Supplemental Material

Table 1: Overview of studies investigating reliability and measurement variability (when indicated) of measurement methods quantifying arm volume of the oedematous limb

Traditional volumetry with overflow													
Reliability	**First author**	Chen et al 2008[27]	Deltombe et al 2007[22]	Galland et al 2002[23]	Gebruers et al 2007 (no lymphoedema) [6]	Gjorup et al 2010[24]	Karges et al 2003[25]	Megens et al 2001[2]	Meijer et al 2004[33]	Mori et al 2015[34]	Sander et al 2002[35]	Taylor et al 2006[11]	**RANGE**
	ICC intra	0.999	0.991	0.996	0.999	0.984	0.990	0.990	0.970-0.980	0.950	0.990	≥0.950	0.950-0.999
	ICC inter	0.990	0.987		0.999			0.990	0.910		0.990		0.910-0.999
	SEM (ml)	Intra 27.20 ml Inter 27.30 ml					11.46 ml (TEM*)				117.00 ml	66.50-81.70 ml	27.20 ml – 117.00 ml
Time-efficiency	**First author**	Galland et al 2002[23]											

	Time (min)	20 min											
Limitations	1) No visual information regarding the shape of the limb[35] 2) Once filled with water, material is not portable[2,25,15] 3) Problems with hygiene[15] 4) Not appropriate in subjects with wounds[24,25,36] 5) No evaluation of the proximal part of the upper arm[7]												
Volumetry without overflow													
Reliability	**First author**	*No publications yet*											
Time-efficiency	**First author**	*No publications yet*											
Limitations	1) No visual information regarding the shape of the limb[35] 2) Once filled with water, material is not portable[2,25,15] 3) Problems with hygiene[15] 4) Not appropriate in subjects with wounds[24,25,36] 5) No evaluation of the proximal part of upper arm[7]												
Inverse volumetry													
Reliability	**First author**	Beek et al 2015 *(no lymphoedema)*[29]	Damstra et al 2006[4]	Erends et al 2014[36] *(no lymphoedema)*									**RANGE**

	ICC intra	0.990	0.997	0.990									0.990-0.997
	ICC inter		0.995										0.995
	SEM (ml)												
Time-efficiency	**First author**	Beek et al 2015[29]	Damstra et al 2006[4]										
	Time (min)	15 min	5 min										
Limitations	1) No visual information regarding the shape of the limb[35] 2) Material is not portable[2,25,15] 3) Problems with hygiene[15] 4) Not appropriate in subjects with wounds[24,25,36] 5) No evaluation of the proximal part of upper arm[7]												
Opto-electronic volumetry													
Reliability	**First author**	Adriaenssens	Deltombe et al 2007[22]										

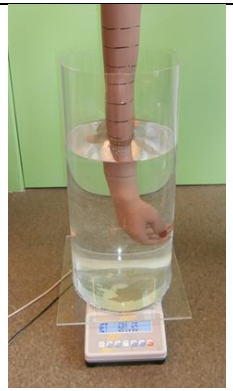
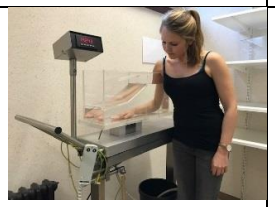
		et al 2013[37]											
	ICC intra	0.999	0.997										
	ICC inter		0.997										
	SEM (ml)												
Time-efficiency	**First author**	Delto mbe et al 2007[22]	Sharkey et al 2018[28]	Stanton et al 1997[11]									
	Time (min)	Few secon ds	2 min	Few second s									
Limitations	1) Device takes a lot of space[38] 2) Expensive equipment[38] 3) The formula used to calculate the volume is unknown and can differ[39] 4) No evaluation of hand volume[4]												
Calculated volume based on circumference measurements													
Reliability	**First author**	Delto mbe et al 2007[22]	Devoogdt et al 2010[26]	Galland et al 2002[23]	Gjorup et al 2010[24]	Karges et al 2003[25]	Taylor et al 2006[11]						**RANGE**
	ICC intra	0.958	0.997	0.995	0.998	0.990							0.958-0.998
	ICC inter	0.937	0.994		0.997		0.970-0.990						0.937-0.997

