Effectiveness of Pulse Oximetry Versus Doppler for Tourniquet Monitoring

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ABSTRACT

Background: Pulse oximeters are common and include arterial pulse detection as part of their methodology. The authors investigated the possible usefulness of pulse oximeters for monitoring extremity tourniquet arterial occlusion. **Methods:** Tactical Ratcheting Medical Tourniquets were tightened to the least Doppler-determined occluding pressure at mid-thigh or mid-arm locations on one limb at a time on all four limbs of 15 volunteers. A randomized block design was used to determine the placement locations of three pulse oximeter sensors on the relevant digits. The times and pressures of pulsatile signal absences and returns were recorded for 200 seconds, with the tourniquet being tightened only when the Doppler ultrasound and all three pulse oximeters had pulsatile signals present (pulsatile waveform traces for the pulse oximeters). **Results:** From the first Doppler signal absence to tourniquet release, toe-located pulse oximeters missed Doppler signal presence 41% to 50% of the times (discrete 1-second intervals) and missed 39% to 49% of the pressure points (discrete 1mmHg intervals); finger-located pulse oximeters had miss rates of 11% to 15% of the times and 13% to 19% of the pressure points. On toes, the pulse oximeter ranges of sensitivity and specificity for Doppler pulse detection were 71% to 90% and 44% to 51%, and on fingers, the respective ranges were 65% to 77% and 78% to 83%. **Conclusion:** Use of a pulse oximeter to monitor limb tourniquet effectiveness will result in some instances of an undetected weak arterial pulse being present. If a pulse oximeter waveform is obtained from a location distal to a tourniquet, the tourniquet should be tightened. If a pulsatile waveform is not detected, vigilance should be maintained.

KEYWORDS: *tourniquet; hemorrhage; first aid; emergency treatment*

Introduction

It is desirable for extremity tourniquets to exert sufficient pressure to stop limb arterial blood flow.[1,2] Military-use data indicate tourniquet arterial occlusion may either be frequently lost or perhaps not initially achieved.[3] Laboratory data show the pressure exerted by extremity tourniquets declines quickly following completed tourniquet application, which is associated with loss of arterial occlusion.[4–7]

The noninvasive, laboratory gold standard for pulse detection distal to an extremity tourniquet is arguably audible Doppler ultrasound. Doppler ultrasound pulse detection depends on maintenance of correct sensor positioning and limitation of background noise: both challenging in a prehospital environment. An alternate noninvasive method of distal pulse detection is pulse oximetry. Pulse oximetry sensors for use on digits are designed to remain in place without operator assistance, do not require precise positioning over an artery, and are not affected by noise. However, pulse oximetry is affected by motion and can be affected by ambient light. Additionally, the designs of current clinical use pulse oximeters are optimized for display of accurate arterial oxygen saturation (Spo_2), not for indicating the presence of a weak arterial pulse.

The study purpose was to compare pulse oximetry pulse detection with Doppler pulse detection distal to an extremity tourniquet. The hypothesis was that pulse oximetry pulse detection would not match Doppler pulse detection.

Methods

The Drake University Institutional Review Board approved this prospective study involving the use of tourniquets on the thighs and arms of 15 healthy volunteers. The tourniquets were previously requested from and donated by m2® Inc. The pulse oximeters were provided by UnityPoint Health Des Moines, Iowa Methodist Medical Center.

Tourniquets

Ratcheting Medical Tourniquets (RMTs; m2® Inc, www.ratchetingbuckles.com) were used because their self-securing, ratchet-based tightening system allows

finer-resolution pressure control than can be achieved with current commercially available windlass systems. The study used two different RMT designs: the Tactical RMT (November 2014 manufacturing lot) and the Pediatric RMT (November 2014 manufacturing lot). The two designs differed only in ladder composition and ladder length: the Tactical RMT ladder had a higher tooth-load failure rating, and the Tactical ladder was 22.4cm long whereas the Pediatric ladder was 10.0cm long. Both tourniquet designs consisted of a fabric strap; a friction buckle composed of two overlapping, 4.0cm-diameter metal rings with a rough, friction-enhancing coating to secure the correctly routed strap around the limb; a thermoplastic polyamide ladder (linear rack with teeth); and a ratcheting buckle. The strap width was 3.8cm, the ladder width was 1.9cm with 2.5 teeth/cm, and the ratcheting buckle was 3.0cm wide by 4.5cm long with a 0.762cm-long slot to allow the cam action of the pawl when ratcheting.

The Tactical RMT was used on all thighs and most upper arms. The Pediatric RMT was used only on upper arms of small enough circumference that the pressure-measuring system could be affected by the Tactical RMT ladder length.

