Anatomical and functional characteristics of carotid sinus stimulation in humans

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Received 12 July 2000; accepted in final form 20 December 2000

Transmission characteristics of pneumatic pressure to the carotid sinus were evaluated in 19 subjects at rest and during exercise. Either a percutaneous fluid-filled \((n = 12)\) or balloon-tipped catheter \((n = 7)\) was placed at the carotid bifurcation to record internal transmission of external neck pressure/neck suction \((NP/NS)\). Sustained, 5-s pulses, and rapid ramping pulse protocols \((+40 \text{ to } -80 \text{ Torr})\) were recorded. Transmission of pressure stimuli was less with the fluid-filled catheter compared with that of the balloon-tipped catheter \((65\% \text{ vs. } 82\% \text{ negative pressure}, 83\% \text{ vs. } 89\% \text{ positive pressure}; P < 0.05)\). Anatomical location of the carotid sinus averaged 3.2 cm \(\text{left}\) and 3.6 cm \(\text{right}\) from the gonion of the mandible with a range of 0–7.5 cm. Transmission was not altered by exercise or Valsalva maneuver, but did vary depending on the position of the carotid sinus locus beneath the sealed chamber. These data indicate that transmission of external \(NP/NS\) was higher than previously recorded in humans, and anatomical variation of carotid sinus location and equipment design can affect transmission results.

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Application of these limitations to the current methodology could include the possibility of the catheter tip becoming occluded by surrounding tissue or the environment of the fluid tip being altered by rapid and intense pressure changes induced by NP/NS. The data from Ludbrook et al. (9) was not confirmed by Thron et al. (24), who measured the transmission of external neck pressure to the esophagus in humans and reported nearly complete internal transmission from the external stimulus. Shubrooks (21) also found almost complete transmission to external neck pressure in dogs that were instrumented with a surgically placed balloon catheter at the carotid sinus. Recently, Smith et al. (22) utilized a balloon-tipped pressure transducer (Mikro-Tip, Millar Instruments; Houston, TX) placed into the rectus femoris muscle to examine changes in intramuscular pressure to external lower body positive pressure. They found 100% internal transmission of positive pressures of 45 Torr. These data indicate that external pressure upon the neck may be transmitted internally at a greater efficiency than previously accepted.

Since the description of a smaller and more versatile neck collar by Eckberg et al. (5), derivatives of this design have been utilized extensively and provide several advantages, including subject comfort and a better vacuum and pressure seal. There have been no studies to examine the transmission characteristics of this often-used NP/NS collar design. In the protocols that used prolonged neck pressure stimuli of greater than 5 s, confounding responses involving aortic baroreflex feedback responses to the carotid baroreflex induced changes in arterial pressure resulted in a decreased closed-loop estimate of maximal gain (17). Therefore, longer NP/NS perturbations likely underestimate the isolated inhibitory contribution of the carotid baroreflex in the regulation of arterial pressure.

The purpose of this investigation was to characterize the internal transmission of carotid sinus manipulation of the neck chamber adapted from Eckberg et al. (5). Two different catheters, which utilize different pressure transduction methodology, were used to record internal tissue pressure during the application of pulsatile neck pressures with two protocols that are commonly used in developing models of isolated carotid baroreflex function of humans. The NP/NS protocols were completed at rest and during exercise. In addition, we examined the variability of carotid sinus location in relation to the anatomical fit of the neck collar and any subsequent alterations in internal transmission of NP/NS stimuli.

METHODS

Subjects. Nineteen healthy male subjects volunteered to participate in this study. Each subject completed a written informed consent as approved by the Ethical Committee of the Fredricksberg Municipalities, Copenhagen, Denmark. The group means (±SE) for age, height, and weight were 24.6 ± 0.5 yr, 182.9 ± 2.9 cm, and 74.5 ± 2.4 kg, respectively.

Procedures. Each experiment consisted of repeated carotid sinus stimulation with the NP/NS technique. Subjects were instrumented and placed in a semirecumbent position. The NP/NS profiles were conducted both at rest, while the head was maintained in a position to allow relaxation of the neck musculature, during a Valsalva maneuver to investigate the effect of increased internal tissue pressure on transmission characteristics, and during low-intensity dynamic leg exercise. Dynamic exercise consisted of 7 min of cycle ergometry at 30% maximum oxygen uptake.

