Oscillatory pressure wave transmission from the upper airway to the carotid artery

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Submitted 13 December 2006; accepted in final form 13 August 2007

Howitt L, Kairaitis K, Kirkness JP, Garlick SR, Wheatley JR, Byth K, Amis TC. Oscillatory pressure wave transmission from the upper airway to the carotid artery. J Appl Physiol 103: 1622–1627, 2007. First published August 16, 2007; doi:10.1152/japplphysiol.01413.2006—Snoring-associated vibration energy transmission from the upper airway to the carotid artery has been hypothesized as a potential atherosclerotic plaque initiating/rupturing event that may provide a pathogenic mechanism linking snoring and embolic stroke. We examined transmission of oscillatory pressure waves from the pharyngeal lumen to the common carotid artery wall and lumen in seven male, anesthetized, spontaneously breathing New Zealand White rabbits. Airflow was monitored via a pneumotachograph inserted in series in the intact trachea. Fifteen 20-s runs of, separately, 40-, 60-, and 90-Hz oscillatory pressure waves [pressure amplitude in the trachea (Ptramp), amplitude 2–20 cmH2O] were generated by a loudspeaker driven by a sine wave generator and amplifier and superimposed on tidal breathing via the cranial tracheal connector. Pressure transducer-a sine wave generator and amplifier and superimposed on tidal spectrum analysis and linear mixed-effects statistical modeling. Both findings confirm transmission of oscillatory pressure waves from the upper airway lumen to the peripharyngeal tissues and across the carotid artery wall to the lumen. Further studies are required to establish the role of this incident energy in the pathogenesis of carotid artery vascular disease.

vibration; peripharyngeal tissue pressure; snoring

EPIDEMIOLOGICAL EVIDENCE SUGGESTS that obstructive sleep apnea (OSA) is a risk factor for cardiovascular diseases, including stroke (30). A number of studies have also linked self-reported snoring to chronic cardiovascular diseases, including hypertension (21), myocardial infarction (7), and ischemic heart disease (17). Case control studies also suggest not only that self-reported habitual snoring is an independent risk factor for stroke but also that the magnitude of that risk is of the same order as that for established risk factors, such as arterial hypertension, heart disease, smoking, age, and hypercholesterolemia (24, 26, 32). While in a number of these studies self-reported habitual snoring has been considered to be a marker for the presence of OSA, other studies have suggested that snoring alone, independent of OSA, may be a risk factor for both hypertension (4) and carotid artery atherosclerosis (18).

Pathophysiologically mechanisms linking cerebrovascular events and sleep-disordered breathing is, however, poorly understood. Some authors have suggested that associated hypertension (2, 25) and the repetitive nocturnal hypoxemia associated with OSA may provide this linkage (31). However, neither of these mechanisms explains why subjects who snore, but are normotensive and have no evidence of nocturnal hypoxemia, have increased risk for stroke (26). In 1994, Hedner and colleagues (13) proposed that repetitive episodes of habitual snoring, occurring over periods of years, may transmit sufficient vibratory energy to the carotid artery walls to damage the carotid artery endothelium, thus providing an initiating event in atherosclerotic plaque formation. Alternatively, on a more acute basis, they also hypothesized that such vibration energy may weaken already deposited atheromatous plaque formations, thus providing a stroke-initiating event.

Recently, our laboratory published data from an animal model (anesthetized rabbit) in which transmission of snoring-related energy to the carotid artery was measured (1). For vibration frequencies between 50 Hz and 1 kHz, induced snoring was associated with a 19-fold increase in energy levels within the peripharyngeal tissues, accompanied by an 11-fold increase in energy levels within the carotid artery lumen. Moreover, snoring-related energy transmission across the carotid artery wall was frequency dependent, with amplification occurring for frequencies in the 75- to 275-Hz bandwidth.

In the present study, we further examine characteristics of vibration transmission through the peripharyngeal tissues and across carotid artery walls, with a particular focus on dose-response characteristics in the primary frequency range (40–90 Hz) often associated with human snores (20).

METHODS

Studies were performed in seven adult, male, supine, spontaneously breathing New Zealand White rabbits (weight 3.15 ± 0.34 kg; mean ± SD). Experimental protocols were approved by the Western Sydney Area Health Service Animal Ethics Committee.