Doppler and Pulse Oximeters

The Doppler monitor used was an Ultrasonic Doppler Flow Detector Model 811 with 9.5MHz adult flat probe (Parks Medical Electronics; www.parksmed.com). The three pulse oximeters used were a Nellcor OxiMax N-600x (assigned the name Pulse Ox 1; Medtronics, www.medtronic.com), a more than 17-years-old Nellcor module inside its Spacelabs Medical multiparameter monitor (assigned the name Pulse Ox 2; Spacelabs Healthcare, www.spacelabshealthcare.com), and a Masimo Radical (assigned the name Pulse Ox 3; Masimo, www.masimo.com). Each pulse oximeter was set to its fastest available signal averaging; those modes were "Fast mode" for Pulse Ox 1 (2 to 3 second averaging), "4 second averaging" for Pulse Ox 2, and "2 second averaging" with "Fast Sat = No" for Pulse Ox 3.

Pressure Measurements

Pressures under each tourniquet were measured using a No. 1 neonatal blood pressure cuff (2.2cm × 6.5cm bladder, single tube). The cuff bladder was inflated to 10mmHg to 15mmHg above atmospheric pressure to avoid complete collapse of the bladder during tourniquet applications. Atmospheric pressure was used as baseline pressure. The cuff was taped to the tourniquet under the strap just beyond the ratcheting buckle attachment rivet.

The inflated bladder was connected to a gas pressure sensor system (Vernier Gas Pressure Sensor, Vernier LabPro interface, and Logger Pro Software; Vernier Software and Technology, www.vernier.com). Pressure was continuously displayed graphically with numeric values displayed every second. This system provided the Doppler and pressure timeline for each experiment. Each tourniquet application's data were saved as complete, combined graphic and numeric data. An example pressure trace is shown in Figure 1.

Friction-Pressure

Friction-pressure was taken when the strap secured with the friction buckle was pulled tightly around the limb and all hands were off the tourniquet. Obtaining a friction-pressure greater than 100mmHg was an application goal, and the person collecting the pressure data with the computer was to alert the appliers of inadequate friction-pressures.

Signal Gone Definitions

The Doppler signal was defined as "Signal Gone" when no audible distal arterial Doppler pulse signal could be heard with the ratcheting buckle returned to its rest position and the applier's hands off the tourniquet. Each pulse oximeter signal was defined as Signal Gone when the assigned rater(s) determined that a pulsatile plethysmographic waveform was no longer present.

Signal Return Definitions

The Doppler signal was defined as "Signal Return" when the distal arterial Doppler pulse signal again became audible. Each pulse oximeter signal was defined as Signal Return when the assigned rater(s) determined that a pulsatile plethysmographic waveform was again present.

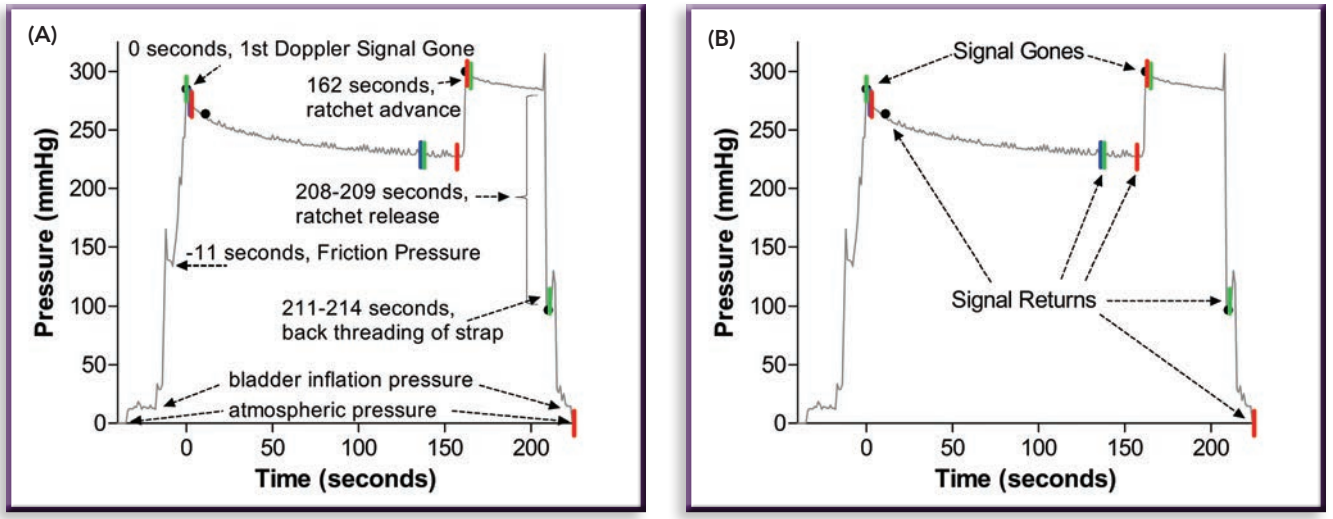
Signal Monitoring

The Doppler pulse signal monitoring locations were the radial artery in the wrist, the dorsal pedal artery on the top of the foot, or the posterior tibial artery at the ankle. The pulse oximeter monitoring locations were the index, middle, or ring finger or the first, second, or third toe. The pulse oximeter locations for each experiment were predetermined by drawing labeled slips of paper from a box in a randomized block design (each pulse oximeter was used at each location five times). The pulse oximeter sensors were the reusable, spring-hinged style designed for use on adult fingers, and each had a small sheet of matte black paper shielding it from the adjacent sensor.

