Improved Tracking of Limb Occlusion Pressure for Surgical Tourniquets

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Abstract—**Constant-pressure tourniquets are widely used to occlude blood flow into a patient's limb to facilitate the performance of a wide variety of surgical procedures. "Adaptive tourniquets" that automatically adjust the cuff pressure to the minimum necessary for occlusion ("limb occlusion pressure") as a function of the patient's changing systolic blood pressure will reduce the incidence of tourniquet-related injuries. However, these devices have not been widely used, largely due to problems in tracking the systolic blood pressure safely, accurately, and reliably in clinical environments with noise present. Initial lab trials and clinical trials compared the performance in tracking limb occlusion pressure during varying noise conditions of a typical oscillometric blood pressure monitor with that of a prototype system. The prototype system functions by detecting noise and rapidly estimating limb occlusion pressure using only data uncorrupted by noise. Results showed that the prototype consistently estimated limb occlusion pressure more rapidly, more accurately, and more reliably than the oscillometric monitor in noisy conditions typical of surgical procedures. The results also indicate that the prototype is feasible for incorporation into an adaptive tourniquet.**

INTRODUCTION

PNEUMATIC tourniquets are used on upper and lower extremities to apply sufficient pressure to a limb to occlude the underlying arteries, thus stopping blood flow into the limb. In this way, tourniquets create a bloodless operative field that makes dissection easier, surgical techniques less traumatic, and operation time shorter [1], facilitate intravenous regional anesthesia (IVRA) [2], and enhance the treatment of limb sarcoma [3]. The benefits derived from tourniquet use are recognized to decrease the surgical and anesthetic risk to the patient, as substantiated by the tourniquet's prevalent use in over one million procedures yearly in North America [4]. However, associated with the use of pneumatic tourniquets are continuing reports of tourniquet-related injuries to the patient [5]. Factors contributing to these complications are pressures employed, cuff characteristics and techniques of application, and excessive periods of inflation [4], [5].

The frequency and degree of tourniquet-induced complications can be reduced by using the minimum cuff pressure that still occludes arterial flow into the limb ("limb occlusion pressure") [6]. Such pressure regulation will eliminate not only the underpressurization hazard that can result in shock, blood in the surgical field, venous congestion, IVRA complications, and nerve damage, but also the overpressurization hazard that can produce paralysis, muscle weakness, and compression injury to underlying tissues [3]–[5].

The limb occlusion pressure required to improve tourniquet safety is a varying parameter that will be different for each operation since this optimal pressure setting will be affected by the ratio of the limb circumference to cuff width [7], type of cuff, method of cuff application, limb position, limb shape, limb physiology, and the patient's intraoperative systolic pressure [1], [3]. However, this optimal pressure value is rarely used by either constant-pressure tourniquets, which must account for worst case conditions [1]–[8], or previously developed adaptive tourniquets [1], [9], which adjust pressures based on systolic pressure estimates but suffer from performance degradation in the presence of limb movement and other noise artifacts occurring during surgery.

OBJECTIVES

The overall objective of our work has been to improve the clinical performance of adaptive tourniquets by developing a safer, faster, more accurate, and more reliable method and apparatus for tracking limb occlusion pressure in moderately noisy surgical environments. Our approach has been to analyze only data obtained from the brief noise-free intervals that often separate recurring noisy periods in realistic clinical situations, and to use these data to examine flow conditions past a variably pressurized cuff kept near the limb occlusion pressure. To facilitate this approach, our first objective was to develop a new cuff that would provide the means to detect noise, estimate limb occlusion pressure rapidly, act as an occluding cuff, and reduce the errors associated with the use of separate occluding and pressure-estimation cuffs on different limbs. Our second objective was to develop and evaluate an algorithm that might make use of this new cuff to estimate limb occlusion pressure more accurately where the algorithm would be based directly on physiological factors (flow past a cuff) and not on oscillometric techniques that indirectly estimate systolic pressure by evaluating the relative heights of oscillometric pulses in relation to a range of cuff pressures [10], [11].

