

Estimation of sweat rates during cycling exercise by means of the closed chamber condenser technology

P. Clarys¹, R. Clijsen^{1,2}, A. O. Barel¹, R. Schouteden¹, B. van Olst¹ and D. Aerenhouts^{1,3}

¹Movement and Sport Sciences, Faculty of Physical Education and Physiotherapy, Vrije Universiteit Brussel, Brussels, Belgium,

²Rehabilitation Research Laboratory, Department of Business Economics, Health and Social Care, University of Applied Sciences and Arts of Southern Switzerland, SUPSI, Landquart, Switzerland and ³Department Urban Coaching and Education, Erasmus University College, Brussels, Belgium

Background/aim: Knowledge of local sweating patterns is of importance in occupational and exercise physiology settings. The recently developed closed chamber condenser technology (Biox Aquaflux[®]) allows the measurement of evaporative skin water loss with a greater measurement capacity (up to 1325 g/h/m²) compared to traditional evaporimeters. The aim of this study was to evaluate the applicability of the Biox Aquaflux[®] to estimate sweat production during exercise.

Methods: Fourteen healthy subjects performed a 20-min cycle ergometer trial at respectively 55% heart rate (HR_{reserve} and 75% HR_{reserve}). Sweat production was estimated by measuring body weight before and after exercise, by calculating the amount of sweat collected in a patch, and by measuring the water flux (in g/h/m²) with the Biox Aquaflux[®] instrument.

Results: The Biox Aquaflux[®] instrument allowed the follow up of sweat kinetics at both intensities. Correlations between the

measurement methods were all significant for the 75% HR_{reserve} trial (with *r* ranging from 0.68 to 0.76) whilst for the 55% HR_{reserve} a significant relation was detected between the patch method and the Biox Aquaflux[®] only (with *r* ranging from 0.41 to 0.79).

Conclusion: The Biox Aquaflux[®] instrument is a practical and direct method for the estimation of local sweat rates under field conditions.

Key words: sweating – sweat rates – physical exercise – measurement methods

© 2016 John Wiley & Sons A/S. Published by John Wiley & Sons Ltd
Accepted for publication 20 April 2016

UNDER CERTAIN physical exercise and occupational conditions knowledge of sweating patterns is of utmost importance (1, 2). Sweating and evaporation of sweat from the skin influence water balance and may be the major cause of dehydration in warm environmental conditions. The negative influence of dehydration on exercise and occupational performance is well documented (3).

Sweating patterns are influenced by a variety of individual and environmental factors. To monitor sweat production and to develop strategies resulting in adequate hydration several methods have been developed to estimate water loss during exercise (4). A very practical method is the comparison of body weight before and after exercise, providing primarily information on total water loss, and whole body sweat rate (5). The absorbancy method allows the estimation of local sweat rates and concentrations, however, patch application disturbs the evaporative environment and may be

susceptible to saturation of the absorptive fabric (4, 6). Using a modified absorbancy method, Smith and Havenith (7) were able to produce a body mapping of regional sweating patterns in athletes under mild exercise induced hyperthermia. Ventilated capsules may be the most commonly used method to measure local sweat rates (4). This method respects the evaporative processes, but unfortunately this cumbersome method is not applicable under all field conditions.

The Biox Aquaflux[®] is a condenser chamber method, developed for measuring transepidermal water loss (TEWL) (8, 9). The maximal capacity for the standard instrument is approximately 250 g/h/m² with the 3 mm orifice cap. However, maximal capacity can be increased 5.3 times when an adapted cap is used. Hence, the theoretical maximal measuring capacity reaches 1325 g/h/m². Using technical absorbents, mounted at the upper back region, Smith and Havenith (7) reported a median sweat rate

of 707 g/h/m² and 1197 g/h/m² at 55% and 75% of VO_{2max} respectively. With the ventilated capsules methodology on a comparable skin area after 70 min of cycling at 60% of VO_{2max}, a sweat rate of 690 g/h/m² was recorded by Morris et al. (4). The latter values fall within the theoretical measurement capacity of the Biox Aquaflux[®] with the adapted chamber.

