Snoring Imaging: Could Bernoulli Explain It All?

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Snoring Imaging*

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Study objectives: **To identify upper airway changes in snoring using CT scanning, to clarify the snoring mechanism, and to identify the key structures involved.**
Participants: **Forty patients underwent CT examination of the head and neck region according to snoring habits; patients were classified into nonsnoring (n = 14), moderately loud snoring (n = 13), and loud snoring (n = 13) groups.**
Design: **Comparative analysis.**
Measurements: **Using CT images, areas, the anteroposterior and transversal distances of the pharyngeal space at different levels, and the thickness and length of the soft palate and uvula and their angle against the hard palate were measured; evidence of impaired nasal passages was noted; the extent of pharyngeal inspiratory narrowing was the ratio between the area at the hard palate level and most narrow area; and expiratory narrowing was the ratio between the area behind the root of the tongue and the most narrow area.**
Results: **Greater pharyngeal inspiratory narrowing ($p = 0.0015$) proportional to the loudness of snoring ($p = 0.0016$), and a longer soft palate with uvula ($p = 0.0173$) were significant for snoring. Impaired nasal breathing was significantly related ($p = 0.029$) only to the loud snoring group. The body mass index and age of snoring persons were also significantly higher.**
Conclusions: **Snoring is associated with typical changes that can be revealed by CT scanning. Greater pharyngeal narrowing is the most important factor. Given the "Venturi tube" shape of the pharynx, the Bernoulli pressure principle plays a major role in snoring. The key structure in snoring is the soft palate: it defines the constriction and is sucked into vibrating by negative pressure that develops at this site. Its repetitive closures present an obstruction to breathing, producing the snoring sound, and should therefore be the target for causal treatment of snoring. Obstacles in the upper airway that increase negative inspiratory pressure could not be confirmed as important for the development of snoring, although they may increase its loudness.**
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Key words: CT; palate, soft; pharynx; respiration disorders; sleep apnea, obstructive; snoring

Abbreviations: BMI = body mass index; OSA = obstructive sleep apnea; UARS = upper airway resistance syndrome

Snoring, obstructive sleep apnea (OSA), and upper airway resistance syndrome (UARS) are sleep-related breathing disorders associated with the increase of upper airway resistance. The resistance is a consequence of partial (snoring, UARS) or complete (OSA) upper airway obstruction. The disorders have the same etiopathogenesis but differ in the severity of the symptoms and their influence on general health. Snoring is considered the "mildest" form, and OSA is the most "extreme" form.[1] Recognizing the structures responsible for these disorders and understanding the mechanism by which they develop are necessary before considering their treatment.

Since the obstructive phenomena are well-defined disturbances, one would expect that they are associated with well-defined anatomic changes. However, typical differences between nonsnoring and snoring

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persons still do not seem to be completely recognized. Faber and Grymer[2] summarized a number of studies describing the imaging techniques available for determining the level of obstructive predominance: lateral cephalography, awake endoscopy, awake endoscopy with the Müller maneuver, endoscopy during sleep, endoscopy with nasal continuous positive airway pressure during sleep, fluoroscopy, CT scanning, magnetic resonance scanning, manometry, and acoustic reflection. They concluded that in spite of the variety of changes described, no reference standard exists for the determination of the predominant obstructive level during obstructive events. They also suggested that further studies are necessary to improve and validate existing methods and to develop new techniques. Such research would improve our understanding of the pathophysiology of OSA and snoring and assist in selecting the correct treatment option for different patients. The aims of our study were to discover the anatomic differences between snoring and nonsnoring individuals using CT imaging, to clarify the mechanisms of snoring development, and to identify the key structures and associated aggravating factors involved.

Materails and Methods

Forty patients undergoing CT examination of the head and neck region—in most cases (n = 34) for carotid angiography—were included in the study. Mean age was 61.8 years (SD, 15.3 years), and 24 of the patients were men. In the course of the CT scanning, the patients were awake and lying in the supine position.