Instrumentation. For each subject the location of the carotid sinus bifurcation was determined using Doppler ultrasound (Ultrasound scanner type 2000, B&K Medical; Gentofte, Denmark). The measurement of the carotid sinus location was referenced as the distance (cm) below the gonion of the mandible (the angular point at which the mandible changes from an anterior-posterior direction to a superior-inferior direction). This reference to the mandibular ridge was utilized to examine the carotid sinus location in relation to the anatomical fit of the NP/NS collar, which was sealed tightly along the mandibular ridge. Local anesthesia (2 ml of lidocaine) was unilaterally administered percutaneously before either one of the two types of catheters were utilized. The location of the anesthesia administration was determined by measuring the length of the catheter introduced from the location of the carotid bifurcation. Because of the distance from the insertion point to the location of the carotid sinus bifurcation (4.5 cm), limited quantity of anesthesia, and superficial administration above the thick fascia covering the carotid sinus region, there was minimal risk of any anesthetic effect on the free nerve endings located at the carotid sinus. In 12 subjects, internal tissue pressure (TP) at the carotid sinus was measured by placing a 2-in., 19-gauge Teflon catheter (Ohmeda) percutaneously under the fascia so that the tip of the catheter was at a depth of 1.0–1.5 cm at the level of the pulse-Doppler echoed identification of the carotid sinus bifurcation. This catheter was chosen to examine the repeatability of previous research findings of internal tissue pressure recordings from an open-ended, fluid-filled catheter. The TP measured by the catheter was transduced utilizing a sterile disposable pressure transducer (PX-260, Baxter) and a pressure monitoring system (Dialogue 2000). The location of the catheter tip was verified by transcutaneous two-dimensional and Doppler ultrasound techniques. The transducer was zeroed to the level of the carotid sinus, and the catheter was kept patent by a continuous drip of saline solution at 3 ml/h. To eliminate potential limitations of recording tissue pressure with a fluid-filled system, a balloon-tipped pressure transducer (Mikro-Tip, Millar Instruments; Houston, TX) was utilized to record TP in seven additional subjects. With the balloon-tipped catheter, two anatomical locations were utilized. First, the catheter tip was advanced to a position just inferior to the mandibular ridge. The purpose of this location was to examine the transmission characteristics of NP/NS at the border of the rim of the NP/NS collar. This position would also represent the internal transmission to the carotid sinus region in an individual with an anatomically high carotid sinus bifurcation in reference to the mandibular ridge. The second catheter location was placed at the location of the carotid bifurcation, which in most subjects occurred in the central portion of the open aperture formed by the NP/NS collar. Heart rate (HR) was measured using a three-lead configuration and processed by an electrocardiogram (ECG) data computer (Dialogue 2000).

Carotid baroreceptor function. Neck pressure stimuli (NP/NS) were applied through a cushioned malleable lead collar that was placed around the anterior two-thirds of the neck. The collar creates a sealed open chamber with the superior border on the lower mandibular ridge and the inferior border...
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along the clavicle thus encompassing the carotid sinus location and allowing for a wide variety of anatomical variability. Graded levels of pressure between +40 and −80 Torr were generated by a variable pressure vacuum source and controlled by two-way solenoid valves (model 8215B, Asco; Florham Park, NJ). For each pulse, the pressure within the neck collar was controlled manually and the external neck chamber pressure was measured by a pressure transducer (model DP45, Validyne Engineering; Northridge, CA). To minimize the respiratory-related modulation of HR and mean arterial pressure (MAP), all carotid baroreflex perturbations were conducted during a held breath at end expiration.