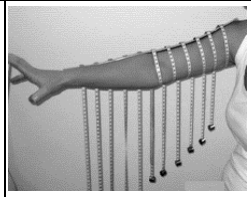
	SEM (ml)		Intra 22.30 ml Inter 25.50 ml			Intra 9.35 ml TEM*)	Inter 64.5-71 ml						Intra 9.35-22.30 ml Inter 22.5-71.00 ml
Time-efficiency	**First author**	Devoogdt et al 2010[26]	Galland et al 2002 *(girth measurements with tapeline)*[23]	Sharkey et al 2018[28]									
	Time (min)	5 min	10 min	10 min									
Limitations	1) No evaluation of hand volume[4]												

Note: * outcome is mentioned as TEM (absolute technical error of measurement); no formula was presented

Table 2. Protocol: overview of the five measurement methods and procedures

Assessment	Picture	Material	Reference points	Method		Outcome
				Setup	Procedure	
Traditional volumetry with overflow[6]	 *(with permission illustration from Gebruers et al 2007[6])*	Cubically shaped tank with overflow (18x18x76 cm) filled with tepid tap water of 20-30°C[40], chair, recipient placed on electronic weighing balance with 0.1g accuracy (KERN 572) on top of a platform of 25 cm height, skin pencil, chair or stool.	Half the distance between acromion and proximal edge of epicondylus lateralis (elbow flexed in 90° whilst marking reference point).	Place a recipient on a scale underneath the overflow. Fill the tank with water until the level of the overflow has reached and flows out. When the water stops dripping (frequency $\leq$ 1 drop per second), calibrate the scale (= 0g). Subject is sitting down next to the tank. Setup time= from setup till the water level in the tank reached the overflow.	Extra water is added to the tank until the water level enters the overflow. During the time water is dripping, reference points are marked. Once the water stops to drip, the scale is tared. Subject lowers the arm into the tank until the water level reaches the marked reference point. The limb needs to be kept straight and perpendicular to the surface, with the palm of the hand placed against the edge of the volumeter. When the limb reaches the reference point, the position has to be maintained until the water stops dripping with frequency $\leq$ 1 drop per second. Read the weight of the water in the recipient. Execution time= started with adding some extra water to the tank before finally taring the scale and ended when water of the overflow dripped with frequency $\leq$ 1 drop per second, after lowering the limb.	Weight of the displaced water (g). Comparison left/right. Measurement of excessive volume of the whole arm = (volume oedematous limb – non-oedematous limb). Setup time, execution time and total time (= setup time + execution time) (seconds).

