Transcutaneous oximetry measurement: normal values for the upper limb

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Abstract

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Introduction: Several studies define normal transcutaneous oximetry measurements (TCOM) for the chest and lower limb, but not the upper limb. Standardised healthy-subject reference values for upper limb TCOM would make interpretation of these measurements in disease or injury more meaningful.

Aim: To determine 'normal' TCOM values for the upper limb in healthy non-smoking adults.

Method: Thirty-two healthy volunteers (16 male, 16 female) had TCOM performed on the chest and at five upper limb positions: lateral aspect of the upper arm midway between the shoulder and elbow; lateral aspect of the forearm, dorsum of the hand, thenar and hypothenar eminences. Measurements were taken using the TCM400 Monitoring System (Radiometer) with subjects breathing room air and whilst breathing 100% oxygen.

Results: Room-air TCOM values (mean (SD), 95% confidence interval (CI)) were: chest: 50 (11.4) mmHg, 95% CI 46.0 to 54.2; upper arm: 53 (9.3) mmHg, 95% CI 49.7 to 56.4; forearm: 45 (11.3) mmHg, 95% CI 40.4 to 48.6; dorsum of hand: 39 (8.5) mmHg, 95% CI 35.5 to 41.7; thenar eminence: 54 (7.7) mmHg, 95% CI 51.7 to 57.2; and hypothenar eminence: 57 (7.5) mmHg, 95% CI 54.1 to 59.6. All readings showed a substantial increase when subjects breathed 100% oxygen. Using the currently accepted threshold for tissue hypoxia of < 40 mmHg, six forearm and 14 dorsum of the hand TCOM readings would have been classified as hypoxic.

Conclusion: Normal upper limb TCOM readings are less than those established for the lower limb. Using lower-limb reference standards could result in false-positive determinations of tissue hypoxia. We recommend TCOM ≤ 30 mmHg as indicative of tissue hypoxia in the upper arm, thenar and hypothenar eminences, and ≤ 20 mmHg in the forearm and dorsum of the hand.

Key words

Transcutaneous oximetry, hyperbaric oxygen therapy, wounds, patient monitoring, standards

Introduction

Transcutaneous oximetry measurement (TCOM) is the process of measuring oxygen tension (partial pressure) on the skin. Originally used in neonatology, TCOM estimates tissue oxygenation non-invasively by measuring the diffusion of extracellular oxygen into a heated sensor on the skin.[1,2] TCOM is clinically useful in determining wound healing potential, selecting amputation level, evaluating revascularisation procedures and assessing the severity and progression of peripheral vascular disease.[3] TCOM has also become an essential component of wound assessment in hyperbaric medicine, as the patients most likely to benefit from hyperbaric oxygen therapy are those with demonstrated peri-wound tissue hypoxia that responds to hyperoxia.[2]

In order for TCOM data to be clinically useful, knowledge of normal values in healthy populations is required. Early studies have reported normal values for the chest and several sensor positions on the lower limb, as well as the reproducibility and reliability of these readings.[4–9] Recent reviews define lower-limb tissue hypoxia sufficient to impair or prevent wound healing as a transcutaneous oxygen partial pressure ($P_{tc}O_2$) < 40 mmHg.[2,10,11] Corresponding healthy-subject reference data for the upper limb are not available, perhaps because the lower limbs are more commonly affected by vascular pathology and, consequently, attention has focused on this area.[12]

Despite the lack of standardised healthy-subject reference values for the upper limb, researchers and clinicians have used TCOM in investigations of upper limb peripheral vascular disease, hemiplegia, scleroderma, lymphoedema, complex regional pain syndrome (CRPS) and surgical procedures.[12–18] A few papers focusing on the upper limb have included values for healthy or normal control subjects.[14,16,19] However, attempts to identify normal reference TCOM data from these studies are limited by variations in technique, subject posture, electrode placement, electrode temperature, and the use of unclear and inconsistent operational definitions for 'normal' and 'healthy.' The aim of this study was to determine normal TCOM values for the upper limb in healthy, non-smoking adult subjects.