Two commonly used protocols for carotid baroreflex control of HR and MAP were examined for internal transmission characteristics. The timing for all pressure stimuli was computer controlled to deliver the manually set NP/NS pulse to the carotid sinus precisely 50 ms after the R wave of the ECG. This allowed synchronicity between the pressure wave from the cardiac cycle and the NP/NS pressure pulse at the carotid sinus. The first protocol utilized individual sustained square-wave pulses of 5 s duration. Each pulse used randomly selected single pressure intensity. The randomized square-wave pulses of 5 s duration. Each pulse used randomly selected single pressure intensity. The randomized process was repeated until three samples of the full range of +40 to −80 Torr pressure stimuli with increments of 20 Torr were completed. This protocol is commonly utilized during investigations with prolonged steady state due to the advantage of allowing the collection of the peak reflex responses in HR and MAP with minimal influence by aortic baroreceptor feedback. The second protocol was a rapid pulse train composed of 12 pulses of 300–500 ms duration. Each pulse was gated to the R wave of the ECG. The magnitude of each pressure pulse was manually adjusted. The magnitude of the pressure profile began with four pulses of +40 Torr, followed by three pulses of reducing positive pressure to 0 Torr. This was followed by five pulses of increasing negative pressure from 0 to −80 Torr in approximately −20 Torr increments. After each pressure pulse, the neck chamber was vented to atmospheric pressure to create square-wave pulsatile stimulus. The carotid sinus stimulus could then be measured in relation to the chamber pressure measurement on each pulse rather than the difference between each change in chamber pressure, as would be the case if the chamber was not vented between pulses. The advantage of this protocol is that it allows for modeling of the complete carotid baroreflex operating range from a single pressure profile and can be completed in minimal time.

After the data were collected at rest with the rapid pulse train protocol, the protocol was repeated during two special conditions. First, data were collected during a maximal Valsalva maneuver to examine any alterations in internal transmission due to increased muscular tension and venous pressure that is common in perturbations that require increased effort by the subject. The second condition was during dynamic leg exercise. The intensity of exercise was set at 30% maximal oxygen uptake. The intensity of exercise was limited to an intensity that would elicit an exercise HR of −120 beats/min or lower. This intensity was chosen because of the fact that during a rapid pulse protocol with a 500-ms duration pulse, a HR above 120 beats/min would disrupt the computer-controlled pulse triggering.

All data for HR, chamber pressure, and internal TP were collected beat-to-beat by one computer utilizing customized software at a sampling rate of 250 Hz and by a second computer utilizing commercial data acquisition software (Windaq, Dataq Instruments; Akron, OH).

Data and statistical analysis. Sections of NP/NS data collection were separated from the raw data file and analyzed for internal transmission of the externally applied stimulus. The transmission percentage was the recorded internal TP divided by the recorded external chamber pressure multiplied by 100% [% transmitted = (TP/chamber pressure) × 100]. In addition, the latency between the external application and internal transmission of pressure stimuli was analyzed. Statistical analysis of the effect of applying correction factors for the fluid-filled catheter, balloon-tipped catheter, or no correction factor (uncorrected) was completed using one-way analysis of variance and Student-Newman-Keuls post hoc analysis. All variables are represented as means ± SE. Significance was accepted at P < 0.05.

RESULTS

Anatomical location of carotid sinus. The Doppler-measured anatomical locations of the carotid sinus bifurcation in the initial 12 subjects indicated wide variability from 0 to 7 cm below the gonion. To determine whether this variability was repeatable and descriptive of the population or only a rare occurrence, Doppler ultrasound was conducted on 83 additional randomly selected hospital employees (n = 95). Figure 1 illustrates the frequency distribution of the location of the right and left carotid sinus bifurcation referenced as the distance below the gonion of the mandible. The location of the carotid sinus bifurcation by Doppler ultrasound in the total sample population measured 3.2 ± 0.1 cm (median 3.0 cm, range 0–6 cm) on the right side and 3.6 ± 0.2 cm (median 3.5 cm, range of 0–7.5 cm) on the left side.

Transmission characteristics of NP/NS. The details of the transmission characteristics across the dynamic

Fig. 1. Frequency distribution of right and left carotid sinus bifurcation. Location of right and left carotid sinus bifurcation was measured from the gonion of the mandible (n = 95). Bifurcation location determined by Doppler ultrasound. Location of the right bifurcation was 3.2 ± 0.1 cm (median 3.0 cm, range 0–6.5 cm) and the left bifurcation was 3.6 ± 0.2 cm (median 3.5 cm, range 0–7.5 cm) below the gonion (angle of the mandible). Values reported are means ± SE.
range of NP/NS stimuli for both protocols are shown in Table 1. The results from both positive and negative pressure transmitted through the open fluid-filled catheter were not significantly different ($P > 0.05$) to those previously reported by Ludbrook et al. (9) with $84.7 \pm 1.3$ and $64.2 \pm 1.7\%$ transmitted internally for positive and negative pressures, respectively. The transmission characteristics of external NP/NS were significantly higher ($P < 0.05$) than previously reported fluid-filled catheter data when measured by a balloon-tipped catheter. Positive pressure was transmitted at $89.1 \pm 1.4\%$, whereas negative pressure was $82.4 \pm 1.9\%$ when recorded at the average anatomical location of the carotid sinus within the open aperture of the sealed collar. The internal transmission at the higher catheter location near the rim of the sealed collar was significantly reduced ($P < 0.05$) to $62.0 \pm 3.0$ and $44.0 \pm 3.7\%$ for positive and negative pressures, respectively, compared with the lower recording site at the carotid sinus bifurcation.