The participants and their spouses answered a questionnaire about their snoring habits, any stops of breathing experienced, daytime sleepiness, and impaired nose breathing. They estimated the loudness of their snoring on an analog scale from 0 (no snoring) to 5 (loudest snoring possible). According to their answers, 14 patients were placed in the nonsnoring group (nonsnorers and snoring loudness estimate 1), 13 patients were placed in moderately loud snoring group (snoring loudness estimates 2 and 3), and 13 patients were placed in the loud snoring group (snoring loudness estimates 4 and 5). None of the patients reported signs of OSA or UARS. The CT images were analyzed using software (DicomWorks; National Electric Manufacturers Association; Lyon, France), which allowed the measurement of pharyngeal areas at the hard palate level, at the most narrow area (at the palatal level), and at the level just above the epiglottis (behind the root of the tongue). We also measured the anteroposterior and transversal distances at the levels mentioned, as well as the thickness and length of soft palate and uvula and their position (angle) against the hard palate. Evidence of impaired nasal passages was also noted. The pharyngeal narrowing was determined as the ratio between the area at the hard palate level and the most narrow area. A body mass index (BMI) was also calculated for each participant.

Results

Results are presented in Table 1 and Figure 1. measured parameters are presented in Figure 2.

Table 1—*Comparison of Parameters Measured or Observed in Snoring and Nonsnoring Groups of Participants**

Parameters Observed/Measured†	Nonsnoring Group (n = 14)	Snoring Groups (n = 26)	p Value
Impaired nasal breathing, No.‡	8	16	0.66
Inspiratory pharyngeal narrowing ratio	3.59 (1.5)	6.65 (4.9)	0.0015
Expiratory pharyngeal narrowing ratio	3.0 (1.7)	4.5 (3.6)	0.0837
Length of the soft palate and uvula, cm	3.5 (0.6)	4.0 (0.6)	0.0173
Thickness of the soft palate, cm	0.8 (0.16)	1.0 (0.6)	0.1887
Angle between the hard palate and the soft palate, degrees	51.1 (9.2)	44.6 (13.3)	0.1125
Area at the hard palate level, cm^2	5.0 (2.3)	6.1 (2.0)	0.1031
Most narrow (palatal) area, cm^2§	1.5 (0.7)	1.1 (0.5)	0.1908
Area behind the root of the tongue, cm^2	3.8 (1.7)	3.9 (1.7)	0.8171
Anteroposterior distance at the hard palate level, cm	1.6 (0.7)	1.9 (0.6)	0.1343
Anteroposterior distance at the most narrow level, cm	0.7 (0.3)	0.5 (0.3)	0.1461
Anteroposterior distance behind the root of the tongue, cm	1.4 (0.3)	1.4 (0.4)	0.5982
Width at the hard palate level, cm	2.1 (0.7)	2.3 (0.6)	0.3925
Width at the most narrow (palatal) area, cm	2.0 (0.6)	1.7 (0.8)	0.2854
Width behind the root of the tongue, cm	2.9 (0.5)	2.9 (0.8)	0.9925
BMI	24.2 (2.77)	27.0 (3.97)	0.0172
Age, yr	55.1 (20.9)	65.5 (10.2)	0.04

*Data are presented as mean (SD) unless otherwise indicated.
†Measured parameters are presented in Figure 2.
‡If the loud snoring group was isolated and compared to the others (nonsnoring and moderate snoring groups), the difference became statistically significant (p = 0.029).
§In all persons, the most narrow area of the pharynx was the region behind the lower part of the soft palate.

Pathophysiology of Snoring

Snoring is a breathing disorder, and for its understanding the physical properties of breathing are employed. Breathing can be defined as the streaming of air driven by alternating negative and positive pressures produced by respiratory lung movements. Both elements, the alternations of respiratory pressure and the streaming of air, are used to explain snoring.

"Obstacle" Theory of Snoring: In normal circumstances, the positive and negative respiratory pressures are low because of the proximity of the upper airway to external space. Obstacles that constrict the upper airway increase the pressures since a higher driving force is necessary to obtain the same respiratory volume. The obstacle snoring theory assumes that increased negative pressure during inspiration retracts the structures of the pharynx and makes them vibrate in the stream of air to produce the well-known sound of snoring and/or complete obstruction in OSA.[3] This explanation is supported by the Müller test, which allows us to see and quantify the retraction.[4]

The Bernoulli Principle Theory of Snoring: This theory assumes that the streaming of the air is the most important factor in the pathophysiology of snoring. For evaluating the effects of the streaming air, the Bernoulli principle—established in 1738 by Daniel Bernoulli (1700–1782)—should be applied.[5,6] Simplified, the principle states that if air (technically a fluid) flows through a pipe of varying cross-section, its velocity is higher and the pressure lower at the constriction compared with at the larger part. A Venturi tube (Fig 3, *top*, *a*) offers the best demonstration of the Bernoulli principle. As rapidly moving air flows through the narrow parts of the upper airway, the Bernoulli principle predicts that negative pressure is created. This sucks the pharyngeal structures inward and generates snoring by their vibrations.