Volumetry without overflow[9]		Cylinder filled with tepid tap water of 20-30°C[40], placed on weighing balance with 0.1g accuracy (KERN 572); both are placed on top of a platform of 25 cm height. Weighing balance is connected with 'Matlab' software programme on laptop, skin pencil.	10 cm proximal to the middle skinfold of the elbow crease.	Place the cylinder on a scale. Tare the scale. Subject is positioned in standing beside the cylinder. Setup time= from setup till the water level in the tank reached a level of 15cm below the upper edge (= arbitrary chosen to preserve standardization).	Perpendicular to the water surface, subject lowers the arm into the cylinder until the water level reaches the marked reference point. Subject is given attention not to touch the border of the cylinder. Once the water level equals the level of the reference point on the upper arm, the assessor clicks on the assessment button; software programme performs 10 volume measurements and calculates mean volume (Volume of upward displaced water = Mass of water/ density of water, density of water with T° between 20-30°C is 1); a signal is given if mean volume or its standard deviation is outside of preset range. Execution time= timed in two phases: 1) application of reference points 2) started from lowering the arm in the tank until predefined reference point was reached and the weight was shown on the computer screen.	Weight of the upward displaced water (g). Comparison left/right. Measurement of excessive lymphoedema volume whole arm = cfr. Supra. Setup time, execution time and total time (= setup time + execution time) (seconds).
Inverse volumetry[4]		Tank filled with tap water of 28°C standing on a weighting device, based on the metal bending principal.	No reference point.	Calibration procedure: Fill the tank with water until the water reaches the overflow. When the water stops dripping at a frequency $\leq$ 1 drop per second, calibrate to zero and drain the water. This procedure needs to be performed only once daily.	Subject places the olecranon in the corner at the opposite side of the tank, elbow flexed in 90°, pronation of the forearm, extension of the fingers. Assessor fills the tank until the water reaches the overflow. When the water stops dripping at a frequency $\leq$ 1 drop per second, the arm is removed from the tank.	Weight of the added water (g). Comparison left/right. Measurement of excessive lymphoedema volume whole arm = cfr. Supra.

				Measurement procedure: Subject is positioned in standing beside the tank. Adjust the height of the tank until subject is standing comfortable. Setup time= from filling the water tank till end of calibration.	The display of the weighting device shows the shortness of water compared with the initial situation. Execution time= started with placing the arm in the tank and ended when water of the overflow dripped with frequency ≤ 1 drop per second.	Setup time, execution time and total time (= setup time + execution time) (seconds).
Calculated volume based on circumferences[26]	 *(with permission illustration from Devoogdt et al 2010[26])*	Perimeter; which is a flexible stainless steel bar with a tapeline fixed every 4cm and a weight of 20g at the end, skin pencil, chair, table with adjustable height.	Proximal border of the olecranon.	Subject is in sitting position with 90° anteflexion of the arm, straight elbow and hand supported on table. No setup time.	Arm circumferences measured at olecranon and at 4, 8, 12, 16 and 20 cm proximal and distal of olecranon. First, the reference point at the upper border of the olecranon. The bar was placed on the dorsal side of the arm: the middle tapeline was placed distal of the reference point perpendicular to the axis of the arm. The other tapelines were placed around the lower arm, also perpendicular to the axis of the arm. Then the circumference at each point was recorded. Afterwards, all tapes except the middle one were removed, and this procedure was repeated for the upper arm[26] Execution time= started with application of the reference point and ended after recording all circumferences of both arms.	Volume of an arm segment of 4cm = $4 \times (C_1^2+C_1C_2+C_2^2)/12\pi$, where C_1 is the upper circumference and C_2 is the lower circumference of each segment[16] Calculated volume of whole arm = sum of the volume of all segments of the arm Comparison left/right. Measurement of excessive lymphoedema volume whole arm = cfr. Supra. Execution time (= total time) (seconds).

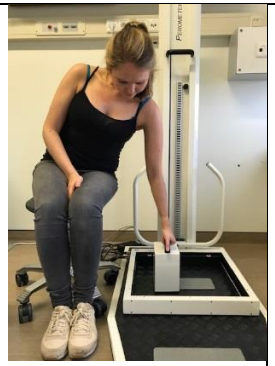
Opto-electronic volumetry[10]		Opto-electronic volumetry device (Perometer®) with a vertical arm, a portable block with handle on top of it, computer provided with 'PeroPlus' software (Pero-System Messgeräte GmbH, Wuppertal, Germany), chair or stool The Perometer consists of a vertically movable frame equipped with infrared light emitters and receptors. The infrared light beams are interrupted by the introduction of the arm into the frame[37]. By moving the frame along the long axis of the arm, a measure is automatically performed every 4.7 mm[28] for a distance which is varying per subject, according to the individual arm length.	No reference point.	Subject is in sitting position next to the device. Hand of the subject is placed on a handle block which position remained unchanged during the entire measurement. The wrist stays in neutral position with closed and connected fingers and the thumb facing forward. The elbow is straight and the armpit is located just above and perpendicular to the ipsilateral border of the frame. No setup time.	Subject keeps a fixed position with the arm straight. Assessor moves the handle of the Perometer slowly up until the frame reaches the armpit, then moves slowly back down; a signal is given when the axilla (moving up) and the floor (moving down), are reached. Execution time= started with providing the instructions how to sit down in a correct and predefined starting position, and ended when the software program finished processing the data. Time to open the program (PeroPlus) is included in the execution time.	Volume of the limb in ml. Comparison left/right. Measurement of excessive lymphoedema volume whole arm = cfr. Supra. Measurement starts for every subject at a height of 58 cm (level of the wrist) end is ended at the corresponding height when the frame reaches the armpit. Subsequently, arm volume is calculated for these measures. Execution time (= total time) (seconds).