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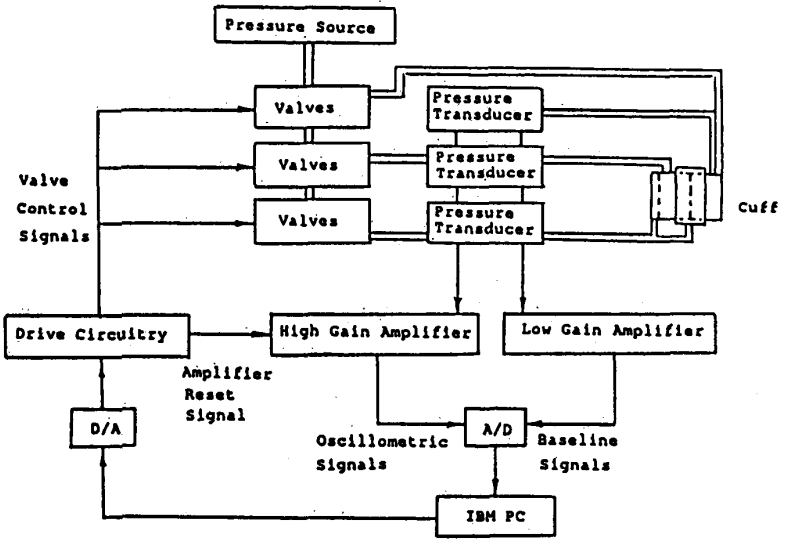

Fig. 1. Components of the prototype system.

System Components

As illustrated in Fig. 1, and as described in greater detail elsewhere [12], the prototype system that was developed is comprised of the following components:

1) a multibladder tourniquet cuff that has identical proximal and middle bladders (2.5 in × 34 in for the leg and 2 in × 24 in for the arm), and a two-piece noise bladder with a 0.25 in wide component at a distal location and a 2 in external section encircling the proximal and middle bladders (fabricated from cuffs made by Aspen Labs/Zimmer that have plastic-reinforced fabric sheaths with removable bladders);

2) one pressure transducer (Cobe Disposable Pressure Transducer) connected to each bladder;

3) three low-gain instrumentation amplifiers for measuring baseline cuff pressures (0–0.5 Hz bandwidth, gain typically 800);

4) a three-channel, high-gain amplifier (Beckman Accutrace 200 EEG Amplifier) to measure and record small pressure pulsations from the three bladders (0.16–15 Hz bandwidth, 60 Hz notch filter, remote reset, gain typically 100 000);

5) an IBM PC with 8 bit A/D and D/A capability;

6) valve and relay drive circuitry;

7) electrically controlled pneumatic valves for pressure regulation (Clippard model EVO-3-12); and

8) a constant pressure source (Aspen model ATS 1000 Automatic Tourniquet).

Component choice and assembly was made to improve the performance of the system. Identical parts of the same cuff were used for occlusion and for estimating limb occlusion pressure to minimize errors associated with multicuff systems arising from differences in location, limb anatomy, and cuff application [1], [3]. Furthermore, the noise sensor was located close to the flow sensor to improve the correlation between the detection of noise and the occurrence of a corrupted flow signal. The pressure transducers and pressure-regulating valves were mounted close to the cuff, with less than 3 ft of connecting hoses, to decrease the total volume of the measurement system. This reduced inflation time and decreased both pneumatic damping and attenuation of the oscillometric signal. Step-response data indicated that the pneumatic system behaved as a second-order underdamped system, with a damping factor near 0.2 and a natural frequency near 50 Hz. Because spectral analysis of oscillometric signals typically showed that frequency components above 8 Hz were 30 dB below peak power components, it appeared that little pulse information was lost by passing the signals through an 8 Hz *RC* low-pass filter before sampling at 18 Hz, a rate sufficiently low to allow for real-time processing of data in between samples. A ninth-order digital FIR bandpass filter, with 3 dB frequencies of 1.4 Hz and 7.6 Hz, was also implemented to reduce baseline wandering of the oscillometric signal.

System Implementation

Noise detection, rapid estimations, and reduction of errors associated with the use of separate cuffs on different limbs were made possible by the development of the multibladder cuff shown in Fig. 2. The proximal bladder of the cuff is used as a "flow valve," systematically blocking and permitting blood flow to the other two bladders through an adjustment of the pressurization to supraocclusive and subocclusive values, respectively. The middle bladder serves as both the occluding device and a flow detector since the pulsatile arterial flow past the proximal bladder displaces the arterial wall to produce small pressure pulses in the middle bladder. The final bladder is a two-piece component that detects motion artifacts, with one section located at the distal end of the cuff to sense the relative movement between the cuff and limb, and the

