68} + \frac{0}{0.7}\} \quad (15)$$

- for f4:

$$cOW_{f4} = \{\frac{0}{0.51} + \frac{0.2}{0.53} + \frac{0.6}{0.56} + \frac{1}{0.59} + \frac{0.2}{0.62} + \frac{0.2}{0.65} + \frac{0}{0.67}\} \quad (16)$$

Example of the construction fuzzy sets AO (cNO, cOW, cOB) based on regression relationships WCM = f2 (BMI) (formula 8) and $WHtR_M$ = f4 (BMI) (formula 10) for the population of Lodz are presented in Figure 3 and Figure 4. WC and WHtR cut - off points designated for men (M) and females (F) based on mapping functions f1 - f4 are summarized in Table 3. As we can notice, the cut-off points for the fuzzy

TABLE III
WAIST CIRCUMFERENCE (WC) AND WAIST CIRCUMFERENCE-TO HEIGHT RATIO (WHtR) CUTOFFS DESIGNATED FOR MEN (M) AND FEMALES (F) BASED ON DIFFERENT MAPPING FUNCTIONS ($f1 - f4$)

BMI	WC cut-off [cm] (mapping functions)				WHtR cut-off [-] (mapping functions)			
	(f1)		(f2)		(f3)		(f4)	
	M	F	M	F	M	F	M	F
18.5	83,6	69,6	72,1	65,1			0,396	0,391
25	94	80	89,4	79,8	0,5	0,5	0,513	0,504
30	102	88	102,7	91,2	0,6	0,6	0,594	0,585
35	110	96	116	102,6			0,667	0,659

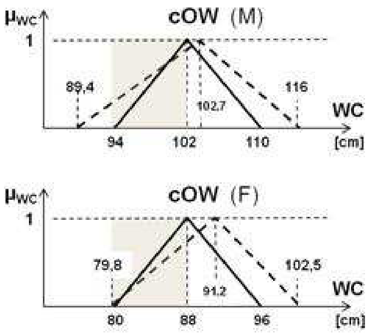

Fig. 4. Graphical form of triangular membership function for the fuzzy set "central overweight" (cOW) for men (M) and females (F). Solid line - developed based on NCEP-ATP III and IDF criteria (function f1); dotted line - developed for the population of Lodz (function f2).

subsets AO are different between themselves and depend on the transforming function. For example, with respect to the triangular MF describing the fuzzy subset cOW of the Lodz inhabitants, both for men and women (Figure 4) we observed the relation:

$$Supp(cOW)_{f1} < Supp(cOW)_{f2} \tag{17}$$

In case of the fuzzy subset cOW determined by WHtR, this relation is not so evident (Table 3). Both for men and women from Lodz, the WHtR cut-off points determined with the use of correlation functions f4 were more close to the current experts recommendations described by function f3.

IV. Final Remarks

Adipose tissue, especially centrally distributed in the body, meets the complex and difficult to unambiguously describe regulatory functions. The excess of visceral fat is the cause of many cardio-metabolic disturbances mainly in the form of insulin resistance and secondary hyperinsulinemia [11], [16]. The current AO classifications are based mainly on the arbitrarily defined WC or WHtR cut-off points, which often are not fully adequate for the characteristic distribution of these indicators for a given population (region).

The paper presents a fuzzy models of AO developed on the basis on simple anthropometric indices such WC and WHtR. For the construction of a MF, the Zadeh's Extension Principle and mapping of the BMI fuzzy sets into adequate AO fuzzy sets using different transformation functions have been applied. The results obtained for the population of Lodz indicate the potential usefulness of the fuzzy set theory in the evaluation of both, the AO and the CMR. For the construction of the MF fuzzy subsets describing the AO it is reasonable to apply the Zadeh's Extension Principle and as a mapping function, the population-specific correlation function.

The results of our study may be a starting point for the construction of more complex fuzzy inference system for the assessment of global cardiovascular or cardiometabolic risk where AO is one of the more important risk factor. Taking into account the growing scale of the adverse health consequences of the obesity epidemic in the world, the artificial intelligence methods including particular fuzzy inference systems should be more widely used.

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