Table 3. Intra-rater reliability (n= 30)

	Method	First assessment (assessor A) Mean volume (SD; Min-Max)	Second assessment (assessor A) Mean volume (SD; Min-Max)	ICC (95% CI)	SEM (95% CI)	Paired samples T-Test P-value
Oedematous limb	Traditional volumetry with overflow	2662.64 (384.63; 1692.4-4401.3)	2681.16 (400.72; 1646.5-4389.8)	.950 (.899 - .976)	87.80 (-153.58 – 190.62)	0.643
	Volumetry without overflow	2253.21 (515.69; 1463.1-4401.3)	2246.16 (501.41; 1401.5-3287.7)	.950 (.898-.976)	113.72 (-216.3 – 229.46)	0.827
	Inversed volumetry	3160.4 (653.85; 2033-4760)	3166.23 (705.58; 1945-4672)	.979 (.957-.990)	98.5 (-187.23 – 198.89)	0.823
	Opto-electronic volumetry	5245.47 (747.32; 4140-7048)	5197.37 (729.05; 4084-6921)	.972 (0.941-.986)	123.52 (-194 – 290.2)	0.137
	Calculated arm volume based on circumferences	3000.88 (764.12; 1911.9-4727.6)	3016.16 (769.97; 1895.9-4776.2)	.999 (.997-.999)	24.26 (-40.26 - 54.82)	0.309
Non-oedematous limb	Traditional volumetry with overflow	2180.99 (534.31; 1337.5-3720.6)	2139.78 (537.86; 1359.9-3689.8)	.983 (.960-.992)	69.90 (-95.79 – 178.21)	0.019*
	Volumetry without overflow	1816.66 (332.32; 1193.0-2623.0)	1817.93 (351.28; 1173.5-2654.2)	.985 (.968-.993)	41.86 (-80.78 – 83.32)	0.910
	Inversed volumetry	2635.97 (552.95; 1655-4150)	2614.07 (587.52; 1624-4231)	.991 (.980-.996)	54.10 (-84.13 – 127.93)	0.128
	Opto-electronic volumetry	4694.6 (551.47; 3832-6128)	4658.9 (575.43; 3685-6333)	.961 (.921-.981)	111.27 (-182.39 – 253.79)	0.219
	Calculated arm volume based on circumferences	2531.95 (564.85; 1547.3-4069.8)	2523.11 (584.37; 8.8)	.995 (.990-.998)	40.63 (-70.80 – 88.48)	0.404