Time and Pressure Determinations

The time and pressure for each Signal Gone and each Signal Return were recorded. The determinations of Signal Gone and Signal Return were by consensus of three listeners for the Doppler and by one or two independent raters for each pulse oximeter.

Figure 1 *Example thigh pressure trace with Signal Gones and Signal Returns.*



The continuous grey line shows the pressure under the tourniquet. The black dots indicate Doppler signal time points. The blue, green, and red lines indicate signal time points for the three respective pulse oximeters (Pulse Ox 1, 2, and 3). Baseline pressure, 0mmHg, is atmospheric pressure. The first small pressure-increase shelf represents bladder inflation pressure of 12mmHg. The pressure at –11 seconds represents friction-pressure (spike followed by hands off, 139mmHg). Zero seconds is the time and 285mmHg the pressure of the first Doppler Signal Gone. The first Signal Gones of all three pulse oximeters are clustered with the first Doppler Signal Gone (0–3 seconds). The first Signal Returns are indicated between 11 seconds (Doppler) and 136, 138, and 157 seconds (Pulse Ox 1, 2, and 3, respectively). The pressure increase at 162 seconds is from a single tooth advance of the ratcheting buckle. The second Signal Gones of the Doppler and each pulse oximeter are clustered at 162, 163, 165, and 165 seconds (Doppler and Pulse Ox 3, 1, and 2, respectively). The pressure spike with precipitous drop at 209 seconds occurs during ratcheting buckle release. The spike in the drop occurs with back threading of the strap through the friction buckle (211–214 seconds). The small pressure shelf is a return to inflated bladder pressure (220–223 seconds). The final pressure is a return to atmospheric pressure (224 seconds). The second Signal Returns occur at 210 seconds for Doppler and 211 seconds for Pulse Ox 1 and 2 and 225 seconds for Pulse Ox 3. (**A**) Pressure trace with labeled times. (**B**) Pressure trace with labeled Signal Gones and Returns.

Pulse Oximeter–Rater Synchrony and Agreement

Pulse Ox 1 had two raters for 32 of the 60 tourniquet applications. Pulse Ox 2 had two raters for 29 tourniquet applications. Pulse Ox 3 had two raters for 31 tourniquet applications. The synchrony of pulse oximeter rater stopwatch timing to the experiment timeline during each tourniquet application was determined, and any timings with greater than 2.13 seconds of asynchrony, one standard deviation from all synchrony absolute differences, were removed from the data set. This led to the removal of one complete set of Pulse Ox 2 data (single rater). The other four data set removals for asynchrony were from pulse oximeters with two raters; the synchronous data sets were retained. Synchronous-rater pulse oximeter timing agreement was 82.5% for calling Signal Gones within 2 seconds of each other and 80.5% for calling Signal Returns within 3 seconds of each other. Therefore, the times and associated pressures reported either are the averages from two raters or are from a single rater.

Duration

The tourniquet was not released until 205 seconds after the first instance of Doppler Signal Gone. After each tourniquet's release, the return (or absence) of the Doppler audible pulse signal was noted. Return of the Doppler signal confirmed that the prior Doppler audible signal absence was due to arterial occlusion and not Doppler probe movement away from the artery.

Tourniquet Appliers

There were five tourniquet appliers. Each had considerable practice applying RMTs before the study, including applying RMTs in one or more prior tourniquet studies for four of the appliers. There was also an applier assistant. The applier assistant pulled directly upward on the tourniquet handle while the applier pulled the strap directly downward, around the limb through the friction buckle. This assistance is not essential but was expected to aid the achievement of friction-pressures greater than 100mmHg.[6]

Tourniquet Recipients

Tourniquet recipients were volunteers familiar with the tourniquet study through a research course. They were a convenience sample of students and instructors. Recipient inclusion criteria were participation in a previous tourniquet study or participation in the related research course, ability to lie down and remain relaxed for 30 minutes, and age 18 years or older. Recipient exclusion criteria were self-reported blood clotting or circulation irregularities, connective tissue disorders, implants in relevant locations, systolic blood pressure higher than 140mmHg, pain syndromes, and peripheral neuropathies. Recipients completed an informed consent and

were able to have a tourniquet removed or to stop participating at any time.