Methods

Ethics approval for this study was granted by the Human Research Ethics Committee of the Townsville Health Services District. Thirty-two (16 male, 16 female) subjects recruited from the hospital staff and general population participated in the study. Exclusion criteria included subjects younger than 18 years; current or former smoker;

known cardiovascular disease including treated or untreated hypertension; significant respiratory disease and any other significant medical condition. Subjects with one arm, or scarring or skin conditions on the upper limb, were also excluded. As subjects were required to have a plastic hood placed over their head to receive oxygen during part of the study, severe claustrophobia was a further exclusion criterion.

All participants were given a study information sheet and informed consent was obtained. Subjects refrained from consuming food or caffeine or performing heavy exercise for two hours prior to participating in the study. Basic demographic data were collected, including dominant hand, weight and height. Oxygen saturation, blood pressure, and pulses on both upper limbs were recorded. The subjects were placed in a supine position on a hospital bed with their head slightly raised on one pillow for the duration of the study. They were offered a blanket for comfort and to limit any vasoconstrictive effects of being cold. The room temperature was maintained between 22.0 and 22.5^{O}C. The participants rested quietly while the sensors were placed.

Participants were randomised to have sensors placed on their right or left arm. The sensor sites were prepared by shaving hair if necessary, wiping clean, rubbing with an alcohol swab and drying with gauze. One sensor was placed as a central reference on the chest at the second intercostal space in the mid-clavicular line.[3,11,20] Five sensors were placed on the arm and hand. One sensor was positioned midway between the highest bony point on the shoulder and the olecranon process on the lateral aspect of the upper arm. Another was sited 5 cm distal to the brachial crease on the lateral aspect of the forearm. One sensor was placed centrally on the dorsum of the hand between the third and fourth metacarpal bones, attempting to avoid large superficial vessels. The final two sensors were placed on the palmer aspect of the hand, on the thenar and the hypothenar eminences. The leads were secured in place with tape to prevent pull on the sensors. Subjects were requested to keep talking to a minimum during the study.

All TCOM assessments were performed by the same technician using the TCM400 $P_{tc}O_2$ Monitoring System (Radiometer Medical ApS, Bronshoj, Denmark). The TCM400 has six electrodes and can record $P_{tc}O_2$ data from all six sensor sites simultaneously. The electrode temperatures were pre-set to 44^{O}C and atmospheric and zero point electrode calibrations were performed as per the manufacturer's recommendations. A 'humidity correction factor' was calculated from the room temperature, saturated water vapour pressure and relative humidity and input into the machine according to the TCM400 operator's manual.[21] $P_{tc}O_2$ values are displayed by the TCM400 in mmHg units as are values reported throughout the TCOM literature and, therefore, have not been converted to kPa in this paper.

We used the TCOM protocol described by Sheffield, which is commonly used in hyperbaric medicine to identify tissue hypoxia and responsiveness to hyperoxia.[22] Part of the protocol includes a 45^{O} limb elevation challenge to identify the presence of large or small vessel disease in the lower limb. Arm elevation is a common treatment ordered for arm injury, post-operative care and oedema management, therefore data on the effects of arm elevation on tissue oxygenation may be useful. It was decided to keep this manoeuvre as part of our TCOM protocol.

Initial normobaric room-air readings from all sensors were recorded after a minimum 20-minute equilibration period, allowing all sensor readings to stabilise.[4] The arm was then elevated to 45^{O} above horizontal and rested on a foam wedge, with sensor readings again recorded after five minutes. The arm was returned to the horizontal position for a minimum five-minute period allowing all sensor readings to re-stabilize, and another set of readings were recorded to ensure TCOM had returned to baseline (data not shown). The subjects then breathed 100% oxygen for 10 minutes via a clear plastic head hood with a soft neck seal, with sensor readings recorded at the end of the 10-minute period. All sites were inspected for injury from sensor warming. No evidence of skin injury was recorded. All collected data were de-identified and recorded onto a pre-formatted worksheet. This information was entered into and all analyses were performed using SPSS Version 17.0.