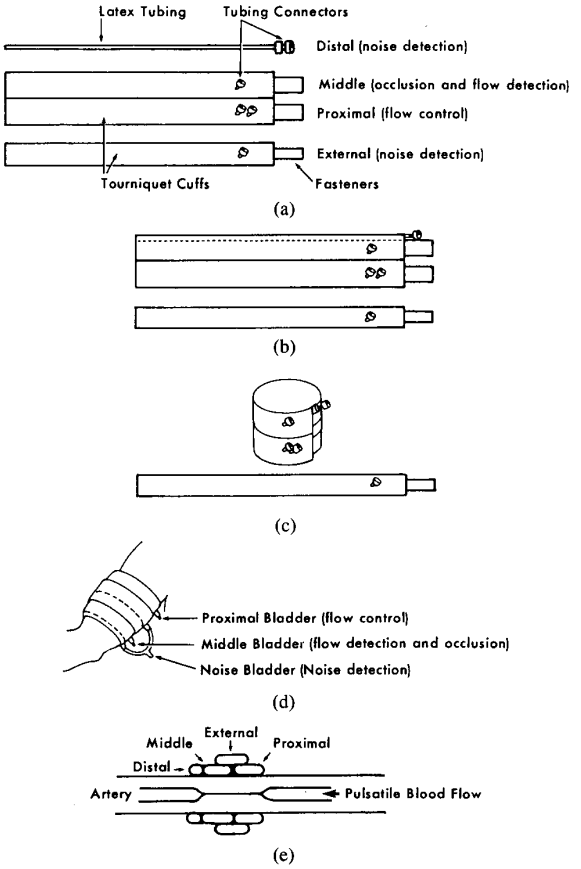

Fig. 2. The figure shows the multibladder cuff, including (a)–(c) its assembly, (d) its application onto an arm, and (e) a simplified cross section view of the cuff on a limb. Separate bladders are used for flow control, flow detection and occlusion, and noise detection.

other positioned over the proximal and middle bladders to detect external impacts against the cuff. Because of its position over and distal to the occluding cuff, no flow-induced pulsations should be present in this bladder.

Fig. 3 shows the relationship between typical waveforms seen in the various bladders. When the middle bladder is properly occluding underlying arteries, pulses in the noise bladder can only be caused by noise artifacts that also disturb the signals in the other bladders. The misinterpretation of noise artifacts for flow-induced signals in the middle bladder is avoided by suspending processing when any pulses are detected in the noise bladder. The absence of noise-induced pulses in the noise bladder indicates that the signal in the middle bladder is not corrupted by noise and accurately reflects the actual state of arterial flow past the proximal bladder, the clinical condition we desire to detect. Under noise-free conditions, the absence or presence of flow-induced pulses in the middle bladder determine if the proximal bladder pressure is above or below the required limb occlusion pressure, respectively.

With this integrated cuff, we attempted to develop an algorithm for estimating limb occlusion pressure which

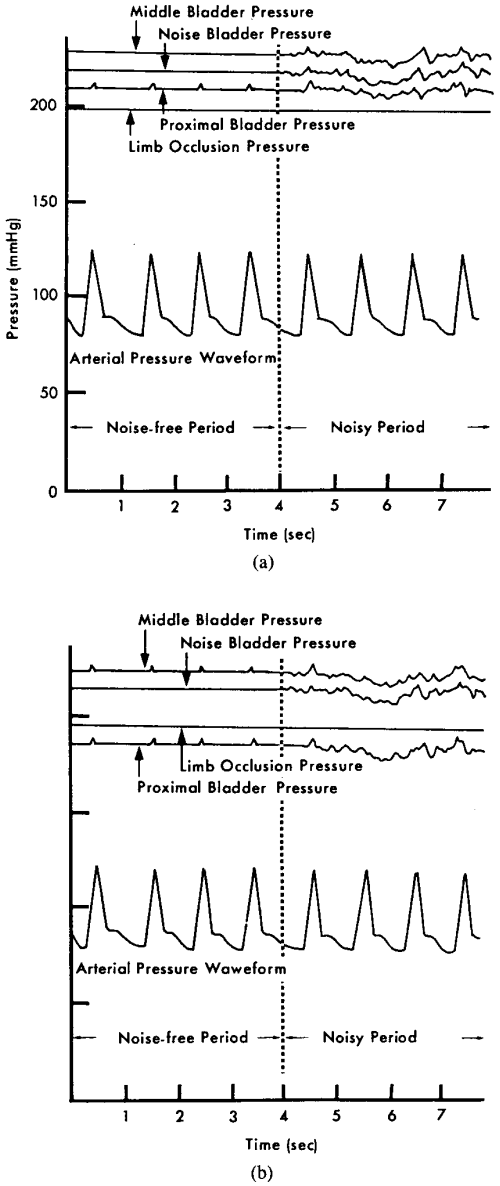

Fig. 3. Typical waveforms observed in the multibladder cuff: (a) with the proximal bladder pressure above the limb occlusion pressure; and (b) with the proximal bladder pressure below the limb occlusion pressure. In the algorithm, when pulses are detected from the noise bladder, processing is suspended to prevent noise artifacts from being mistaken for flow-induced pulses at the middle bladder. When no signal is detected from the noise bladder, the absence or presence of flow-induced pulses from the middle bladder reveal whether the proximal pressure is above or below the required limb occlusion pressure.