Excessive volume	Traditional volumetry with overflow	481.65 (384.63; -56.9-1498.2)	541.38 (400.72; -307.5-1195.3)	.813 (.646-.906)	169.81 (-273.09 – 392.55)	0.179
	Volumetry without overflow	419.07 (330.83; -128.6-1285.7)	428.7 (289.04; -33.8-1227.0)	.777 (.582-.888)	146.36 (-277.24 – 296.5)	0.803
	Inversed volumetry	524.43 (355.2; -140-1159)	552.17 (378.95; -195-1593)	.922 (.843-.962)	102.52 (-173.2 – 228.68)	0.315
	Opto-electronic volumetry	550.87 (415.75; -201-1420)	538.47 (366.25; -207-1308)	.921 (.842-.962)	109.90 (-203.00 – 227.80)	0.670
	Calculated arm volume based on circumferences	476.93 (367.31; -126.8-1345.3)	493.05 (361.99; -28.1-1454.7)	.987 (.973-.994)	41.58 (-65.37 – 97.61)	0.130

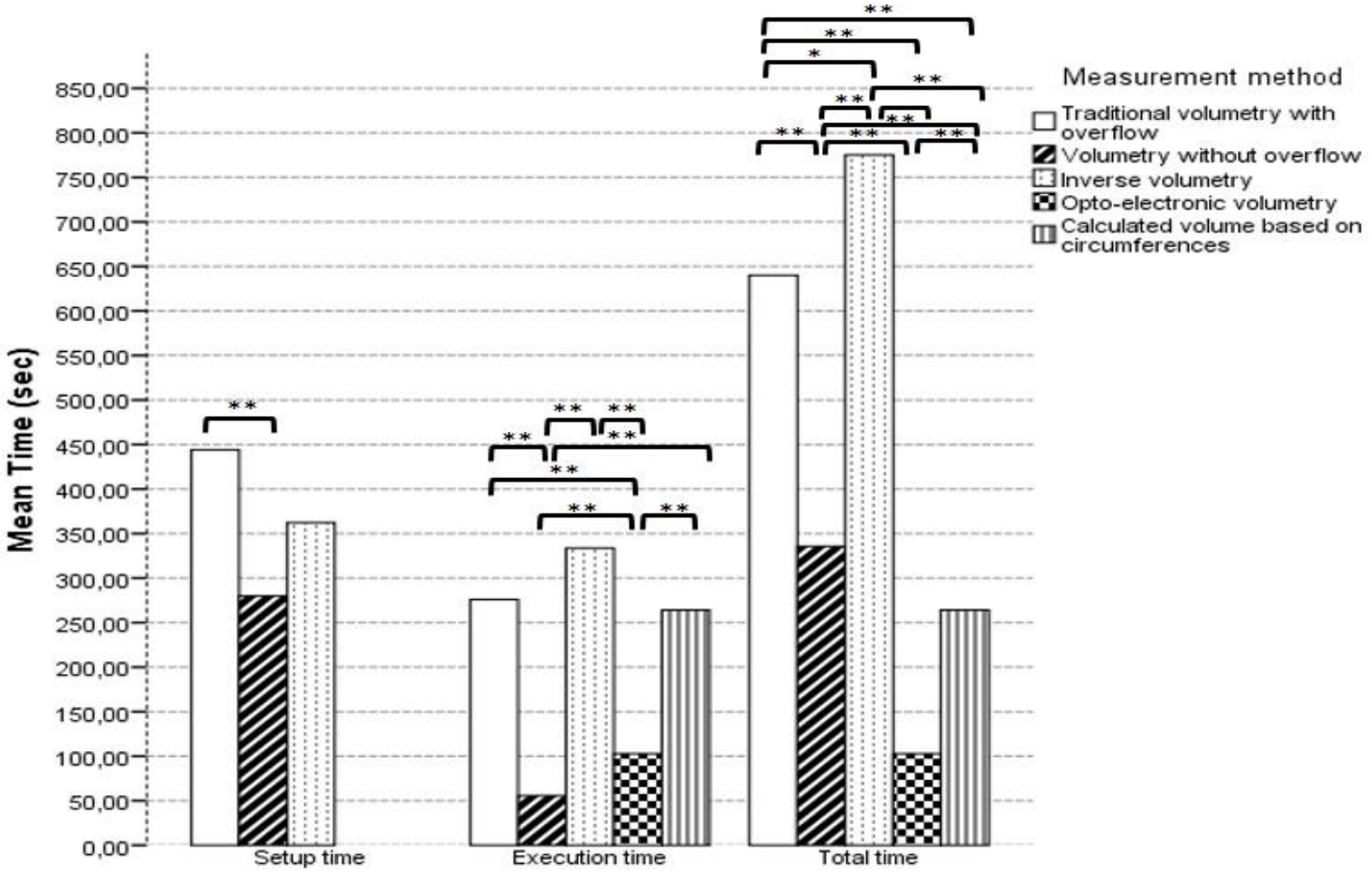
Abbreviations: SD= standard deviation, ICC= intraclass correlation coefficient, CI= confidence interval, SEM= standard error of measurement, * corresponds with p-value <.05, ** corresponds with p-value <.01