The importance of sweat rate on the hydration status during physical activity in athletic, recreational and occupational setting indicates the need for more practical assessment methods of sweat production during a variety of activities. The water vapour flux as measured with the closed chamber methodology may be used as a measure for regional actual sweat rate. Therefore, the aim of this study was to investigate the possible use of the closed condenser chamber technology to estimate the vapour flux due to sweating during exercise at respectively 55% and 75% of maximal heart rate HR_{reserve}. Therefore, vapour flux data obtained with the Biox Aquaflux[®] instrument were compared with gravimetric values obtained with respectively body weight differences pre- vs. post exercise and the patch method.

Materials and Methods

Participants

Fourteen healthy male volunteers (mean age 26.1 ± 3.3 years, BMI 22.6 ± 1.8 kg/m²) participated in the study. The volunteers received full information regarding the study objectives and were informed of the risks or possible discomforts before providing written informed consent. The study was approved by the ethical committee of the Vrije Universiteit Brussel. Participants needed to present themselves twice in the laboratory separated by 1 week for collection of anthropometric data and to perform a 20 min cycle ergometer trial.

Anthropometrics

Body height was measured with a wall mounted stadiometer accurate up to 0.1 cm (Stanley Microtoise 04-116; Black & Decker, Mechelen, Belgium). Body weight was measured in minimal clothing on each of the two visits before and after the cycle ergometer trials, using a precision balance to the nearest 2 g

(Allscales Europe WLT60/120/x/L3; Aalborg, the Netherlands). Based on body height and body weight measured before the first cycle ergometer trial, BMI was calculated. Body surface area (10) was estimated using the formula of DuBois and DuBois (11).

Cycle ergometer trials

Participants performed two 20 min cycle ergometer trials at fixed HR with a 1 week interval. Each participant performed one trial at 55% HR_{reserve} and one at 75% HR_{reserve}. Half of the subjects performed the 55% HR_{reserve} during the first occasion, the other half started with the 75% HR_{reserve} trial. Target HR was calculated with the HR_{reserve} method of Karvonen and Vuorimaa (12), i.e. target HR = ((HR_{max} - HR_{rest}) × % intensity) + HR_{rest}. The average target HR for the 55% trial was 107 ± 4 b.p.m. and for the 75% trial was 148 ± 9 b.p.m. HR was monitored continuously before and during the exercise protocol using a heart rate monitor (Polar FT4; Polar Electro, Dendermonde, Belgium).

Sweat rate

Sweat rate during the 20 min cycle ergometer trials was determined in three different ways. First, sweat rate was calculated using the difference in body weight before and after the trial using the following formula:

$$\text{Sweat rate (g/h/m}^2\text{)} = (20 \text{ minute body weight change (g)} \cdot 3) / \text{BSA (m}^2\text{)}$$

Second, sweat rate was determined using the patch method. For this purpose, a sterile cotton patch (Sterilux ES 5 × 5 cm, N.V. Paul Hartmann, Sint-Renelde, Belgium) was weighed on a precision balance (Sartorius B120S; Sartorius Mechatronics, Vilvoorde, Belgium) to the nearest 0.001 g. Immediately before the participant started cycling, the patch was placed on the participant's upper back, more precisely 10 cm to the left or right of the T3 vertebra, which was randomly determined. The patch was covered with a plastic sheet and fixed to the skin using impermeable tape (Tegaderm 3M; Diegem, Belgium). The patch was removed immediately after the exercise protocol and weighed again. Using the following formula sweat rate was calculated:

$$\text{Sweat rate (g/h/m}^2\text{)} = 20 \text{ minute patch weight change (g)} \cdot 1200^*$$

*Conversion from minutes to 1 h factor 3; from cm^2 to m^2 factor 400.