STATISTICAL ANALYSIS

The primary output of this study was a determination of the normal range of TCOM readings when measured on the arm of healthy volunteer subjects. Baseline demographic characteristics of male and female subjects were compared using Fisher's Exact Test or Student's t-test, as appropriate. Descriptive statistics (mean, standard deviation, 95% confidence interval (CI)) are reported for TCOM readings for the six sensor sites. Differences between TCOM readings for male and female subjects were evaluated using Student's t-test. Based on previous reports of mean TCOM readings at other upper limb sites ranging from approximately 58 to 74 mmHg with a standard deviation of approximately 10 mmHg,[13–15,17] the sample size of 32 subjects was expected to allow us to estimate TCOM readings with a 95% CI of ± 3.5 mmHg for the overall group, and to have 80% power (with $\alpha = 0.05$) to detect a 10 mmHg difference in mean TCOM readings of males versus females using Student's t-test. Correlations between baseline perfusion measures of systolic blood pressure (SBP), diastolic blood pressure (DBP), and oxygen saturation (SpO_2) in the randomised limb and room-air as well as on-oxygen TCOM readings at each sensor site were evaluated using linear regression, with Bonferroni correction for multiple observations.

Table 1
Demographic and baseline characteristics of the 32 subjects

Variable	Males (*n* = 16)		Females (*n* = 16)		Combined	
Age (yr, mean (SD))	46.1	(0.8)	47.5	(13.0)	46.8	(11.8)
< 50 years old (*n*)	9		8		17	
Body mass index (kg m^{-1}, mean (SD))	26.5	(2.9)	27.3	(7.1)	26.9	(5.4)
Underweight (BMI< 20) (*n*)	0		1		1	
Overweight (BMI > 25) (*n*)	10		2		12	
Obese (BMI > 30) (*n*)	2		4		6	
Oxygen saturation (SpO_2) (%, mean (SD))	97.2	(1.2)	98.0	(1.5)	97.6	(1.4)
Heart rate (beats min^{-1}, mean (SD)	66.7	(9.8)	70.6	(17.1)	68.6	(13.9)

Table 2
Mean (standard deviation) and 95% confidence interval (95% CI) for TCOM readings for each sensor at each protocol stage (mmHg); * *P* < 0.001 for difference between male and femals subjects (see text)

Sensor (mmHg)	Room air (20 min)		Arm elevated (5 min)		Oxygen(10min)	
Chest	50.1	(11.4)	51.2	(11.7)	358.1	(53.5)
95% CI	46.0–54.2		47.0–55.4		338.8–377.3	
Upper arm	53.0	(9.3)	53.1	(10.4)	379.8	(67.8)
95% CI	49.7–56.4		49.3–56.8		355.3–404.2	
Forearm	44.5	(11.3)	40.7	(11.3)	298.4	(68.1)
95% CI	40.4–48.6		36.6–44.8		273.8–322.9	
Dorsum	38.6	(8.5)	29.4	(9.8)	217.4 *	(73.5)
95% CI	35.5–41.7		25.9–33.0		191.0–243.9	
Thenar eminence	54.4	(7.7)	46.0	(9.1)	248.0	(48.1)
95% CI	51.7–57.2		42.8–49.3		230.7–265.4	
Hypothenar eminence	56.8	(7.5)	51.6	(7.7)	206.3	(60.7)
95% CI	54.1–59.6		48.8–54.3		184.5–228.2	

Results

Data were collected from all 32 subjects. Demographic and baseline data are shown in Table 1. The subjects ranged in age from 25 to 78 years. More men than women were overweight (Fisher's Exact Test, *P* = 0.022), but otherwise there were no differences in the baseline demographics of males and females.