we anticipated would be more accurate than current methods because it would be based directly on flow past a cuff, more reliable since data acquisition would be suspended during noisy periods, and more rapid because the pressure in the proximal cuff would be maintained near the limb occlusion pressure to narrow the range of pressures being searched. The flowchart shown in Fig. 4 outlines the algorithm that was developed and explains how, once the

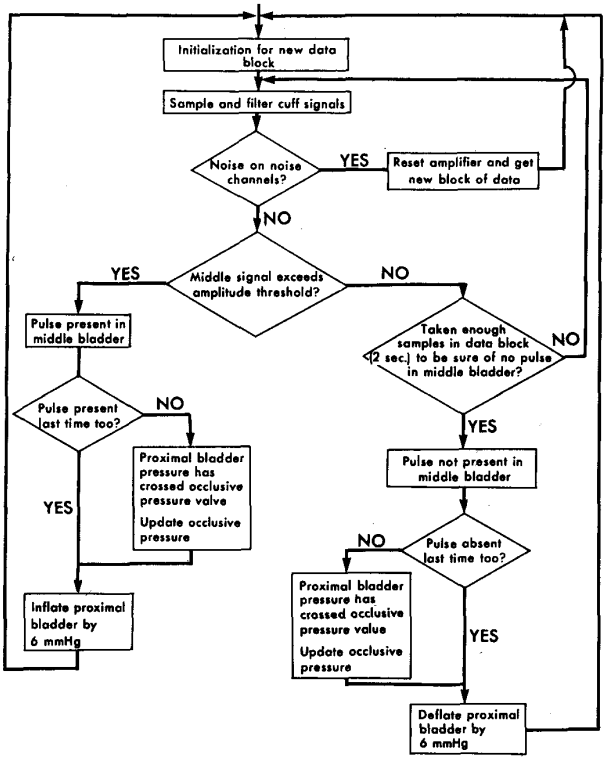

Fig. 4. Simplified flowchart describing the occlusive pressure tracking algorithm.

proximal cuff pressure approaches the limb occlusion pressure, it is adjusted to dither across this target pressure to track changes in systolic blood pressure and provide a rapid estimate of the required tourniquet pressure during noise-free time periods. To reduce the magnitude of short-term changes in tourniquet pressure as a function of the variability in successive determinations of the limb occlusion pressure, a three-point moving average of the estimates was then calculated. A more detailed algorithm description and program listing is available elsewhere [12]. This technique of tracking limb occlusion pressure is similar in some respects to a method developed by Krueger [13], who tracked systolic (or diastolic) pressure by sensing the presence and amplitude of Korotkoff sounds to decide whether a single occluding cuff was above or below systolic (or diastolic) pressure, and making appropriate cuff pressure changes based on this decision. However, Krueger's method is not suitable for use in an adaptive tourniquet because it requires blood flow past the cuff to produce Korotkoff sounds for analysis, because it would be sensitive to noise and transducer placement, and because it offers no reliable way to ensure that the data being processed are not corrupted by noise.

The algorithm that was developed was evaluated in two phases: lab trials were performed to evaluate accuracy and reliability under controlled conditions; and clinical trials were then performed to evaluate the speed, tracking ability, and safety of available methods for updating tourniquet pressure during surgical procedures.

Lab Trials

Lab trials were performed at the Vancouver General Hospital to compare, under similar and reproducible conditions, the accuracy and reliability of estimates of limb occlusion pressure made in a noisy environment by both the prototype and a typical commercially available blood pressure monitor. The monitor chosen for comparison was the Hewlett Packard 78354A Patient Monitor, which estimates blood pressure using an oscillometric algorithm that is representative of oscillometric algorithms widely used in commercially available monitors [15]. Records were made only of the oscillometric monitor's estimates of systolic pressure, which correspond to limb occlusion pressure when the estimates are made using a tourniquet cuff instead of a standard blood pressure cuff. The oscillometric monitor was tested on 15 individuals who were positioned comfortably in a supine position. The multibladder tourniquet cuff shown in Fig. 2 was wrapped on the subject's right arm between the elbow and shoulder. The proximal bladder was then used to obtain estimates of limb occlusion pressure with the oscillometric monitor while an ultrasonic arterial flow detector (Arteriosonde 1010), with its transducer placed distal to the cuff over the brachial artery, simultaneously indicated the onset of flow. Both the cuff pressure, as indicated by the oscillometric monitor's display, at which flow-induced sounds were first heard and the limb occlusion pressure estimate provided by the oscillometric monitor were recorded. This scheme of simultaneous measurements on the same limb eliminates the temporal and spatial pressure variations that make it difficult to compare blood pressure estimates done at different times on different limbs [14].