Protocol

1. Recipient age, limb circumference, and blood pressure information was collected.
2. Recipients lay down throughout each application, with foam support and mid-range flexion of the relevant limb.
3. Recipients were directed to maintain the relevant limb in a completely relaxed state.
4. Sensor placements were established for a clear, audible Doppler pulse signal and for pulsatile pulse oximeter waveforms.
5. Tourniquets were applied directly on skin, with the friction buckle on the lateral aspect of each limb and the free end of the strap pulled downward through the friction buckle.
6. The limb order of use was left mid-thigh, left mid-upper arm, right mid-thigh, right mid-upper arm, with each entire iteration taking approximately 9 minutes.
7. After achieving friction-pressure, the tourniquet was tightened via advancement of the ratcheting buckle a single ladder tooth at a time just until the Doppler signal was gone. (This degree of tightening was to increase the probability that the Doppler signal would return at least once during most tourniquet applications.)
8. After a 10-second pause, the pulse oximeter raters were queried for any remaining pulsatile traces. If any pulsatile traces were still present, the ratcheting buckle was advanced an additional ladder tooth. This was to be repeated until all pulsatile traces were gone.
9. An additional single ladder tooth advance would occur whenever both the Doppler audible signal had returned and all pulse oximeters had pulsatile traces. This step remained operative until tourniquet release 205 seconds after the Doppler signal was first declared gone.
10. The number of ladder teeth advanced to the first Doppler Signal Gone was recorded.
11. During the tourniquet release and removal, sensor pressure returns to friction-pressure, the inflated bladder pressure, and atmospheric pressure were checked.
12. After sensor return to atmospheric pressure, a "3, 2, 1, stop" countdown was used to assess the time synchrony of each pulse oximeter rater stopwatch with the pressure sensor data experiment timeline.
13. Recipients verbally rated discomfort as None, Little, Moderate, or Severe.[8]
14. Any comments relating to the application were recorded.

Statistical Analysis

Numeric time and pressure data were organized in Microsoft Office Excel 2003 (Microsoft Corp; www.microsoft.com). Doppler versus pulse oximeter Signal Gones time and pressure data were analyzed using repeated measures multivariate analysis of variance with Tukey–Kramer post hoc tests.

Contingency data were analyzed using χ^2 tests for Doppler versus each pulse oximeter at every second from 1) the first Signal Gone to the last Signal Return and 2) from the first Doppler Signal Gone to tourniquet release via release of the ratcheting buckle. Contingency data were also analyzed using χ^2 tests for Doppler versus each pulse oximeter at every discrete 1mmHg interval from the first Doppler Signal Gone to tourniquet release. The time points and pressure points from the first Doppler Signal Gone to tourniquet release were deemed to be the more relevant for evaluating the potential usefulness of a pulse oximeter for field monitoring of tourniquet effectiveness because release would not be expected to occur until definitive care of the injury was occurring.

Graphing and statistical analyses were performed with GraphPad Prism version 5.02 for Windows (GraphPad Software Inc; www.graphpad.com). Statistical significance was set at $p \leq .05$.

Results

Tourniquets were applied to seven men and eight women. None requested any early tourniquet removals. Recipient characteristics are shown in Table 1.

Table 1 *Characteristics of Tourniquet Recipients*

Characteristic	Median (Minimum–Maximum)
Age (years)	21 (18–56)
Extremity circumference (cm)	
Right mid-thigh	50.5 (44.0–59.2)
Right mid-brachium	28.0 (25.0–30.0)*
Left mid-thigh	51.0 (44.0–59.2)
Left mid-brachium	29.0 (24.5–30.5)*
Blood pressure (mmHg)	
Right arm, systolic	102 (88–118)
Right arm, diastolic	64 (54–76)
Left arm, systolic	102 (86–120)
Left arm, diastolic	62 (50–78)

*The median mid-brachium circumference of the arms that received the Pediatric Ratcheting Medical Tourniquet was 25.7cm and the maximum was 27.3cm.

Excluded Data

Pressure data from arms small enough to require the Pediatric RMT were excluded. Time and pressure data from one arm application were excluded following the first Signal Gones because no Doppler Signal Return occurred on tourniquet release, indicating a change in Doppler sensor position had occurred. Time and pressure data from one arm and two thigh applications were excluded following the second Signal Gones because no Doppler Signal Returns occurred on tourniquet release, indicating a change in Doppler sensor position had occurred.

Signal Time and Pressure Comparisons

As can be seen in Figure 1, the first Signal Gones of the pulse oximeters were generally close in time and pressure to the first Signal Gone of the Doppler. This was generally true of any Signal Gones that resulted from a tightening of the tourniquet; in Figure 1, see the abrupt, discrete pressure increase at 162 seconds and tight grouping of second Signal Gones for Doppler and each pulse oximeter. Signal Returns had much more variable spacing, especially those Signal Returns that occurred prior to release of the tourniquet; see the ratchet release pressure drop at 209 seconds in Figure 1.

As indicated in Table 2, all tourniquet applications achieved a first Doppler Signal Gone. Of the 60 first Doppler Signal Gones, seven thigh and two arm Doppler Signal Gones were preceded by a pulse oximeter Signal Gone on the immediately preceding ratcheting buckle single ladder tooth advance. One thigh, first Doppler Signal Gone was preceded by a pulse oximeter Signal Gone two ladder teeth prior, during the ratcheting buckle advance.

The strategy of limiting the initial advance of the ratcheting buckle to the least number of ladder teeth needed to achieve Doppler Signal Gone succeeded in providing one or more pre–tourniquet release Doppler Signal Returns with almost every thigh tourniquet application and most arm tourniquet applications. The times and pressures of the Signal Gones within any single tourniquet application were generally closely clustered because most Signal Gones occurred in response to the same ratcheting buckle advance on the ladder (Figure 2A, 2B). Doppler Signal Gones occurred at slightly higher pressures than did pulse oximeter Signal Gones ($p = .011$).