There was also no association between TCOM measurements and age, body mass index or hand dominance (right versus left). Baseline measures of perfusion were clinically normal in all subjects: mean (standard deviation (SD)): $BP_{systolic}$ = 117.6 (9.9); $BP_{diastolic}$ = 71.0 (9.4); and oxygen saturation = 97.6 (1.4). All but two subjects were right-handed.

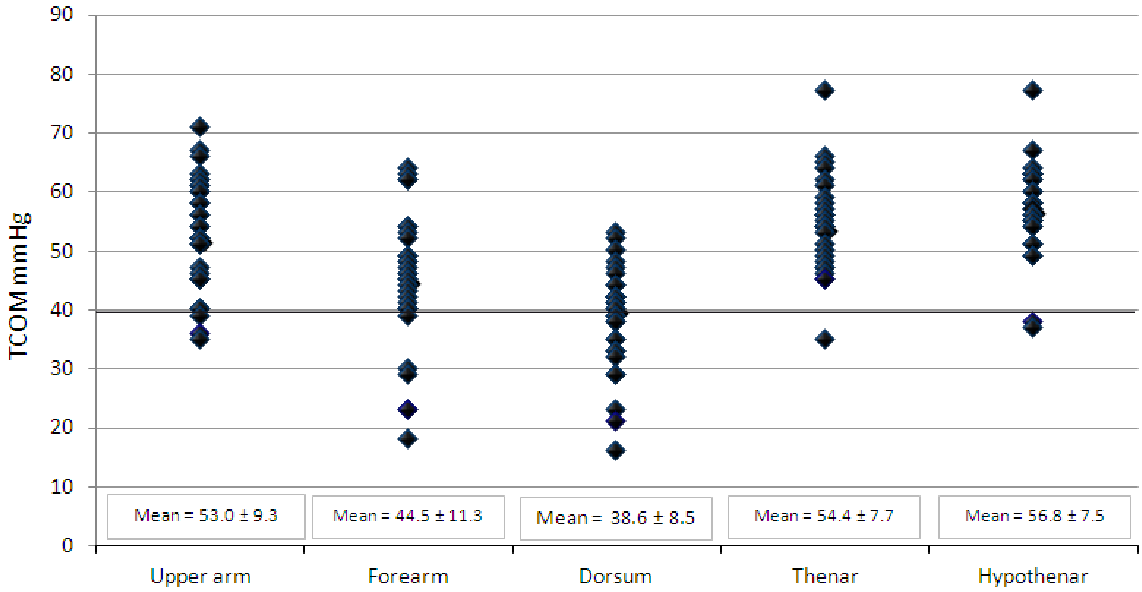
The TCOM readings for each sensor site were normally distributed, both in the aggregate and for males and females separately. The mean (SD) and 95% confidence intervals for the sensor readings at each protocol stage are shown in Table 2.

The only significant difference between male and female TCOM readings were the on-oxygen measurements at the sensor placed on the dorsum of the hand (260.1 (95% CI 222.4 to 297.7) versus 174.8 (95% CI 149.5 to 200.0); Student's *t* = -4.006, *P* < 0.001). Expert consensus is that in normal subjects breathing 100% oxygen at normobaric pressure, TCOM on the extremities always increase to a value ≥ 100 mmHg.[10] However, at the dorsum sensor site two readings in females failed to reach this threshold.

Figure 1 shows the distribution of the TCOM readings obtained during the 20-minute room-air stage of the study protocol. Using the lower extremity reference value of 40 mmHg, 16.25% of the upper extremity readings obtained in our healthy volunteers would have been identified as 'hypoxic'.