Thirdly, sweat rate was measured using the Biox Aquaflux[®] condenser chamber method on the upper back, 10 cm to the left or right from the T3 vertebra, contra laterally from the attached patch. Biox Aquaflux[®] sweat measurements were performed every 5 min after taking a baseline TEWL measurement (T0) until the end of the exercise protocol (T20) resulting in 4 measurements of sweat production (respectively at 5, 10, 15 and 20 min of exercise).

The Biox Aquaflux[®] probe was placed in contact with the skin allowing a 1 min flux stabilization period. After 60 s of skin contact the Biox Aquaflux[®] values (g/h/m^2) were noted on the scoring sheet. The mean sweat rate according to the Biox Aquaflux[®] during the cycle trial was calculated as follows (baseline TEWL measurement time 0 was not included since at time 0 there was no sweat production):

$$\sum 4 \text{ measurements} / 4$$

The condenser chamber method is a device primarily used in dermatological research focusing on skin barrier function and TEWL. The instrument was equipped with an adapted cap increasing the theoretical measurement range of the Biox Aquaflux[®] up to 1325 g/h/m^2 . The angular independence of the measuring head in relation to the evaluated surface makes measurements during exercise protocols in a realistic setting possible. This is not achievable with the open chamber methodology needing a horizontal measuring surface and avoidance of all environmental air movements (13).

Environmental conditions. All measurements were carried out in an unventilated chamber with a mean temperature and humidity of respectively $26.4 \pm 1.5^\circ\text{C}$ and $36.9 \pm 4.2\%$ in the 55% $\text{HR}_{\text{reserve}}$ trial and $26.3 \pm 1.3^\circ\text{C}$ and $34.8 \pm 5.0\%$ in the 75% $\text{HR}_{\text{reserve}}$ trial.

Data analysis

Data analyses were performed with the use of the IBM SPSS Statistics 22.0 for Windows (IBM

Corporation, Armonk, NY, USA). All data were assessed for normal distribution using the Kolmogorov–Smirnov goodness of fit test, indicating the appropriateness of parametric testing. Pre- body weight and patch weight values vs. post values were compared using the paired sample *t*-test. For each exercise intensity, sweat rates as calculated using the three different methods were compared using a one-way ANOVA. If indicated a paired samples *t*-test with Bonferroni correction was applied to detect differences between the three methods. Pearson correlations were calculated between the three methods for both intensities.

Results

All subjects were able to perform the trials at the two intensities. Mean body weight decreased significantly in the 55% $\text{HR}_{\text{reserve}}$ trial and the 75% $\text{HR}_{\text{reserve}}$ trial (respectively from $71.75 \pm 7.60 \text{ kg}$ to $71.51 \pm 7.59 \text{ kg}$ in the 55% $\text{HR}_{\text{reserve}}$ trial and from $71.86 \pm 7.79 \text{ kg}$ to $71.38 \pm 7.73 \text{ kg}$ in the 75% $\text{HR}_{\text{reserve}}$ trial; both $P < 0.001$). Mean patch weight increased from $0.532 \pm 0.010 \text{ g}$ to $0.875 \pm 0.270 \text{ g}$ in the 55% $\text{HR}_{\text{reserve}}$ trial and from $0.532 \pm 0.007 \text{ g}$ to $1.427 \pm 0.304 \text{ g}$ in the 75% $\text{HR}_{\text{reserve}}$ trial (all $P < 0.001$). Outcome values ranged between 0.05 to 0.730 kg for the difference in body weight, from 0.04 g to 1.57 g for the difference in patch weight and from 9.3 g/h/m^2 to 706 g/h/m^2 for the Biox Aquaflux[®] values.

At an intensity of 55% $\text{HR}_{\text{reserve}}$, sweat rate according to the Biox Aquaflux[®] differed significantly from both the calculations based on the change in body weight ($P = 0.006$) and the patch method ($P = 0.012$). The patch and change in body weight methods gave similar sweat rates (Table 1 and Fig. 1).