Anesthesia. Anesthesia was induced with an intramuscular injection of ketamine (35 mg/kg) and xylazine (5 mg/kg) and then maintained using an intravenous infusion of ketamine (15 mg·kg⁻¹·h⁻¹) and xylazine (4.5 mg·kg⁻¹·h⁻¹). Animals were euthanized at the completion of the study using intravenous pentobarbital sodium.

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Surgical preparation. A ventral neck skin incision was used to expose the cervical trachea. Separate cannulae were inserted into the tracheal lumen through incisions made between the 3rd and 4th tracheal cartilage rings cranially and the 10th and 11th tracheal cartilage rings caudally.

The caudal end of the cranial tracheal segment cannula was connected in series with the caudal tracheal segment via a pneumotachograph (8300A, Hans Rudolf, Kansas City, MO). In this manner, the animal could continue breathing via the upper airway while airflow was monitored with the pneumotachograph.

A transducer-tipped catheter (Millar SPR-524, Millar Instruments, Houston, TX) was positioned with its tip (sensor oriented toward the pharyngeal lumen) in the tissues adjacent to the left common carotid artery bifurcation and used to monitor pressure in the surrounding tissues, i.e., carotid tissue pressure (Pcti). A second catheter was introduced into the left common carotid artery lumen and then advanced until its tip (sensor oriented toward the pharyngeal lumen) was positioned at the common carotid artery bifurcation (carotid sinus) (Fig. 1). This latter catheter was used to monitor carotid sinus pressure (Pcs) and was secured in place by ligating the common carotid artery. The transducer-tipped catheters have a linear response between 0 and 10 kHz, with an operating pressure range of −67.9 to +407.9 cmH2O. Positioning of each catheter was verified via postmortem dissection at the conclusion of each study.

Experimental setup. The experimental arrangement is shown in Fig. 1. A loudspeaker (S15.8, 15 in., 500 W, minimum frequency 40 Hz, Cerwin-Vega, Simi Valley, CA) was connected to the cranial tracheal cannula via a three-way tap. A pressure transducer (LCVR 0–200 cmH2O, Celesco, Dandenong, Australia) connected to a side port in the cranial tracheal cannula monitored tracheal pressure (Ptr).

Vibration generation. A sine-wave generator (model 160A, BWD Electronics Pty.) and amplifier (PA-9312, Inter M) were used to drive the loudspeaker at set primary frequencies and amplitudes. When the loudspeaker was connected to the cranial tracheal cannula lumen, this arrangement allowed oscillatory pressure waves of preset frequency and amplitude to be superimposed on tidal breathing airflow patterns.

Protocol. Three primary frequency levels of superimposed oscillatory pressure waves (40, 60, and 90 Hz) were studied. Signal amplitudes from 2 to 10 cmH2O were applied at each of these designated frequencies. Before each application of oscillatory pressure, a 15- to 20-s period with no oscillation was recorded. Pressure oscillations were then applied (3-way tap connecting the speaker to the airway in the open position, see Fig. 1) in 15- to 20-s runs, with three runs being performed for each combination of frequency and amplitude. At the end of the oscillation study period, tap-closed control runs were performed for each frequency/amplitude combination by positioning the three-way tap such that the pressure wave generated by the loudspeaker was vented to the atmosphere and not into the upper airway. Data were digitized (sampling frequency 4,000 Hz, MacLab 16s, ADInstruments, Sydney, Australia) and stored on a MacIntosh computer for later analysis.

Data analysis. Data were analyzed in the frequency domain using spectral analysis with a 1,024 point fast Fourier transformation size (Chart version 3.6.1/s, AD Instruments, Sydney, Australia). A 10-s steady-state period, commencing a few seconds after the beginning of each run, was selected for analysis, and the oscillation amplitudes for the Pcti, Pctiamp, and Pcs signals at the primary frequency, as generated by the loudspeaker for that run (i.e., Pctiamp, Pctiamp, and PCsamp, respectively), were obtained. For each run, vibration transfer across the carotid artery wall was expressed as the Pcsamp-to-Pctiamp ratio (Pcsamp/Pctiamp).

Statistical analysis. To stabilize the variance between individual rabbits, individual values for Pctiamp and Pcsamp were expressed as their natural logarithm (ln). Using all available run data, a linear mixed-effects statistical model (28) was used to examine the effect of tap status (tap open, oscillation with tap closed, and no oscillation; fixed effect), input amplitude (Ptramp), and input frequency (both fixed effects) on, first, ln Pctiamp and ln Pcsamp (individual rabbits; random effect). In addition, the linear mixed-effects model was also used to examine the effect of input frequency on the calculated transmission function (i.e., Pcsamp/Pctiamp). The linear mixed-effects model was used to allow comparisons between different tap states of the effect of different amplitudes and frequencies (f) on the ln Pcsamp and ln Pctiamp. For each tap status, an equation, \( \ln Pctiamp = a + b1(f) + c \), where \( a, b1, \) and \( c \) are constants, was fitted to the data. \( P < 0.05 \) was considered significant.