Three measurements, each occurring during different noise conditions (noise-free, low-noise, and moderate-noise conditions), were taken on each subject. Noisy runs consisted of alternating 5 s periods of noise and noise-free intervals to facilitate the simultaneous use of the ultrasonic device during the noise-free sections since limb movement generally created a Doppler signal that would obscure the flow-induced signal. Movement artifacts were generated by rocking the arm of a passive subject at a frequency of about 1 Hz, with 0.5 in movement of the elbow creating low-noise conditions and 2 in movement at the elbow producing moderate-noise conditions. While a rocking motion was permitted, the orientation of the limb remained constant for the duration of the lab trial run. This simulation of clinical artifact conditions was defined after evaluating the nature and range of limb movements typical of common surgical procedures in which tourniquets are employed, such as diagnostic and therapeutic arthroscopies, joint replacements, trauma surgery, and plastic surgery.

The ability of the prototype to detect the onset of flow past an occluding cuff and estimate limb occlusion pressure under varying noise conditions was tested using the same protocol. During lab trials, the algorithm of the prototype was modified to employ a stepped deflation scheme similar to that used by the oscillometric monitor, instead

of the dithering pressure regulation employed in clinical situations, because such a steady deflation not only made flow detection with the ultrasonic device easier, but also standardized the conditions under which both the oscillometric monitor and the prototype estimated limb occlusion pressure. Furthermore, the middle bladder was set to subocclusive pressures in the lab trials to permit the ultrasonic device to detect arterial flow at a site distal to the multibladder cuff.

The differences between paired simultaneous manual and device measurements ("paired estimates") were then analyzed to examine the accuracy and reliability of the estimates of limb occlusion pressure made by the oscillometric monitor and the prototype under varying noise conditions in a manner similar to that recommended by the Association for the Advancement of Medical Instrumentation (AAMI) for assessing the accuracy and reliability of commercially available automated sphygmomanometers [14]. Even though the number of subjects used in this initial study falls short of the number recommended by the proposed AAMI standard for evaluating the performance of commercially available sphygmomanometers, it is sufficient for providing an initial indication of the prototype's feasibility for the proposed application.

Clinical Trials

Clinical trials were performed in the Health Sciences Centre Hospital at the University of British Columbia to compare the speed and safety of the prototype with the oscillometric monitor used for reference purposes during similar surgical procedures performed by the same surgeon. Data were collected during six surgical arthroscopies of the knee. With the multibladder cuff wrapped around the limb undergoing surgery, the middle bladder was initially maintained at the constant tourniquet pressure normally selected for the procedure. The proximal bladder was then used by either the prototype or the oscillometric monitor to make estimates of limb occlusion pressure. These estimates were recorded, together with simultaneous estimates of systolic pressure made by the anesthetist on a limb not affected by the surgical procedure, when available. The resulting data were collected to permit a comparative evaluation of the safety and speed of adaptive tourniquet schemes that might use estimates of systolic pressure from another limb, or estimates of limb occlusion pressure derived from the same limb by means of an oscillometric monitor, or estimates of limb occlusion pressure derived from the same limb by the prototype.

Results

A comparative evaluation of the prototype and the oscillometric monitor was based on the following criteria:

1) accuracy, i.e., the average difference of paired estimates collected during lab trials;

2) reliability, i.e., the standard deviation of differences of paired estimates collected during lab trials;

3) speed, i.e., the average estimation time and maximum time between estimates during clinical trials; and

4) safety, i.e., the likelihood that an occlusive cuff will be maintained above the limb occlusion pressure, without excessive pressure application.

Table I summarizes the lab trial results, consisting of an analysis of paired estimates measured from 15 subjects to compare the average difference and standard deviation of the differences obtained with both the oscillometric monitor and the prototype during varied noise conditions. Table II shows the results of clinical trials concerning estimation speed in a noisy environment that were obtained during six knee arthroscopies, three each for both the oscillometric monitor and the prototype.

In general, the results summarized in Tables I and II showed that the presence of noise affected the performance of both the oscillometric monitor and the prototype. However, the degree to which noise affected the ability of each monitor to track limb occlusion pressure was noticeably different.

Results of Lab Trials of the Oscillometric Monitor

The oscillometric monitor is based on a widely employed technique for estimating mean arterial pressure, systolic pressure, and diastolic pressure (e.g. [16], [17]). It rejects noise by using a "matched pulse" scheme for accepting data, processing only pairs of pulses that are similar in amplitude and time separation [15]. Thus, the monitor requires a series of noise-free periods, typically 2 s each and totaling 40 s, in order to collect enough data to construct an adequate table of pulse heights and cuff pressures for estimating these three parameters of pressure. Because the monitor waits for a matched set of pulses before continuing with its deflation process, the presence of detected noise for prolonged periods can trigger alarms (after 60 s at a given pressure level or 2 min of total elapsed time) that will abort the estimation cycle.