TABLE 1. Mean sweat rates according to change in body weight, patch method and Biox Aquaflux[®] at exercise intensities of 55% and 75% $\text{HR}_{\text{reserve}}$ (mean \pm SD)

	Body weight change	Patch method	Biox Aquaflux
55% $\text{HR}_{\text{reserve}}$ sweat rate (g/h/m^2)	389 ± 206^a	364 ± 280^a	206 ± 109^b
75% $\text{HR}_{\text{reserve}}$ sweat rate (g/h/m^2)	729 ± 203^a	1054 ± 372^b	446 ± 120^c

^{a,b,c}Within one row, means with the same indices measurement methods do not differ significantly ($\alpha = 0.05$).

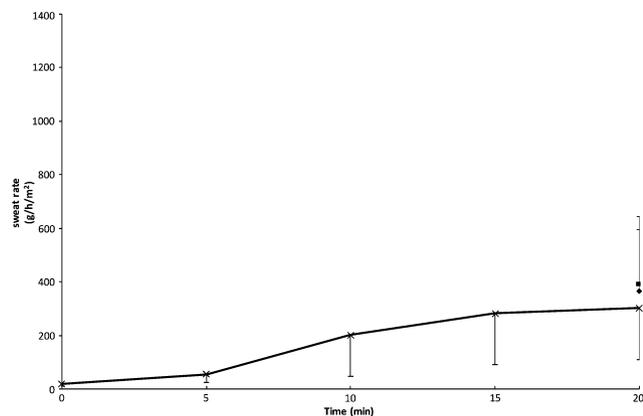


Fig. 1. Transepidermal water loss (TEWL) before and sweat rate during the cycle ergometer trial at 55% $HR_{reserve}$ measured with the Biox Aquaflux[®] during the trial and at the end of the trial (body weight method and patch method) (X = Biox Aquaflux; ◆ = patch method; ■ = body weight).

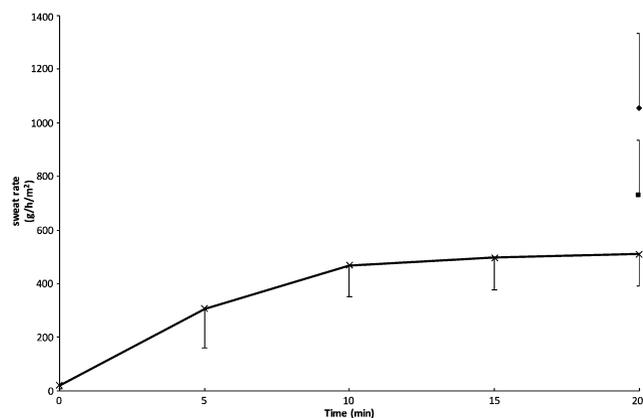


Fig. 2. Transepidermal water loss (TEWL) before and sweat rate during the cycle ergometer trial at 75% $HR_{reserve}$ measured with the Biox Aquaflux[®] during the trial and at the end of the trial (body weight method and patch method) (X = Biox Aquaflux; ◆ = patch method; ■ = body weight).

At an intensity of 75% $HR_{reserve}$ sweat rates derived from all three methods differed from each other (all $P < 0.001$) as presented in Table 1 and Fig. 2. The patch method delivered highest sweat rates while the lowest sweat rates were obtained with the Biox Aquaflux[®].

TABLE 2. Correlations between the sweat rates derived from the three different methods at both (a) 55% $HR_{reserve}$ and (b) 75% $HR_{reserve}$

	Δ -BW	Δ -Patch	Biox Aquaflux [®]
(a) 55% $HR_{reserve}$			
Δ -BW		0.42 ($P = 0.145$)	0.52 ($P = 0.58$)
Δ -Patch			0.79 ($P = 0.001$)
Biox Aquaflux [®]			
(b) 75% $HR_{reserve}$			
Δ -BW		0.75 ($P = 0.002$)	0.76 ($P = 0.002$)
Δ -Patch			0.68 ($P = 0.008$)
Biox Aquaflux [®]			

Correlations between the measurement methods were all significant at the 75% $HR_{reserve}$ trial whilst at the 55% $HR_{reserve}$ a significant relation was detected between the patch method and the Biox Aquaflux[®] only [see Table 2(a) and (b)].