There was a counter-intuitive negative correlation between both baseline $BP_{systolic}$ and room-air TCOM reading (ß = -0.35, r^2 = 0.163, *P* = 0.022), and baseline SpO_2 and on-oxygen TCOM readings (ß = -19.1, r^2 = 0.129, *P* = 0.043) at the dorsum sensor site, but neither of these remained significant after adjusting for multiple comparisons. There were no other significant correlations between perfusion measures and TCOM readings at any sensor site.

Figure 1
Distribution of TCOM readings at each sensor site on the upper limb (< 40 mmHg is regarded as hypoxic in the lower leg)



Discussion

TCOM is a non-invasive method of estimating tissue oxygenation for both the upper and lower limbs. The current normal reference values being used to interpret upper limb TCOM data originate almost entirely from chest and lower limb studies. This study demonstrates that the lower limb reference values lack specificity when used for upper limb TCOM. The inadequacy of using the lower-limb reference value of 40 mmHg is most apparent for the forearm and dorsum sensors: 18.8% of the forearm and 43.8% of the dorsum TCOM readings in our healthy subjects would be classified as 'hypoxic' using this value. Using a reference value of 30 mmHg for the upper arm as well as the thenar and hypothenar eminences would accurately characterise 100% of those TCOM readings; a much lower reference value of 20 mmHg (approximately two standard deviations below the mean reading in healthy subjects) would be required to accurately characterise 97% of the forearm and dorsum TCOM readings of this study.

Three papers have reported TCOM for the upper limb of normal healthy subjects. Cutaneous hypoxia in patients with systemic sclerosis (scleroderma) was investigated using the forearm as the measurement site, comparing their TCOM data with those of 10 'normal' controls.[14] However, the forearm TCOM exceeded 90 mmHg in one of the controls and 100 mmHg in another, suggesting air leak during measurement and precluding the use of these figures as upper limb reference values.

The reliability of TCOM on the dorsum of the hand was investigated in healthy volunteers and stroke patients with and without CRPS.[16] The dorsum TCOM from 18 healthy controls averaged 74.4 (11.8) mmHg on the first day of measurement, and 71.3 (10.3) mmHg on the second day of measurement. These values are substantially higher than the dorsum mean TCOM readings obtained in our study. This might be explained by the positioning of the patients. They recorded dorsum TCOM with subjects sitting upright with their arms resting on a table at the height of the heart, as opposed to the standard supine posture used in most clinical situations and studies, including ours.[16]

Planar optical oxygen sensors were compared to TCOM during tourniquet-induced forearm ischaemia in six non-smoking healthy males.[19] Forearm TCOM readings of 70.8 (19.1) mmHg again were higher than the mean forearm TCOM reading found in our study. However, that study used a lower than recommended electrode temperature of 40°C, which might introduce measurement bias into the results.

In our study, we attempted to control for factors that may unduly influence our results. Recent exercise, caffeine intake, cigarette smoking,[23] room temperature, subject posture, electrode temperature, calibration, and measurement technique all may alter TCOM. Therefore, we carefully adhered to defined inclusion and exclusion criteria and used a standardised measurement protocol. We attempted to duplicate the room environment and electrode temperature used in earlier studies. Previous TCOM studies on normal subjects were performed at a room temperature maintained between 21°C and 23°C.[4,6,7,9] Our study was performed in a draft-free room in the hospital environment at a temperature of 22.0–22.5°C. In line with earlier studies, our electrodes were set to 44°C, a temperature that promotes maximal vasodilatation but limits the risk of thermal injury.[4,5,7–9,22,24]

A possible explanation for the differences in our results compared to those of prior studies is that the TCM400 monitoring system may measure tissue oxygenation differently than earlier models. A curious observation is that our study recorded no normobaric room-air TCOM > 80 mmHg, yet such high values are prevalent in earlier lower limb studies.[4,5,8,9] We are unaware of any published studies evaluating measurement validity in different TCOM machines measuring the same physiologic value. The manufacturer of the TCM400 reports the device is accurate to within ± 2 mmHg.[21]