Table I suggests that both low-amplitude noise and moderate-amplitude noise affected the accuracy, reliability, and safety of the oscillometric monitor. While noise-free measurements satisfied the proposed AAMI standards by differing from the simultaneous manual measurements by less than 5 mmHg with a standard deviation of less than 8 mmHg [14], the noisy estimates failed to meet these standards. These results suggest that the oscillometric monitor at times accepted cyclic noise as being valid oscillometric matched pulses, resulting in errors in estimated limb occlusion pressure in which the polarity and magnitude of the error depended on the cuff pressure at which the error occurred. It should also be noted that the oscillometric monitor failed to occlude the artery of two subjects before beginning its data acquisition cycle, as flow was detected by the ultrasonic flow detector even before the oscillometric monitor began to deflate the cuff. These runs, excluded from the study, underestimated the limb occlusion pressure by more than 30 mmHg. This error probably resulted from the use of a standard tourniquet cuff instead of a standard blood pressure cuff since the

TABLE I
SUMMARY OF THE RESULTS OF LAB TRIALS WITH 15 SUBJECTS USED TO ASSESS THE ACCURACY AND RELIABILITY OF BOTH THE OSCILLOMETRIC MONITOR AND THE PROTOTYPE IN THE PRESENCE OF VARIOUS NOISE ARTIFACTS

	Average Difference Between Paired Manual and Device Estimates (mmHg)		Standard Deviation of Differences Between Paired Manual and Device Estimates (mmHg)	
Condition	Oscillometric Monitor	Prototype	Oscillometric Monitor	Prototype
Noise-free	4.6	−0.1	4.7	3.9
Low noise	9.7	−0.3	8.3	3.5
Moderate noise	12.1	0.8	9.8	5.4

For evaluation, the proposed AAMI standard for automated sphygmomanometers was used, which requires that the average difference between simultaneous device and manual measurements of blood pressure be less than 5 mmHg with a standard deviation of less than 8 mmHg.

TABLE II
RESULTS OF CLINICAL TRIALS USED TO ASSESS THE SPEED OF BOTH THE OSCILLOMETRIC MONITOR AND THE PROTOTYPE ALGORITHM AS EACH DEVICE MADE MEASUREMENTS OF LIMB OCCLUSION PRESSURE DURING THREE KNEE ARTHROSCOPIES

Average Estimation Time (s/estimate)		Maximum Time Between Estimates (s)	
Oscillometric Monitor	Prototype	Oscillometric Monitor	Prototype
5310/50 = 106	3198/256 = 12.5	228	95

padded, narrower tourniquet cuff generates smaller flow-induced oscillometric pulsations than the blood pressure cuff. These errors occurred despite the fact that the algorithm used by the oscillometric monitor is designed to check that the cuff inflation level is sufficient for occluding blood flow in underlying arteries before beginning its data acquisition cycle.

Results of Lab Trials of the Prototype

The prototype system uses a multibladder cuff to sense the occurrence of noise-free periods when it can detect flow past a variably pressurized proximal bladder to make estimates of limb occlusion pressure. Thus, this system requires a series of brief noise-free periods, of duration less than 2 s, as it tracks the limb occlusion pressure by making appropriate adjustments of the proximal pressure based on flow conditions past the proximal bladder. The number of noise-free data periods needed for an estimate depends on the variability of the limb occlusion pressure and on the difference between the limb occlusion pressure and the pressure in the proximal bladder at measurement times. As these variables increase, the time spent searching for the limb occlusion pressure increases.

As summarized in Table I, the results indicate that the prototype performed consistently well for different noise conditions, with the average difference between simultaneous estimates and the standard deviation of these differences meeting the proposed AAMI guidelines for all cases. Furthermore, the prototype was able to provide limb occlusion pressure estimates for the two subjects described above in which the oscillometric monitor failed to occlude blood flow.

Results of Clinical Trials

As indicated in Table II, the results show that the prototype was able to track limb occlusion pressure significantly better than the oscillometric monitor. This can be seen by comparing both the average estimation time and the maximum time between estimates. The importance of rapid pressure tracking is graphically displayed in Figs. 5 and 6, which show the intraoperative limb occlusion estimates made at the tourniquet cuff by both the prototype and the oscillometric monitor and compare these to the intraoperative systolic pressure estimates derived from another limb. Not only were large limb occlusion pressure changes of 40 mmHg/min observed, but these changes were not associated with a similar change in systolic estimates measured on another limb. Such rapid changes appear to represent valid variations in limb occlusion pressure and do not appear to be errors caused by motion artifacts in view of the following: these wide variations in limb occlusion pressure could be reproduced in a lab environment by taking noise-free measurements on a leg fixed in different orientations, as shown in Figs. 7 and 8; and earlier lab trials with the prototype established the accuracy and reliability of the prototype in noisy environments. Consequently, while systolic pressure is one of the factors that affects limb occlusion pressure, changes in limb positions can be a more significant factor during periods of stable systolic pressure levels. A change in limb orientation could have caused these variations by changing the elevation of the cuff with respect to the heart, by shifting the cuff position along the limb to affect the cuff–limb interface, or by altering the circumference of the limb as tissue was stretched or relaxed.