Table 4. Details regarding the scoring procedure on clinical feasibility

		Traditional volumetry with overflow	**Volumetry without overflow**	**Inverse volumetry**	**Opto-electronic volumetry**	**Calculated volume based on circumferences**
Clinical feasibility	**Limitations** Outcome *(0= no limitation, 1= limitation)*					
	No visual info shape limb	1	1	1	0	1
	Not portable	1	1	1	1	0
	Problems with hygiene	1	1	1	0	0
	Not appropriate when having wounds	1	1	1	0	0
	No evaluation of proximal part upper arm	1	1	0	0	0
	Difficult to apply with limited postural balance	0	1	0	0	0
	Extensive device	0	0	1	1	0
	Expensive device/procedure (>3000 euros)	0	0	1	1	0
	No segmental evaluation of limb	1	1	1	0	0

	Formula for calculating volume is unknown	0	0	0	1	0
	No evaluation of hand volume	0	0	0	1	1
	Indirect volume measurement	0	0	0	0	1
	Total score	6	7	7	5	3
	Ranking clinical feasibility	**3**	**4**	**4**	**2**	**1**

Figure 1. Comparison of setup time, mean execution time and mean total time of five different measurement methods assisted with ANOVA post hoc analyses (n= 30)



* statistical significant difference between the mean times of both methods (p<.05)
** statistical significant difference between the mean times of both methods (p<.01)
Note: Games-Howell post hoc analysis was applied.