The transmission during rapid pulse trains recorded at rest and during exercise with the open fluid-filled catheter was significantly lower during positive pressure stimuli ($P < 0.05$), but not different during negative pressure stimuli ($P > 0.05$) compared with the data recorded during the 5-s sustained pulse protocol. However, the pressure transmission recorded during rapid pulse trains in the balloon-tipped catheter was significantly higher than the transmission by the open fluid-filled catheter ($P < 0.05$). There was no difference in transmission characteristics of the balloon-tipped catheter between rapid pulse trains and prolonged 5-s pulse protocols ($P > 0.05$).

The temporal relationship between the external chamber pressure and internal TP during a rapid ramping pulse train and the gating sequence to the R wave of the HR are indicated in Fig. 2. This pattern was the same regardless of the catheter utilized. The differences between peak transmission percentage of open and balloon-tipped catheters was due to the intrinsic limitations of recording tissue pressure with each catheter and not the dynamic response of the catheters to changes in pressure. One observation that was consistent with both catheter protocols of negative pressure was the increased time required for the tissue pressure to return to the prestimulus pressure value when the negative pressure was halted. However, this delay in tissue pressure restoration had minimal affect on calculated carotid parameters. There was good repeatability of pressure profiles within each subject, and the variability presented in Table 1 was a result of individual differences not within-subject differences.

Because of the time requirements for collection of the full range of 5-s pulses (+40 to −80 Torr) only the rapid pulse trains were utilized during exercise. Maintaining a patent neck catheter without tissue interference was a technical challenge during exercise with the open fluid-filled catheters that was not present with the balloon-tipped catheter. Five subjects maintained clear pressure transduction from the open fluid-filled catheter during exercise. An important observation was that there was no significant difference in internal transmission of NP/NS stimuli during low-intensity exercise compared with rest with the utilization of either catheter.

### DISCUSSION

The major findings in this investigation were that 1) the transmission of external neck pressure to the carotid sinus tissue was higher than had been previously reported (9); 2) the transmission profiles were unchanged from rest to exercise; 3) an increase in local tissue pressure from the Valsalva technique did not affect the transmission profiles; and 4) correction of internal transmission resulted in minimal and nonsignificant changes in calculated carotid baroreflex parameters. The data collected utilizing the open fluid-filled catheter for 5-s pulses resulted in transmission recordings very similar to those reported by Ludbrook et al. (9). However, the pitfalls that may occur with the measurement of tissue pressure by a transmission methodology designed for a fluid-fluid interface resulted in some major inaccuracies. Tissue occlusion of the catheter tip or alterations in the fluid-tissue environment, as could occur with the rapid, high-intensity pressure changes of NP/NS, may have accounted for at least part of the incomplete transmission recorded with the open fluid-filled catheters. The balloon-tipped cath-