RESULTS
In all rabbits, during the injection of oscillatory pressure waves into the upper airway lumen, pressure oscillations at the applied primary frequency were detected, both in the tissues adjacent to the carotid artery wall (i.e., contained in the Pcti signal) and within the carotid artery lumen (i.e., contained within the Pcs signal; Fig. 2).

Pcti. When the tap was open, with an input frequency of 90 Hz and an input amplitude pressure range of 0.7–1.5 cmH2O2, the absolute measured pressure amplitude in the tissues was 0.2 ± 0.07 cmH2O2 (mean ± SE).

Table 1 and Fig. 3 show results from linear mixed-effects modeling of ln Pctiamp in six rabbits (Pcti data were not obtained in 1 rabbit) under all three experimental conditions (no oscillations, and oscillation with tap closed and tap open). When no oscillations were applied, ln Pctiamp values did not differ across the 40- to 90-Hz frequency band. During the tap-closed condition, ln Pctiamp was also constant across the tested frequency band, but values were increased relative to the no-oscillation condition. During the tap-open condition and with oscillatory pressure waves being injected into the airway, ln Pctiamp increased both progressively with increasing frequency and in steps associated with each applied increase in Ptramp (both \( P < 0.05 \)). Thus ln Pctiamp was determined by both the amplitude (Ptramp) and the frequency of the input oscillatory pressure wave, according to the following relationship: ln Pctiamp = \( a1(\text{Ptramp}) + b1(f) + c1 \), where \( a1, b1, \) and \( c1 \) are constants. Between each tap state, there was no difference in the effect of increasing Ptramp; however, the effects of frequency (b1) and background noise (c1) were significantly different between tap states (see Table 1).
was no difference in the effect of increasing \( P_{\text{tramp}} \); however, \( b_2 \), \( b_2 \), and \( c_2 \) were significantly different between tap states (see Table 2).

When the tap was open, with an input frequency of 90 Hz and an input amplitude pressure range of 0.4–1.5 cmH\(_2\)O\(^2\), the absolute measured \( P_{\text{csamp}} \) was 0.1 ± 0.01 cmH\(_2\)O\(^2\).

Table 2 and Fig. 4 show linear mixed-effects modeling determined relationship between the input parameters and the \( P_{\text{csamp}} \) when there was no significant effect of increasing frequency on \( P_{\text{csamp}} \); however, the effect of frequency (\( b_2 \)) and background noise (\( c_2 \)) were significantly different between tap states (see Table 2).

\( P_{\text{csamp}}/P_{\text{ctiamp}} \). Analysis of the carotid wall transmission function (\( \ln P_{\text{csamp}}/P_{\text{ctiamp}} \)) was performed for the tap-open oscillation condition only. Using linear mixed-effects modeling, there was no significant effect of increasing frequency on \( P_{\text{csamp}}/P_{\text{ctiamp}} \) (\( P > 0.2 \)). The mean \( P_{\text{csamp}}/P_{\text{ctiamp}} \) across all rabbits, runs, and frequencies was 1.8 ± 0.3, i.e., a \( (P_{\text{csamp}}/P_{\text{ctiamp}}) \% \) of ~180%.

**DISCUSSION**

In a previous study, our laboratory demonstrated that induced snoring in anesthetized rabbits, achieved by applying a compressive forces at the skin surface to increase peripharyngeal tissue pressure, was associated with detectable levels of vibration-related energy within the carotid artery lumen (1). In the present study, we examined the transmission characteristics for vibratory pressure waves passing from the upper airway lumen, through the peripharyngeal tissues, and across the carotid artery walls into the carotid artery lumen, with a particular focus on the fundamental frequency band most often associated with human snoring, i.e., <100 Hz. The major findings of this study were that, in the 40- to 90-Hz frequency band, 1) pressure oscillations present in the upper airway were transmitted from the airway to the carotid artery lumen; 2) this transmission was frequency dependent with more efficient transfer of higher frequencies; and 3) there is amplification of such vibrations as they transmit the carotid artery walls.