Discussion

Using three different methods sweat production was estimated during a cycle protocol at two intensities to evaluate the applicability of the Biox Aquaflux[®] for sweat measurements during exercise. The Biox Aquaflux[®] instrument is easy to handle and allows measurements on different skin areas not disturbed by airflow and humidity in the experimental room. The latter are difficult to avoid under physical performance protocols.

The different methods resulted in different absolute quantities of sweat produced when calculated as grams of sweat produced per hour and per square meter body surface. In the 75% $HR_{reserve}$ trial, highest values were noticed for the patch method while the closed chamber technology resulted in the lowest absolute quantities. The high values under the patch during the 75% $HR_{reserve}$ trial compared to the two other methods may be partially explained by the covering and hence the local occlusion of this skin region where the sweat is collected. The disturbed skin physiology may lead to an increased accumulation of water in the patch. However, the sweat rates measured with the patch at 75% $HR_{reserve}$ are comparable to the values reported by Smith and Havenith (7). The lower value of the Biox Aquaflux[®] instrument compared to the changes in body weight may be explained by the regional differences in sweating. Indeed, the change in body weight is due to a combination of all body regions with different sweat intensities whilst the Biox Aquaflux[®] is collecting information from one single area, which was found not to have the highest sweat rates (7).

The Biox Aquaflux[®] values collected at the different intervals during exercise are in good agreement with the values obtained with ventilated capsules as reported by Morris et al. (4). Indeed during their 70 min exercise protocol at 60% of VO_{2max} , sweat rates increased from 468 g/h/m² at their 10' interval to 612 g/h/m² at their 30' interval and up to 666 g/h/m² at

their 50' interval finishing with a sweat rate of 690 g/h/m² after 70 min. With exercise intensities in this study, respectively, beneath and above the exercise intensity of Morris et al. (4) the Biox Aquaflux[®] estimated sweat rates after 10 min of cycling reached 202 g/h/m² and 469 g/h/m² at 55% and 75% of HR_{reserve} respectively. At the end of our experiment (20 min) sweat rates derived by the Biox Aquaflux[®] reached respectively 302 g/h/m² for the 55% HR_{reserve} trial and 511 g/h/m² for the 75% HR_{reserve} trial.

The highest flux rate obtained with the Biox Aquaflux[®] (706 g/h/m²) is far beneath the theoretical maximal values of 1325 g/h/m², when using the adapted cap for the condensation chamber.

Despite differences in mean values, high correlations between the different methods were found during the 75% HR_{reserve} trial. At the 55% HR_{reserve} trial only the patch test was significantly correlated with the Biox Aquaflux[®] values. This may be an indication that a certain sweating threshold is required before one can collect reliable estimates with the methods used. Also, at that intensity, the body weight method and the patch method delivered comparable results.

The sweat rates as collected with the Biox Aquaflux[®] during the 55% HR_{reserve} trial show a clear increase in the sweating activation towards a more steady state sweat rate. This may be an indication that the instant measurement of sweat rates as carried out with the Biox Aquaflux[®] can be used to obtain more

information concerning the underlying mechanisms of sweating and sweat gland (dys)function. Indeed as proposed by Xhaufaire-Uhoda et al. (14) these instant measurements can contribute in the quantification of the imperceptible perspiration (skin surface water loss, (SSWL)) under specific conditions such as during moderate exercise, antiperspirant application and diabetic neuropathy. According to Morris et al. (4) the dynamics of sweat travelling to the skin during non-steady state sweating deserves more attention, a question that can only be tackled with instruments with a considerable SSWL measurement capacity.