The pre–tourniquet release Signal Returns were generally spread out in time and, to a lesser extent, in pressure; they occurred as pressure declined under the tourniquet (Figure 2C, 2D). Signal Returns had to occur with all four monitoring devices before an advance of the ratcheting buckle would take place. Of the 55 pre–tourniquet release Doppler Signal Returns, two thigh Doppler Signal Returns were preceded by a pulse oximeter Signal Return. The time and pressure differences of those two pulse oximeter Signal Returns from their trailing Doppler Signal Returns were 88 seconds, 9mmHg and 59 seconds, 5mmHg.

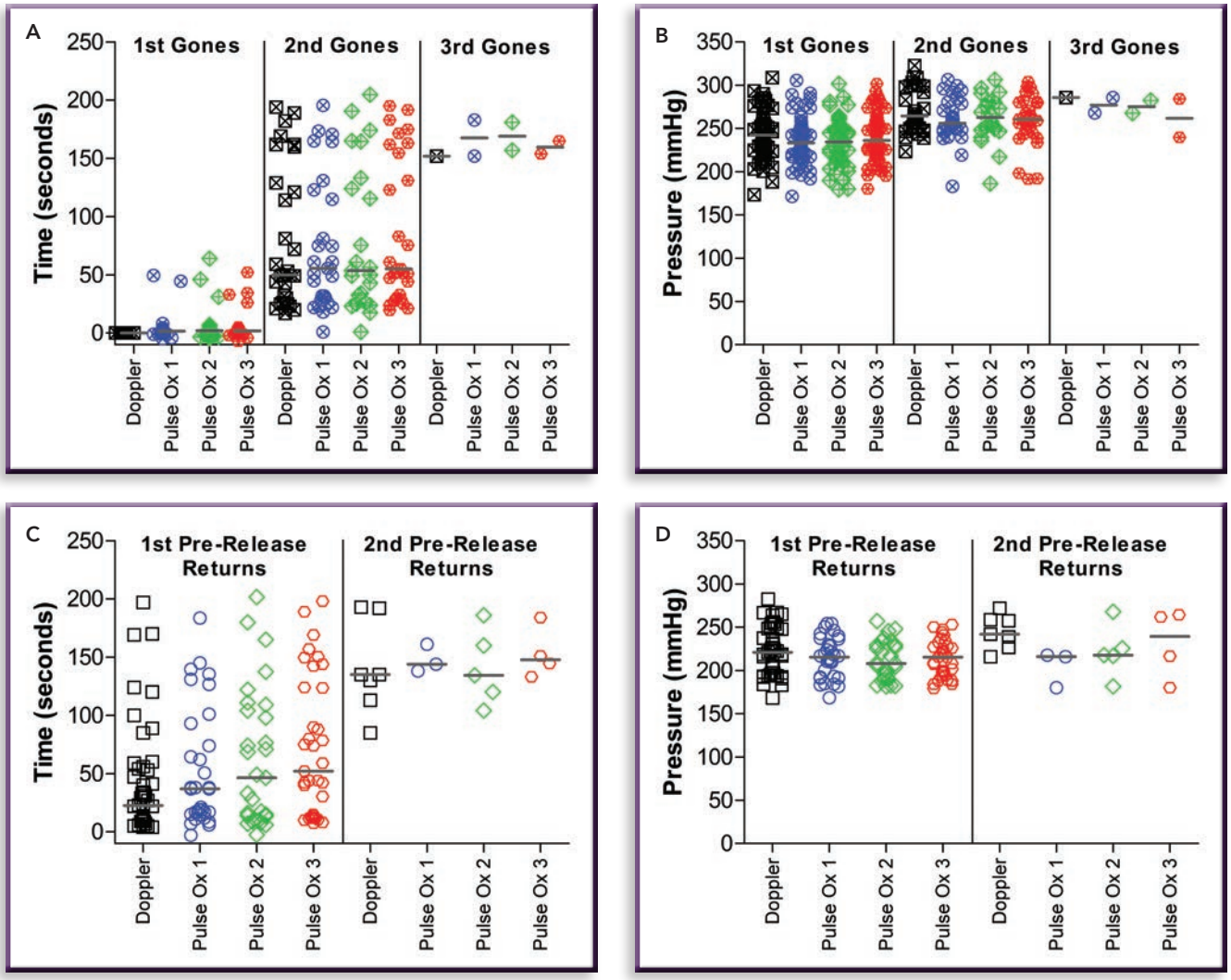
Table 2 *Changes in Pulse Status as Indicated by Doppler Signal*

Doppler Signal	Extremity	
	Thigh	Arm
First		
Gones	30	30
Returns		
Prerelease	29	19
Postrelease	1	10*
Second		
Gones	15	14
Returns		
Prerelease	4	3
Postrelease	10†	9‡
Third		
Gones	NA	1
Returns		
Prerelease	NA	0
Postrelease	NA	1

Gones, no audible distal arterial Doppler pulse signal present with the ratcheting buckle in its rest position and the applier's hands off the tourniquet; Returns, audible distal arterial Doppler pulse signal present after being gone; Prerelease, before tourniquet release; Postrelease, after tourniquet release; NA, not applicable.
*One first Doppler Signal Gone on the arm did not have a Doppler Signal Return.
†One second Doppler Signal Gone on the thigh did not have a Doppler Signal Return.
‡Two second Doppler Signal Gones on the arm did not have Doppler Signal Returns.