The methodology chosen to generate oscillatory pressures within the upper airway lumen is similar to methodology previously used by our laboratory (3) and others (29) to investigate the effect of pressure oscillations on upper airway reflexes. In the present study, the speaker cone was connected to the airway at the level of the trachea. Using this experimental setup, we tested the effect of increasing frequency and amplitude of oscillatory pressure waves on upper airway reflexes.
Fig. 4. Graphical representation of the fitted functions obtained using the linear mixed-effects model showing the effect of increasing input frequency and signal amplitude (Ptramp) on Ln Pcsamp calculated at average a, b, and c (see Table 2). All data are significant at P < 0.05. No-oscillation (dashed line) and tap-closed oscillation (dotted line) data have been calculated at the average Ptramp for these states of 0.02 cmH2O², which represents the background noise in the system. For the tap-open oscillation condition (solid lines), data have been calculated for Ptramp between 0.5 to 2 cmH2O², as indicated by the numbers on the right of the line. Note that there is a reduction in the background noise with increasing frequency. Also note that, at lower Ptramp and 40-Hz frequency, there is no significant difference between tap-open conditions and background noise; however, increasing Ptramp results in an increase in Ln Pcsamp across all frequencies. *P < 0.05, indicating a significant slope with increasing frequency.

The methodology used in this study to assess total pressures within and surrounding the carotid artery has been employed in a number of previous studies (1, 15, 16), and its limitations have been discussed elsewhere (15, 16). Due to the invasive nature of the measurements, the absolute pressures at baseline are unlikely to be equivalent to the pressures present before the introduction of the catheter. Since fluid dynamic linkage of local pressures to the catheter sensor is also undoubtedly complex, in this study we have focused on the responses to perturbations to the system, i.e., the amplitude of the oscillatory pressure rather than the baseline pressures.

Linear mixed-effects modeling was used for the statistical analysis (28). This method analyzes each of the subjects within the group and allowed us to determine the effect of both the fixed-input variables of Ptramp and frequency on each of the outputs. With this analysis, baseline variability between rabbits can be treated as a random variable, which allows trends for the group to be examined.

Spectral analyses of human snoring have demonstrated fundamental frequencies in the range of 34–332 Hz (11, 24, 28), with the main energy component in one study around ~130 Hz (8). A wide variety of fundamental snoring frequencies has been reported in human subjects, from as low as 30 Hz in subjects with oral snoring and around 80 Hz in subjects with nasal snoring (19). We chose the lower range of frequencies, because these frequencies are present in human snoring (11, 19) and are reported to cause arterial damage (5). In rabbits, we have recently demonstrated that, during induced snoring, recorded frequencies were >50 Hz, although the majority of the power was in frequencies >100 Hz (1). Our model differs from that of Amatoury et al. (1), because we have chosen to investigate frequencies <100 Hz, because these frequencies are more relevant to the fundamental frequencies recorded in snoring human subjects (20, 23, 27).

In addition, and in contrast to Amatoury et al. (1), we have chosen to use sound waves to generate oscillatory tissue pressures, rather than create conditions that set tissues into oscillatory motion, thus generating sound. Our approach was chosen because it allowed specific frequencies to be chosen and tested independently. This model is not, however, equivalent to natural snoring, as snoring sounds are generated by vibrations of the structures of the upper airway, such as the soft palate, pharyngeal walls, epiglottis, uvula, and tongue, and are made up of a composite of a number of frequencies (19). Thus the methodology chosen relied on the sound pressure to vibrate the pharyngeal tissues, rather than the tissues to vibrate the air, as we have described previously (1). It is likely that the amplitude of the tissue vibrations generated using sound pressure are less than would occur during the generation of natural snoring, and indeed our data suggest that there has been significant damping of the oscillatory signal from the air to the tissues and the carotid sinus.

Pcti. This study has demonstrated that oscillatory pressures present in the upper airway lumen are transmitted to the tissues surrounding the carotid artery wall, and that increasing input pressure amplitude and increasing frequency increased the amplitude of vibration at the carotid artery walls. Transmission of oscillatory pressures to the tissues surrounding the carotid artery has been demonstrated in our laboratory’s previous study (1). However, in that study, the effect of increasing oscillatory pressure amplitude and frequency on transmission was not examined.

Pcs. In addition to demonstrating transmission of oscillatory pressures to the tissues surrounding the carotid artery, this study demonstrates, at least for frequencies in the 40- to 90-Hz range, that there is transmission of oscillatory pressures from the upper airway lumen to the carotid artery lumen, and this transmission is also greater with increasing oscillatory input pressure amplitude and frequency.