References

2. Megens AM, Harris SR, Kim-Sing C, et al. Measurement of upper extremity volume in women after axillary dissection for breast cancer. *Arch Phys Med Rehabil* 2001; 82(12): 1639–1644.
4. Damstra RJ, Glazenburg EJ and Hop WC. Validation of the inverse water volumetry method: a new gold standard for arm volume measurements. *Breast Cancer Res Treat* 2006; 99(3): 267–273.
6. Gebruers N, Truijen S, Engelborghs S, et al. Volumetric evaluation of upper extremities in 250 healthy persons. *Clin Physiol Funct Imaging* 2007; 27(1): 17–22.
7. Tierney S, Aslam M, Rennie K, et al. Infrared optoelectronic volumetry, the ideal way to measure limb volume. *Eur J Vasc Endovasc Surg* 1996; 12(4): 412–417.
9. Martignon M, Vankerckhove S, Fung LH, et al. Evaluation of the reliability of four measuring methods of hand's perimeter and volume: Buoyancy Forces ValGrado system, circumference measurement, Figure-of-Eight Method and Manu3metrix Scanner. In: *8th International Lymphoedema Framework Conference*, Rotterdam, 6–9 June 2018.
10. Stanton AW, Northfield JW, Holroyd B, et al. Validation of an optoelectronic limb volumeter (perometer). *Lymphology* 1997; 30(2): 77–97.
11. Taylor R, Jayasinghe UW, Koelmeyer L, et al. Reliability and validity of arm volume measurements for assessment of lymphedema. *Phys Ther* 2006; 86(2): 205–214.
15. Boland R and Adams R. Development and evaluation of a precision forearm and hand volumeter and measuring cylinder. *J Hand Ther* 1996; 9(4): 349–358.
22. Deltombe T, Jamart J, Recloux S, et al. Reliability and limits of agreement of circumferential, water displacement, and optoelectronic volumetry in the measurement of upper limb lymphedema. *Lymphology* 2007; 40(1): 26–34.
23. Galland C, Auvert JF, Flahault A, et al. Why and how postmastectomy edema should be quantified in patients with breast cancer. *Breast Cancer Res Treat* 2002; 75(1): 87–89.
24. Gjorup C, Zerahn B and Hendel HW. Assessment of volume measurement of breast cancer-related lymphedema by three methods: circumference measurement, water displacement, and dual energy x-ray absorptiometry. *Lymphat Res Biol* 2010; 8(2): 111–119.
25. Karges JR, Mark BE, Stikeleather SJ, et al. Concurrent validity of upper-extremity volume estimates: comparison of calculated volume derived from girth measurements and water displacement volume. *Phys Ther* 2003; 83(2): 134–145.
26. Devoogdt N, Lemkens H, Geraerts I, et al. A new device to measure upper limb circumferences: validity and reliability. *Int Angiol* 2010; 29(5): 401–407.
27. Chen YW, Tsai HJ, Hung HC, et al. Reliability study of measurements for lymphedema in breast cancer patients. *Am J Phys Med Rehabil* 2008; 87(1): 33–38.
28. Sharkey AR, King SW, Kuo RY, et al. Measuring limb volume: accuracy and reliability of tape measurement versus perometer measurement. *Lymphat Res Biol* 2018; 16(2): 182–186.
29. Beek MA, te Slaa A, van der Laan L, et al. Reliability of the inverse water volumetry method to measure the volume of the upper limb. *Lymphat Res Biol* 2015; 13(2): 126–130.
32. Borthwick Y, Paul L, Sneddon M, et al. Reliability and validity of the figure-of-eight method of measuring hand size in patients with breast cancer-related lymphoedema. *Eur J Cancer Care* 2013; 22(2): 196–201.
33. Meijer RS, Rietman JS, Geertzen JH, et al. Validity and intra- and interobserver reliability of an indirect volume measurements in patients with upper extremity lymphedema. *Lymphology* 2004; 37(3): 127–133.
34. Mori T, Lustman A and Katz-Leurer M. Self-measurement of upper extremity volume in women post-breast cancer: reliability and validity study. *Physiother Theory Pract* 2015; 31(4): 283–287.
35. Sander AP, Hajer NM, Hemenway K, et al. Upperextremity volume measurements in women

with lymphedema: a comparison of measurements obtained via water displacement with geometrically determined volume. *Phys Ther* 2002; 82(12): 1201–1212.
36. Erends M, van der Aa T, de Grzymala AP, et al. Validity and reliability of three-dimensional imaging for measuring the volume of the arm. *Lymphat Res Biol* 2014; 12(4): 275–281.
37. Adriaenssens N, Buyl R, Lievens P, et al. Comparative study between mobile infrared opto-electronic volumetry with a perometer and two commonly used methods for the evaluation of arm volume in patients with breast cancer related lymphedema of the arm. *Lymphology* 2013; 46(3): 132–143.
38. Levenhagen K, Davies C, Perdomo M, et al. Diagnosis of upper quadrant lymphedema secondary to cancer: clinical practice guideline from the oncology section of the American Physical Therapy Association. *Phys Ther* 2017; 97(7): 729–745.
39. Veraart JCJM, Movig I, Asselman AH, et al. The volometer and the perometer: a clinical comparison. *Scr Phlebol* 1995; 5: 9–11.
40. King TI 2nd. The effect of water temperature on hand volume during volumetric measurement using the water displacement method. *J Hand Ther* 1993; 6(3): 202–440.