Besides displaying results of the clinical trials, Figs. 5 and 6 also illustrate the pressures that might have been used in the cuffs of adaptive tourniquets based on adaptive schemes employing 1) estimates of systolic pressure derived from another limb, 2) estimates of limb occlusion pressure made at the site of the tourniquet cuff by the oscillometric monitor, and 3) estimates of limb occlusion pressure made at the site of the tourniquet cuff by the prototype.

An adaptive scheme that uses systolic pressures estimated from another limb requires that the estimates be corrected to account for different cuff sizes and types, limb circumferences, and techniques of cuff application. Such a scheme must also include an additive constant to account for errors in pressure regulation, systolic pressure estimations, and cuff application, and to account for the maximum increase in the patient's systolic pressure and limb occlusion pressure that is likely to occur between estimates [1], [12]. For Figs. 5 and 6, this corrective factor was estimated from measured limb circumference in-

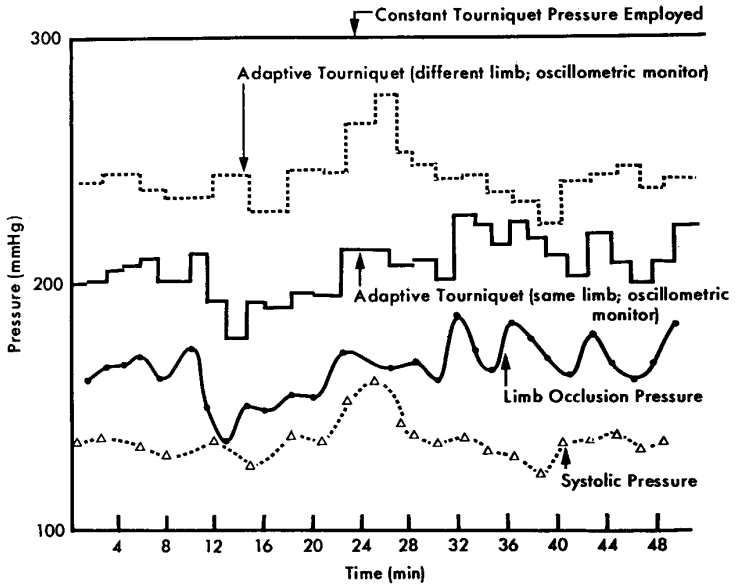

Fig. 5. This graph shows the results of a clinical trial, including 1) systolic pressure estimates from the patient's arm made by an oscillometric monitor and 2) limb occlusion pressure estimates made by an oscillometric monitor at the site of the tourniquet cuff. Also shown are the constant tourniquet pressure actually used, the projected adaptive tourniquet pressure derived from a different limb, and the projected adaptive tourniquet pressure derived from the same limb.

formation and the previously derived ratio between cuff width and limb circumference [7].

In contrast to the adaptive scheme based on systolic estimates from another limb, both adaptive schemes shown in Figs. 5 and 6 that are based on measuring limb occlusion pressure at the site of the tourniquet cuff do not require a multiplicative factor. Instead, these adaptive schemes use only an additive constant to account for errors in estimation, errors in pressure regulation, and maximum increases in systolic pressure and limb occlusion pressure between estimates [1], [12].

All adaptive schemes would result in the use of lower tourniquet pressure than the constant pressure actually employed, indicating that any adaptive algorithm can help to reduce the average tourniquet pressure used during surgery. However, as shown in Figs. 5 and 6, the use of systolic pressure estimates from another limb would have resulted in higher mean tourniquet pressures than those projected from the use of limb occlusion pressure estimates at the actual site of the tourniquet cuff. Although blood pressure estimates from another limb were advantageously unaffected by motion artifacts generated at the tourniquet by the surgical procedure, these estimates required large corrective factors to account for differences in cuffs, limb, and cuff application. Furthermore, as shown in Fig. 6, measurements on another limb did not track the wide variations in limb occlusion pressure caused by changes in limb position, a shortcoming that could produce potentially hazardous underpressurization errors if only systolic pressure estimates are used. The use of