The post–tourniquet release Signal Returns occurred in response to a large pressure decrease in a very short interval, so a few seconds of difference in Signal Return times corresponded to large differences in Signal Return pressures. Post–tourniquet release Signal Returns probably have little clinical relevance for field monitoring of the adequacy of tourniquet tightness and are not graphically shown. The differing times for the pulse oximeters to show a pulsatile waveform post–tourniquet release do, however, have clinical relevance as indicators of pulse oximeter internal signal-processing effects on when and if a pulsatile waveform is displayed. After tourniquet release, the delay before post–tourniquet release, pulse oximeter Signal Returns ranged from 1 to 31 seconds.

Figure 2 *Times and pressures of Signal Gones and Signal Returns.*



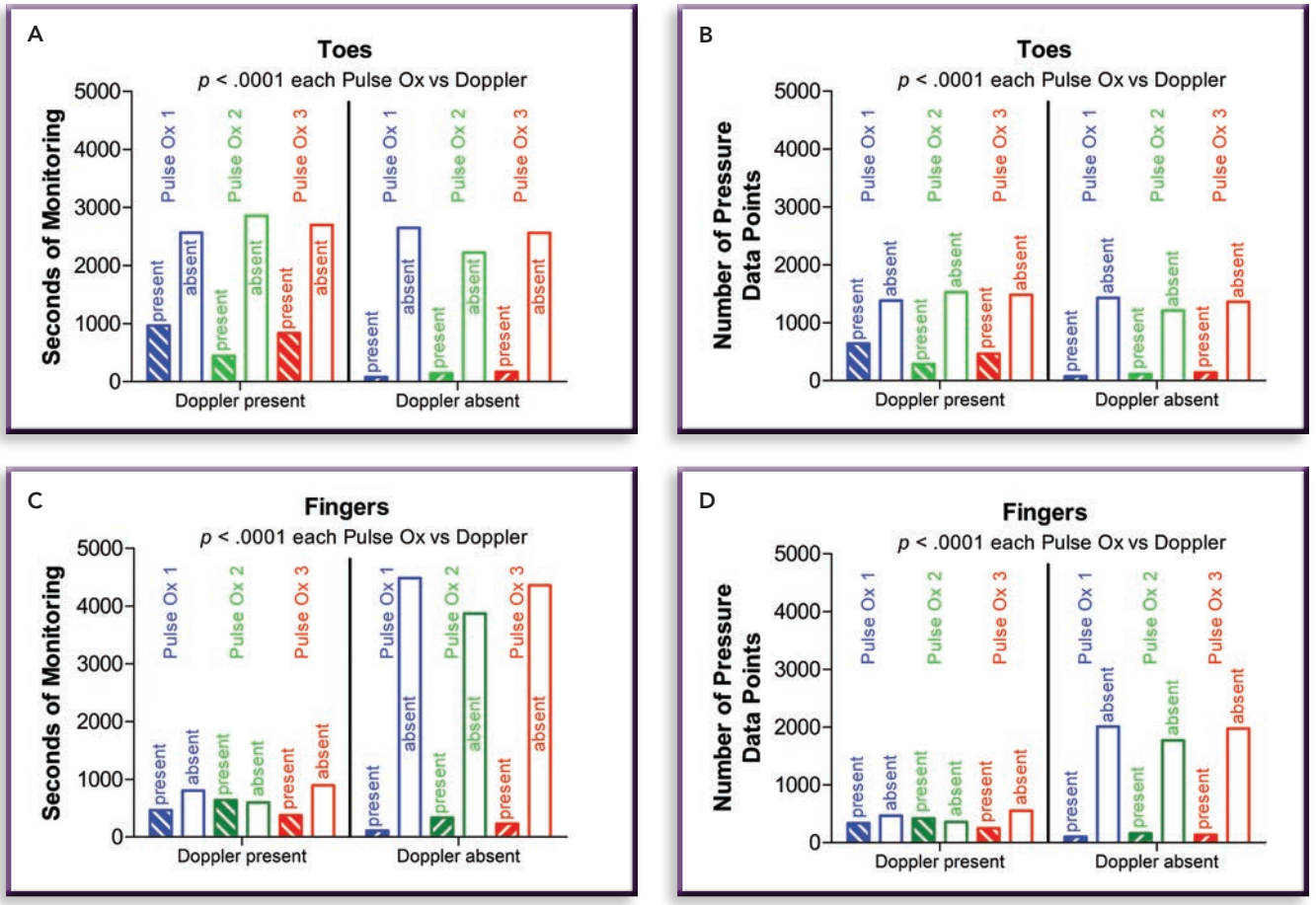
Black squares indicate Doppler signals. Blue circles indicate Pulse Ox 1 signals. Green diamonds indicate Pulse Ox 2 signals. Red hexagons indicate Pulse Ox 3 signals. Symbols with x's inside indicate Signal Gones. Symbols without x's inside indicate Signal Returns. Grey lines within each group of symbols indicate medians. (**A**) Times of Signal Gones. Most first Signal Gones were tightly clustered. Ratcheting buckle advances to create second and third Signal Gones only occurred after all four monitoring devices had Signal Returns. (**B**) Pressures of Signal Gones. Second Signal Gones were at slightly higher pressures than were first Signal Gones, which would decrease the chance of third Signal Returns. (**C**) Times of pre–tourniquet release Signal Returns. Pre–tourniquet release Signal Returns were not tightly clustered in time and did not always occur for every monitor. (**D**) Pressures of pre–tourniquet release Signal Returns. Pre–tourniquet release Doppler Signal Returns occurred at higher pressures than did pulse oximeter Signal Returns.