Conclusion

In conclusion, the high correlation between the Biox Aquaflux[®] instrument and the other field methods for estimating sweat production indicates the potential of the closed chamber methodology as an additional field method. A direct comparison between the Biox Aquaflux[®] and the ventilated capsules method may be the next step for further validation of this method. In addition, working at different environmental temperatures and humidity may be a way to estimate the maximal measuring capacity.

Acknowledgments

The authors would like to thank Bob Imhof for the technical support concerning the Biox Aquaflux[®] instrument.

References

1. Deren TM, Coris EE, Bain AR, Walz SM, Jay O. Sweating is greater in NCAA football linemen independently of heat production. *Med Sci Sports Exerc* 2012; 44: 244–252.
2. Gonzalez RR, Chevront SN, Montain SJ, Goodman DA, Blanchard LA, Berglund LG, Sawka MN. Expanded prediction equations of human sweat loss and water needs. *J Appl Physiol* 2009; 107: 379–388.
3. Chevront SN, Kenefick RW, Charkoudian N, Sawka MN. Physiologic basis for understanding quantitative dehydration assessment. *Am J Clin Nutr* 2013; 97: 455–462.
4. Morris NB, Cramer MN, Hodder SG, Havenith G, Jay O. A comparison between the technical absorbent and ventilated capsule methods for measuring local sweat rate. *J Appl Physiol* 2013; 114: 816–823.
5. Maughan RJ, Shirreffs SM, Leiper JB. Errors in the estimation of hydration status from changes in body mass. *J Sports Sci* 2007; 25: 797–804.
6. Godek SF, Peduzzi C, Burkholder R, Condon S, Dorshimer G, Bartolozzi AR. Sweat rates, sweat sodium concentrations, and sodium losses in 3 groups of professional football players. *J Athl Train* 2010; 45: 364–371.
7. Smith CJ, Havenith G. Body mapping of sweating patterns in male athletes in mild exercise-induced hyperthermia. *Eur J Appl Physiol* 2011; 111: 1391–1404.
8. Farahmand S, Tien L, Hui X, Maibach HI. Measuring transepidermal water loss: a comparative in vivo study of condenser-chamber, unventilated-chamber and open-chamber systems. *Skin Res Technol* 2009; 15: 392–398.
9. Imhof RE, De Jesus ME, Xiao P, Ciortea LI, Berg EP. Closed-chamber transepidermal water loss measurement: microclimate, calibration and performance. *Int J Cosmet Sci* 2009; 31: 97–118.
10. BlueCross BlueShield Association (BCBSA) TECT. Iontophoresis for medical indications TEC Assessment Program. Chicago, IL: Blue-Cross BlueShield Association (BCBSA), Technology Evaluation Center (TEC), 2003.
11. Du Bois D, Du Bois EF. A formula to estimate the approximate surface area if height and weight be

- known. 1916. *Nutrition* 1989; 5: 303–311; discussion 312–303.
12. Karvonen J, Vuorimaa T. Heart rate and exercise intensity during sports activities. Practical application. *Sports Med* 1988; 5: 303–311.
13. Pinnagoda J, Tupker RA, Agner T, Serup J. Guidelines for trans-epidermal water loss (TEWL) measurement. A report from the Standardization Group of the European Society of Contact Dermatitis. *Contact Dermatitis* 1990; 22: 164–178.
14. Xhaufaire-Uhoda E, Mayeux G, Quatresooz P, Scheen A, Pierard GE. Facing up to the imperceptible perspiration. Modulatory influences by diabetic neuropathy, physical exercise and antiperspirant. *Skin Res Technol* 2011; 17: 487–493.

Address:
Peter Clarys
Faculty of Physical Education and
Physiotherapy
Vrije Universiteit Brussel
Pleinlaan 2
1050 Brussel
Belgium
Tel: + 32 2 629 27 39
Fax: + 32 2 629 27 36
e-mail: pclarys@vub.ac.be