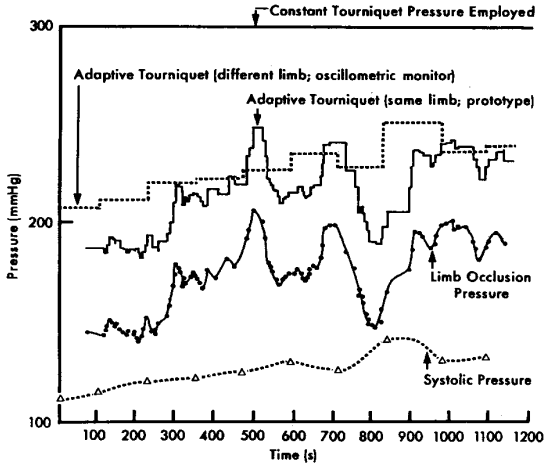

Fig. 6. This graph shows the results of a clinical trial, including 1) systolic pressure estimates from the patient's arm made by an oscillometric monitor and 2) limb occlusion pressure estimates made by the prototype at the site of the tourniquet cuff. Also shown are the constant tourniquet pressure actually used, the projected adaptive tourniquet pressure derived from a different limb, and the projected adaptive tourniquet pressure derived from the same limb.

the oscillometric monitor to estimate limb occlusion pressure at the site of the tourniquet cuff offered some improvements by taking into account the effects of limb orientation. However, the monitor was unable to estimate the limb occlusion pressure of some subjects when a narrow tourniquet cuff was employed. Also, the observed ef-

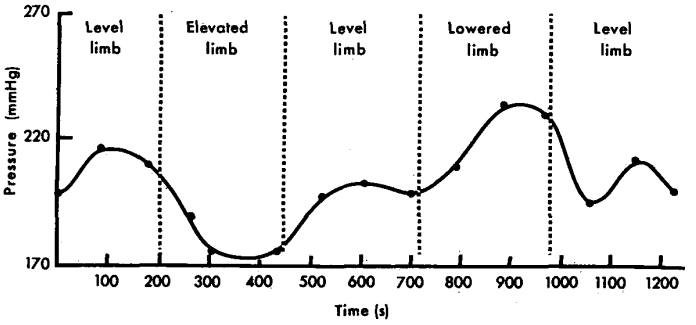

Fig. 7. This graph shows how limb occlusion pressure estimates made by the oscillometric monitor varied with limb position during a noise-free lab trial.

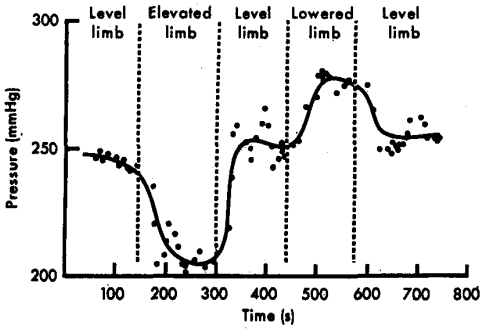

Fig. 8. This graph shows how limb occlusion pressure estimates made by the prototype varied with limb position during a noise-free lab trial.

fects of noise in delaying the estimation process, reducing the level of accuracy, and degrading the reliability resulted in measurements by the oscillometric monitor which were slow and hazardous. These problems were not observed when using the prototype, which was able to estimate limb occlusion pressure at the site of the tourniquet cuff rapidly and consistently in varying noise conditions.

Discussion

The initial results indicate that the algorithm and strategy employed in the prototype would be feasible for incorporation into an adaptive tourniquet. The prototype functions more reliably, more accurately, more rapidly, and more safely than a representative oscillometric monitor for this purpose.

To facilitate routine clinical use of the prototype for tracking limb occlusion pressure in the future, the prototype system requires some improvements, such as a smaller dedicated high-gain signal amplifier, a more efficient algorithm for adjusting pressure (perhaps based on optimization techniques), and further refinements of the wide multibladder cuff to improve its fit onto tapered limbs [12]. However, work done with this prototype has provided the basis for further research into adaptive tourniquets by demonstrating the clinical benefits derived from tracking limb occlusion pressure at the tourniquet site during surgery, showing the need for a specialized cuff with both occluding and flow-detecting capabilities, and revealing the improved tracking ability offered by a system that occludes, detects flow, and detects noise to update the limb occlusion pressure of a tourniquet rapidly, accurately, and reliably.

Acknowledgment

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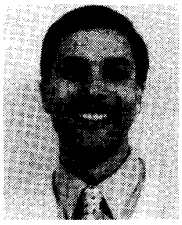

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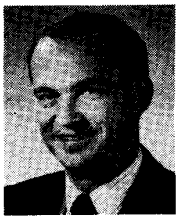

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