Of the 31 Doppler Signal Returns that occurred post–tourniquet release, one was preceded by a pulse oximeter Signal Return. That pulse oximeter Signal Return preceded tourniquet release by 21 seconds and 0mmHg.

As shown in Figure 3, the matching of pulse oximeter signal presence with Doppler signal presence was different for toes and fingers. The pulse oximeter sensors that were used had better signal detection when used on fingers than on toes. This was true when analyzed by time points and analyzed by pressure points. The sensitivity and specificity values of each pulse oximeter for Doppler pulse detection between first Doppler Signal Gone and pre–tourniquet release are shown in Table 3.

Inclusion of the time points from any first Signal Gone to that of the last Signal Return resulted in slightly increased sensitivities for Doppler pulse detection. Nevertheless, the time-based pulse oximeter miss rate for Doppler pulse present remained high for toes and significant for fingers. The time-based pulse oximeter missed Doppler presence between first Doppler Signal Gone and pre–tourniquet release was 41% to 50% of the time for toes and 11% to 15% of the time for fingers and between first any Signal Gone and last Signal Return was 38% to 47% of the time for toes and 11% to 17% of the time for fingers. The pressure-based pulse oximeter miss rate for Doppler pulse presence from Doppler Signal Gone to pre–tourniquet release was 39% to 49%

Figure 3 *Time- or pressure-based matching of signal presence or absence between the Doppler and each pulse oximeter.*



Each panel shows time- or pressure-based matching of the presence or absence of a Doppler signal with that of each pulse oximeter for every second or every discrete 1mmHg interval from the first Doppler Signal Gone to tourniquet release. Pulse oximeter signals were predominantly not present when a Doppler signal was absent. However, pulse oximeter signals were absent a significant portion of the tourniqueted time and pressure during which a Doppler signal was present, especially when pulse oximeters were on toes. Blue indicates Pulse Ox 1 versus Doppler. Green indicates Pulse Ox 2 versus Doppler. Red indicates Pulse Ox 3 versus Doppler. Vertical bars with colored diagonal lines indicate the presence of the respective pulse oximeter signal. Clear vertical bars indicate the absence of the respective pulse oximeter signal. Vertical bars in the left half of each graph indicate the pulse oximeter signal status while a Doppler signal was present. Vertical bars in the right half of each graph indicate the pulse oximeter signal status while a Doppler signal was absent. (**A**) Thigh tourniquet applications with pulse oximeter sensors on toes: time-based data. (**B**) Thigh tourniquet applications with pulse oximeter sensors on toes: pressure-based data. (**C**) Arm tourniquet applications with pulse oximeter sensors on fingers: time-based data. (**D**) Arm tourniquet applications with pulse oximeter sensors on fingers: pressure-based data.

of the pressure points for toes and 13% to 19% of the pressure points for fingers.

Evaluation of the sensitivity and specificity confidence intervals for each toe indicated that, with the pulse oximeter sensors used in this study, some differences in signal detection may exist between the various toes, perhaps related to toe length. The sensitivity and specificity confidence intervals for each finger also indicated the possibility of some differences in signal detection between the various fingers. None of the toes, however, had specificities close to the specificities of any of the fingers.

Discomfort

The discomfort ratings are shown in Table 4. Most applications received discomfort ratings of None or Little.

Discussion

The key finding of this study is that use of a pulse oximeter to monitor limb tourniquet effectiveness will likely result in some instances of an undetected weak arterial pulse being present. This will be true even more frequently with the use of a standard adult finger sensor on a toe. These findings leave Doppler ultrasound as the de facto gold standard for noninvasive monitoring of tourniquet effectiveness in laboratory studies and offer caution if using pulse oximetry to monitor tourniquet effectiveness in a field setting.