### Table 1. Transmission percentages for 5-s and rapid pulse train neck pressure-neck suction protocols

<table>
<thead>
<tr>
<th>Positive Pressure</th>
<th>Negative Pressure</th>
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<tr>
<td>($+20$ to $+40$ Torr)</td>
<td>($-20$ to $-80$ Torr)</td>
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<tr>
<th>5-s Pulse</th>
<th>5-s Pulse</th>
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<tbody>
<tr>
<td>Open catheter ($n = 12$)</td>
<td>$84.7 \pm 1.3$</td>
</tr>
<tr>
<td>Balloon catheter</td>
<td>$89.1 \pm 1.4\dag$</td>
</tr>
<tr>
<td>Low ($n = 7$)</td>
<td>$59.2 \pm 3.2^*$</td>
</tr>
<tr>
<td>High ($n = 4$)</td>
<td>$60.8 \pm 3.6^*$</td>
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<table>
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<tr>
<th>Rapid pulse train</th>
<th>Rapid pulse train</th>
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<tr>
<td>Open catheter</td>
<td>$88.7 \pm 2.1\dag$</td>
</tr>
<tr>
<td>Exercise</td>
<td>$87.4 \pm 2.5\dag$</td>
</tr>
<tr>
<td>Balloon catheter</td>
<td>$88.3 \pm 2.8\dag$</td>
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Transmission % of external neck pressure-neck suction measured at the carotid sinus for 5-s protocol and for rapid ramp pulse train protocol at rest and during exercise. Values presented as external positive and negative pressure stimuli represent the measured neck chamber pressure. High, balloon catheter placement at the superior rim of the neck collar. Low, balloon catheter placement at the verified location of the carotid sinus. Values of means ($\pm SE$) are the percentage of the external stimulus measured by the internal pressure transducer at the carotid bifurcation. There was no difference in internal transmission between rest and exercise with the rapid ramp pulse train or with Valsalva technique. *Significant difference between rapid pulse train and 5-s pulse stimulus transmission for specific catheter type ($P < 0.05$). †Significant difference in transmission between the fluid-filled and balloon-tipped catheter for the specific external pulse protocol ($P < 0.05$).
eter does not rely on a fluid interface. Therefore, the transmission of external pressure recorded with this method does not have the same limitations in recording tissue pressure and would reflect tissue pressures more faithfully. Whereas in some subjects, the transmission recordings in the fluid-filled catheter did not reflect the square-wave generation recorded by the neck chamber pressure transducer and resulted in a curvilinear pressure profile, the balloon catheter demonstrated insignificant delay in transmission of external pressure and mirrored the external neck chamber pressure square-wave pressure change. Additionally, the reduced pressure transmission recorded with the balloon catheter at the superior position of the rim of the collar indicated that internal transmission of NP/NS was not uniform within the aperture of this collar design. This discovery has critical relevance in those cases where the anatomical location of the carotid sinus lies in a superior/inferior location approximating the rim of the sealed neck chamber and to those

Fig. 2. Rapid pulse train carotid baroreflex stimulus and cardiovascular reflex responses. Schematic illustration represents one rapid pulse carotid baroreflex train (+40 to −80 Torr) and the resulting reflex responses in heart rate (A) and blood pressure (B). C: pressure recorded within the external neck chamber. D: pressure recorded at the carotid sinus with the fluid-filled catheter. E: expanded overlap view of the external chamber pressure and internal neck pressure recorded by the balloon-tipped catheter on a separate rapid pulse train illustrating the temporal congruency and improved internal transmission.
investigators using the single-sided chamber design (15).

**Importance of carotid sinus location and collar position.** The wide variation in the location of the carotid sinus had not been reported with regard to potential methodological problems with the NP/NS technique. To illustrate the diversity that may occur in the anatomical location of the carotid sinus, magnetic resonance images (MRI) of the carotid bifurcation were obtained and matched to the cervical vertebra images of two individuals (see Fig. 3). The Doppler ultrasound measurement of the carotid sinus for the individual in Fig. 3A was measured at the point of the gonion (0 cm) of the mandible. The MRI image placement of the carotid sinus in Fig. 3A was at the C2-C3 vertebral level. This vertebral locus was higher than the commonly used thyroid cartilage anatomical landmark, which occurs at the level of C3-C4. The Doppler ultrasound measurement of the carotid sinus for the individual in Fig. 3B was measured at a point 7 cm below the gonion of the mandible. The MRI image placement of the carotid sinus in Fig. 3B was at the C7 vertebra. The sealed neck collar was placed along the lower mandible with the rim of the collar in contact with the gonion. This was the purpose of utilizing the gonion of the mandible as an external landmark rather than the thyroid cartilage. Although the average carotid sinus location was \( \approx 3 \) cm below the gonion of the mandible, the observed variability of the anatomical location coupled with the decreased internal transmission characteristics recorded just below the rim of the sealed collar does bring into question the possibility of poor transmission of the applied stimulus in individuals with a carotid sinus anatomical location near the gonion of the mandible or the clavicle.