It is common practice to place a sensor on the anterior chest wall as a central reference that is reported to provide information regarding the cardio-respiratory status of the patient. Some clinicians use it to provide a 'relative value' with which to compare the TCOM value obtained near the wound site, and others calculate a 'regional perfusion index' (limb TCOM/chest TCOM) to aid limb assessment.[11,20,22] The conventional view is that the chest sensor measurement, unaffected by peripheral vascular disease, would be at least as high as the limb values. The mean chest sensor value in our study was lower than the mean values for the upper arm and two hand sensor sites. In fact, the chest sensor reading was below that of at least one arm/hand sensor reading in more than three-quarters of our healthy subjects. This differential was most pronounced for the thenar and hypothenar sensors, where 78% and 75% of the sensor readings, respectively, were greater than the chest sensor reading. One subject's room air chest sensor value was 13 mmHg, with arm/hand sensor readings ranging between 38 and 63 mmHg. This was confirmed by changing the TCOM machine and electrolyte solution and repeating the study at a later date.

A recent study investigating the chest and foot reference values of TCOM in diabetic patients compared to non-diabetic patients, also using the TCM400 monitoring system, similarly found the chest sensor TCOM readings in healthy non-diabetic patients were low with wide variation (chest 58.22 ± 12.47); indeed values in the 80s were considered outliers in that study.[25] The study used a different electrode temperature (43°C) and room temperature (25°C), and did not input a humidity control factor, suggesting those aspects of the TCOM protocol may not explain the low chest TCOM values observed in either study. Perhaps a more plausible explanation for low and varied chest TCOM values is that the values simply reflect a varied inter-individual tissue composition at this measurement site. A recent expert consensus statement confirms that a percentage of patients have an abnormally low chest TCOM reading, and the value of this site as a central reference is questionable.[10]

Our study has limitations. The selection of suitable sensor sites was dictated by the availability of flat surface areas where a fixation ring could be applied. Additionally, we wanted sites that would be clinically useful and relevant to the conditions and pathologies that affect the upper limb. The dorsum of the hand and palmer surfaces fit the above requirements; however, these are not straightforward measurement sites. The dorsum of the hand is dominated by bony metacarpals and large superficial blood vessels which we attempted to avoid during measurement. However, in attempting to explain the low values at this sensor site during air breathing and 100% normobaric oxygen, it is feasible that they could be due to the influence of de-oxygenated blood in the large superficial vessels close to the skin at this site. This could also be a possible explanation for the significantly lower values found in females breathing 100% oxygen; anecdotally the blood vessels in female subjects were often noticed to be more prominent.

The conventional view is that the palmer surfaces are not suitable measurement sites because areas of thickened skin are thought to produce artificially low TCOM values.[11,20] Contrary to this view, our study found that the palmer sensor sites recorded the highest TCOM with the least dispersion. Further studies investigating TCOM on palmer surfaces may be worthwhile. Our study was also limited in that we used one instrument type for TCOM. A further study comparing earlier and later model machines might be worthwhile but, as discussed above, the manufacturer of the TCM400 reports an accuracy of ± 2 mmHg.[21] Finally, our study speaks only to the specificity of healthy, disease-free upper limb TCOM values; we cannot comment on the sensitivity of our proposed thresholds in patients who have tissue hypoxia.

Conclusion

Normal upper limb TCOM readings are less than those established for the lower limb, and using lower-limb reference standards could result in false positive determinations of tissue hypoxia. Due to the wide variability in TCOM at the different sensor sites, we recommend TCOM ≤ 30 mmHg as indicative of tissue hypoxia in the upper arm, thenar eminence, and hypothenar eminence, and a TCOM ≤ 20 mmHg as indicative of tissue hypoxia in the forearm and dorsum of the hand. The value of the chest sensor as a central reference is questionable.

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