Some patients with field-placed extremity tourniquets arrive at more advanced care locations with distal arterial pulses present.[3] Pulse oximetry is an already widespread monitoring technology that looks at pulsatile blood

Table 3 *Sensitivities and Specificities of Pulse Oximeters for Doppler Pulse Detection*

	Sensitivity,* % (95% CI)		Specificity,* % (95% CI)	
	Time	Pressure	Time	Pressure
Toes				
Pulse Ox 1	92 (91–94)	90 (87–92)	51 (49–52)	51 (49–53)
Pulse Ox 2	76 (72–79)	71 (66–76)	44 (42–45)	44 (42–46)
Pulse Ox 3	83 (81–86)	77 (73–80)	49 (47–50)	48 (46–50)
Fingers				
Pulse Ox 1	88 (86–90)	77 (72–81)	83 (82–84)	81 (80–83)
Pulse Ox 2	76 (74–78)	72 (68–76)	85 (84–86)	83 (82–85)
Pulse Ox 3	75 (72–78)	65 (60–69)	80 (79–81)	78 (76–80)

CI, confidence interval.
Three different pulse oximeters were used. Pulse oximeter (Pulse Ox) 1: Nellcor OxiMax N-600x; Pulse Ox 2: a more than 17-years-old Nellcor module inside its Spacelabs Medical multiparameter monitor; and Pulse Ox 3: a Masimo Radical.
*Sensitivity and specificity values are for comparisons for every second or every discrete 1mmHg pressure point from the first Doppler Signal Gone to tourniquet pressure release (release of the ratcheting buckle).

Table 4 *Discomfort Ratings Associated With Tourniquet Applications*

Tourniquet Location	Discomfort Rating			
	None	Little	Moderate	Severe
Thigh (n = 30)	2	21	7	0
Arm (n = 30)	6	21	3	0

flow in digits, so the use of pulse oximetry to monitor tourniquet effectiveness when a distal digit is still present is appealing. However, current pulse oximeters are designed with a priority on providing Spo_2 values that accurately indicate arterial hemoglobin saturation with oxygen. This priority results in variable amounts of signal processing, some of which may decrease detection of very weak arterial pulsatile flow. In fact, the worst situations for pulse oximetry accuracy are those of large blood flow changes, such as during tourniquet application and tourniquet release; low arterial flow, such as occurs under a tourniquet that is no longer quite tight enough; and sensor motion, such as is likely during casualty transport.

Despite the caveats of pulse oximetry, it does avoid the major disadvantages of Doppler ultrasound for tourniquet effectiveness monitoring in a nonlaboratory setting. Those disadvantages are (1) difficulty maintaining precise sensor positioning regarding anatomic location, orientation relative to the underlying artery, and pressure exerted on the underlying artery and (2) background noise.

Loss of tourniquet arterial occlusion can be thought of as a time-dependent phenomenon with total risk increasing as the time from tourniquet application increases. In the mere 200 second timespan used in this study, the strategy of tourniquet tightening only sufficiently to achieve arterial occlusion resulted in loss of tourniquet arterial occlusion in 48 of 59 tourniquet applications and a second loss of tourniquet arterial occlusion in seven of those 48 applications in the limited time remaining after additional tightening. These losses of arterial occlusion occurred in a nonchallenging, laboratory environment with no transportation-related movement of the subjects, no major changes in the muscle tension of the subjects, and no reason for changes in the subjects' blood pressures. Clearly, the risk for loss of tourniquet arterial occlusion exists in the demanding conditions encountered during patient care. Additionally, the consequences of loss of tourniquet arterial occlusion increase with the magnitude and duration of arterial inflow in the absence of venous return.[2] Ideally, limb tourniquet use times are short, but even in the continental United States, limb tourniquet durations longer than 2 hours are reported.[9–13] Pulse oximetry is currently the only hands-free, commonly available monitoring technology that offers continuous monitoring for an extremity distal arterial pulse. The risks and consequences of loss of tourniquet arterial occlusion indicate a strong need for vigilance after tourniquet placement. Therefore, despite the sensitivity drawbacks, incorporating distal monitoring with pulse oximetry probably has value when feasible.

For application to field use, this study had the standard laboratory limitations of an ideal setting: no subject limb or total body motion, and low ambient noise levels. Both Doppler ultrasound and pulse oximeter detection of distal arterial pulses would be expected to be worse in field use. An additional application limitation is that the results are only for the presence or absence of a visibly pulsatile waveform and are not for the presence or absence of pulse oximeter Spo_2 or heart rate numbers.

Two strengths of this study are the use of human subjects and several different pulse oximeters. Two additional strengths are the randomized block design, which ensured each pulse oximeter sensor was used an equivalent number of times on each digit, and the use of paired raters, whose high level of agreement regarding the presence or absence of a pulsatile waveform suggests ecologic validity concerning the likely waveform judgments of other users.

Conclusion

Current pulse oximetry can be thought of as a screening technology for extremity tourniquet effectiveness. When a pulsatile waveform is obtained from a location distal to an extremity tourniquet, the tourniquet should be tightened. When a pulsatile waveform is not detected, vigilance should be maintained.

Disclosures

None of the authors have any financial relationships relevant to this article to disclose, and there was no outside funding.

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