Furthermore, investigators have utilized different NP/NS collar designs, with the design being developed for specific investigational purposes. The primary purpose of all collar designs is to isolate the carotid sinus and develop a sealed chamber that can maximally transfer pressure stimuli to alter carotid sinus transmural pressure. The data collected in the present investigation illustrated the importance of two factors. First, some individuals had carotid sinus bifurcation locations that resulted in a maximal transmission of external pressures difficult. Hence, investigators are encouraged to measure the carotid sinus bifurcation with Doppler ultrasound when possible and to use this measurement as an exclusion factor for experimental subjects that display extreme superior/inferior anatomical carotid bifurcation loci. Second, a specific collar design may prohibit the number of individuals whereby the carotid sinus location would freely lie within the aperture of the sealed chamber. An extreme example of this dilemma would be illustrated by the recent work of Raine and Cable (15). In an attempt to develop a simple NP/NS carotid baroreflex system, a small sealed chamber designed from commercial headphone chambers was utilized. This equipment design could also be utilized to selectively stimulate the carotid sinus in a unilateral protocol (27) as opposed to

Fig. 3. Magnetic resonance images of variation in carotid bifurcation location. Images of two individual subjects that represent the range of the anatomical location of the carotid sinus bifurcation. Arrow, location of the carotid bifurcation. Dotted line, location of the carotid bifurcation to the corresponding level of cervical vertebrae. The carotid bifurcation for subject A measured externally 0.5 cm below the gonion (angle of the mandible) by Doppler ultrasound and corresponded to C3 level. The carotid bifurcation for subject B measured externally 7.0 cm below the gonion, corresponding to the C7 level. Anatomical variation in carotid sinus location may be of concern with specific neck collar designs and the neck pressure/neck suction technique.
the common bilateral simultaneous stimulation. Because of the limited size of the chamber aperture, it is possible that attenuated pressures would be transmitted to the carotid sinus, or in some individuals, the pressure stimuli would not be located over the locus of the carotid sinus. In either case, the results would be misleading or unobtainable.

Transmission of external pressure stimuli during exercise. One concern of utilizing NP/NS with exercise was that increases in tension of the musculature of the neck would further attenuate the transmission of external pressure or during the sustained 5-s NP/NS protocol the internal pressure would diminish due to tissue adaptation. In reference to increased muscular contraction attenuating an external pressure stimulus, a recent study by Smith and colleagues (22) found that the intramuscular pressure transmission of a sustained external positive pressure (lower body positive pressure of +45 Torr) was maintained during rest and throughout maximal muscular contraction. Also, Aratow and colleagues (1) reported further uninhibited transmission of lower body negative pressure to the muscle of the thigh during contraction. Therefore, it was unlikely that the transmission characteristics of NP/NS would be diminished or altered even with mild to moderate tension increases in the neck musculature due to the fact that transmission of positive pressure and the concurrent changes in tissue was uniform even at elevated external pressures (80 Torr). The findings of the present investigation indicated that the transmission percentages of NP/NS measured by the balloon-tipped catheter were consistent between rest and exercise conditions and even with increased muscular and tissue pressure due to a Valsalva technique. Therefore, calculations based on estimated CSP would include the same error across experimental conditions, and any reflex response changes measured would then reflect alterations in the integration of afferent information from the altered CSP and the reflex peripheral responses rather than alterations in pressure transmission characteristics.

Effect of correcting CSP on carotid baroreflex parameters. One area that would benefit from correcting the estimated CSP and calculated carotid baroreflex for accurate transmission percentages is the comparison between animal and human studies on carotid baroreceptor function. Animal studies often have the advantage of direct measurement of CSP (4, 10, 23, 25, 26). The measured variables of reflex function in these studies should reflect very accurate physiological values and are often different from the reported variables in human studies (2, 11, 13, 14, 16) where estimations of CSP alteration are mathematically derived. Additionally, animal studies often use methodological approaches that allow cardiac output and peripheral resistance to reach more of a steady-state environment to evaluate carotid baroreflex function. This steady-state evaluation is difficult to reproduce in human investigations using NP/NS. The short stimulus duration in rapid pulse and 5-s protocols reflect both parasympathetic and sympathetic components, although there is inadequate time for maximal sympathetic responses to occur. The consistently higher calculated gains reported in animal studies may in part be attributed to technical differences in experimental design. However, the correction of the external chamber pressure for transmission percentage with the neck pressure technique in human studies may bring the calculated reflex gains between animal and human studies closer together.