Pcs/Pcti. In the present study, the Pcs/Pcti was greater than unity, implying that transmission across the carotid artery wall has resulted in an increase in energy of the transmitted wave. This finding is suggestive of carotid artery wall resonance. The carotid artery is an elastic structure and, as such, may vibrate in response to the application of oscillatory pressures at a specific resonant frequency, thus amplifying the incident pressure wave. The natural or resonant frequency of vibration for the arterial system is thought to facilitate transmission of the blood from the heart to the peripheral blood vessels (35). Previous workers have demonstrated that both in vitro canine carotid arteries (12, 14) and human iliac arteries (34) have between one and four resonant frequencies <120 Hz, all at similar frequencies to those tested in the present study. In our study, however, we detected no significant effect of frequency...
on Pcs/Pcti; i.e., there was no unique resonant frequency. This suggests that, unless resonance is occurring across the whole 40- to 90-Hz frequency band, in a similar manner to that described by others (12, 14, 34), resonance may not be the unique explanation for our findings. For example, an alternative explanation may be that the vibrations are focused onto the luminal side of the carotid bifurcation, because the anatomical structure of the bifurcation focuses oscillatory pressures such as occurs with focusing of sound waves with an ear trumpet.

Significance of findings. This is only the second study to demonstrate transmission of vibratory pressures from the pharynx to the carotid artery lumen in an animal model, and the approach is different from our laboratory’s previously reported model (1). This experimental model allows us to test vibratory frequencies that may be more relevant to the fundamental frequencies reported in human snoring (8, 11, 19, 20) and to test the effect of specific frequencies on the arterial wall. In particular, we are testing frequencies that have been demonstrated by other workers to be resonant frequencies in canine carotid (12, 14) and human iliac (34) arteries and that are thought to result in arterial damage (33).

Arterial walls, in general, are known to be resonant, and indeed, it is hypothesized that the arteries may be “tuned” to heart rate to allow pulse wave propagation via the elastic arteries from the heart to other structures in the body (35). However, this constant oscillation of the arterial walls is also hypothesized to result in “fatigue” from constant mechanical loading, which may be the mechanism that induces atherosclerotic plaque rupture (33). Treating hypertension and reducing pulse rate may reduce this chronic fatiguine stress (33). We have demonstrated that oscillatory pressures, at similar frequency to human snorers, are transmitted from the upper airway lumen and vibrate carotid arterial walls. If this situation is repeated on a chronic basis, as would occur with habitual snoring, it may conceivably lead to “fatigue” and rupture of carotid atherosclerotic plaque. Oscillatory pressures of similar frequencies have been implicated in damage to arteries elsewhere in the body. Vibration-induced injury is thought to be one of the mechanisms by which poststenotic dilatation of arterial walls occurs (9). The frequencies resulting in vascular injury to manual workers, known as vibration-induced white finger (10), are similar to the frequencies in human snoring. Recently, vibration-induced endothelial damage in the rat tail artery was demonstrated to be both frequency and amplitude dependent (6), with rupture of the internal elastic lamina occurring at 30, 60, and 120 Hz after a period of only 4 h. Thus there is evidence that arterial damage can result from vibration at the same frequency as that recorded during snoring. The vibrations during snoring may have implications for the pathogenesis of stroke, as hypothesized by Hedner et al. (13), where arterial vibrations related to snoring may dislodge atherosclerotic plaques and be an initiating event for stroke. Alternatively, the vibration of the artery may result in endothelial damage and be an initiating event for atherosclerosis.

Conclusion. This study demonstrates that low-frequency pressure oscillations, similar to those occurring in natural snoring in humans (8), are transmitted from the pharyngeal lumen and reach the wall of the carotid artery wall bifurcation and the carotid artery lumen. In addition, we demonstrate that there is amplification of these oscillatory pressure waves across the arterial wall. We speculate that, as hypothesized by Hedner et al. (13), these oscillations may constitute a pathogenetic mechanism for stroke. Further studies, particularly an examination of transmission of natural snoring vibrations to the carotid artery walls in humans, will be required to establish the clinical significance of these findings.

ACKNOWLEDGMENTS

The authors thank Colin Sullivan for helpful discussion, Katherine Medina for assistance with the experimental work, and Peter Martens for technical support.

GRANTS

This study was supported by the National Health and Medical Research Council of Australia and the Australian Lung Foundation.

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