A common methodology for producing a model of carotid baroreflex function is the mathematical logistic function described by Kent et al. (8). This produces a
sigmoid stimulus-response curve with calculations of estimated threshold, saturation, and maximal gain for the carotid baroreflex. Correction of external neck pressure for internal transmission using the data from the fluid-filled catheter that was similar to the original findings reported by Ludbrook et al. (9) was found to have a significant impact on calculated baroreflex parameters compared with calculations without the correction factor. This impact on calculations of group mean data included significant increases in the threshold and maximal gain and a decrease in the saturation of the carotid baroreflex using the Kent model ($P < 0.05$). However, when external chamber pressures were corrected to reflect transmission data obtained from the balloon-tipped catheter, the calculated CSP and subsequent carotid baroreflex parameters were not significantly different ($P > 0.05$) from values calculated without transmission correction because of the mathematical estimation equations of the Kent model. A graphical and mathematical representation of the difference in calculated baroreflex parameters between a correction factor derived from the fluid-filled catheter data and a correction from the balloon catheter data or uncorrected data are illustrated in Fig. 4.

The calculation of maximal gain is a major use of the application of the Kent logistic model. The calculations of estimated threshold and saturation rely on the mathematical calculation of maximal gain. Accurate calculation of carotid baroreflex parameters including maximal gain would require correction for internal transmission. Internal transmission correction with results from the fluid-filled catheter or previous findings by Ludbrook et al. (8) would result in maximal gains that were significantly augmented compared with gains calculated without correction or data obtained from the balloon-tipped catheters and thus impact calculations of threshold and saturation parameters. The findings from the current investigation support the conclusion that the data obtained from the balloon-tipped catheter were more representative of the transmission characteristics of neck collar pressure than was obtained with the fluid-filled catheters and that correction for internal transmission utilizing these data would result in minimal changes in calculated baroreflex parameters. Furthermore, we suggest that the differences between animal and human results in carotid baroreflex modeling, and calculated parameters cannot be attributed to by experimental limitations of internal transmission of external neck pressure.

In summary, the asymmetric internal transmission characteristics of external pneumatic pressure to the carotid sinus recorded with a fluid-filled catheter in the current investigation were consistent with the findings originally reported by Ludbrook et al. (9). However, these data underestimated the actual percentage of transmission of an external pressure stimulus due to the limitations of a fluid-filled catheter system to accurately detect changes in tissue pressure. The data from the balloon-tipped catheter utilized in the current investigation indicated that the transmission of external positive and negative pressure to the neck were higher than previously reported and transmitted to the carotid sinus region without a kinetic delay. The internal transmission of external neck pressure was adequate to negate the requirement of a correction factor to calculate accurate carotid sinus transmural pressures and carotid sinus baroreflex parameters.

A significant anatomical variation in the location of the carotid sinus was measured. This variation was found to have an impact on the internal pressure transmission at the carotid sinus region in those individuals that displayed the superior/inferior range of carotid sinus loci. Internal transmission in these regions displayed an attenuated response to external neck pressure stimuli compared with individuals with carotid sinus loci, which were in the middle-open region of the neck collar. From these measurements, the authors recommend the following: 1) the location of the carotid sinus should be verified by Doppler ultrasound or other methodology; 2) the collar design and placement should allow for variation in the location of the carotid bifurcation to eliminate potential interference or error; 3) investigators utilizing small or experimental collar designs should consider this anatomical loci variation of the carotid sinus in the development of their experimental design and data analysis and interpretation; and 4) calculated carotid baroreflex parameters are minimally affected by correction of internal transmission.

We appreciate the laboratory support provided by Rita Welch-O’Connor, Paul Fadel, and Michael Williams and the secretarial support in preparation of the manuscript by Lisa Marquez. The authors also extend gratitude to Carina Nørgaard for expertise in Doppler imaging and the subjects for their interest and cooperation.

This study was supported in part by a Danish National Research Foundation Grant 304-14, Copenhagen, Denmark. This research was submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy for R. G. Querry as submitted to the University of North Texas Health Science Center.

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