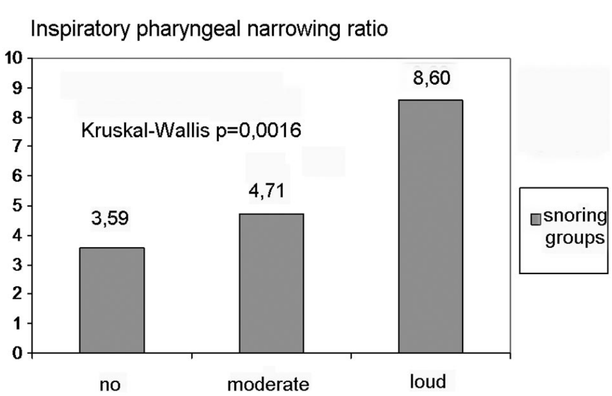

FIGURE 1. Inspiratory pharyngeal narrowing ratio (the ratio between the area at the level of the hard palate and the most narrow area) in nonsnoring, moderate, and loud snoring groups.

DISCUSSION

At the beginning of our study, we wanted to check the presence of clinically recognized reasons for snoring, such as obstacles in the nose, a narrow pharynx (in obese persons), backward displacement of the soft palate, enlarged tonsils, and a voluminous root of the tongue in snoring persons.[7] In CT images, these factors should appear as identifiable and measurable constrictions.

In our study, there were 24 persons with objective and/or subjective nasal breathing impairment. Contrary to our expectations, these impairments were not significantly associated with snoring (p 0.66). However, if we isolated the loud snoring group and compared it to the others, the relationship became significant (p 0.029). This finding is interesting, as it implies that obstacles in the nose are not essential

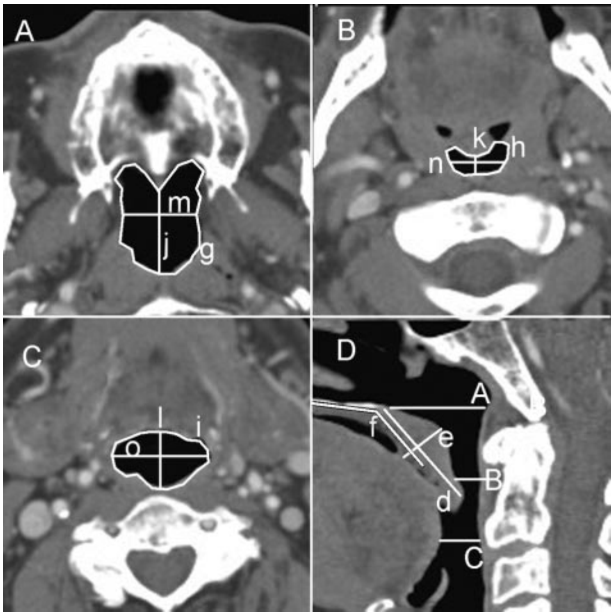

FIGURE 2. Distances, areas, and angle measured from the CT scan images. *Top left*, *A*: Hard palate level. *Top right*, *B*: Soft palate level. *Bottom left*, *C*: Level behind the root of the tongue. *Bottom right*, *D*: Sagittal projection of the pharynx. d = length of the soft palate and uvula, e = thickness of the soft palate, f = angle between the hard palate and the soft palate, g = area at the hard palate level, h = most narrow area, i = area behind the root of tongue, j = anteroposterior distance at the hard palate level, k = anterposterior distance at the most narrow level; l = anteroposterior distance behind the root of the tongue, m = width at the hard palate level, n = width at the most narrow area, o = width behind the root of the tongue.

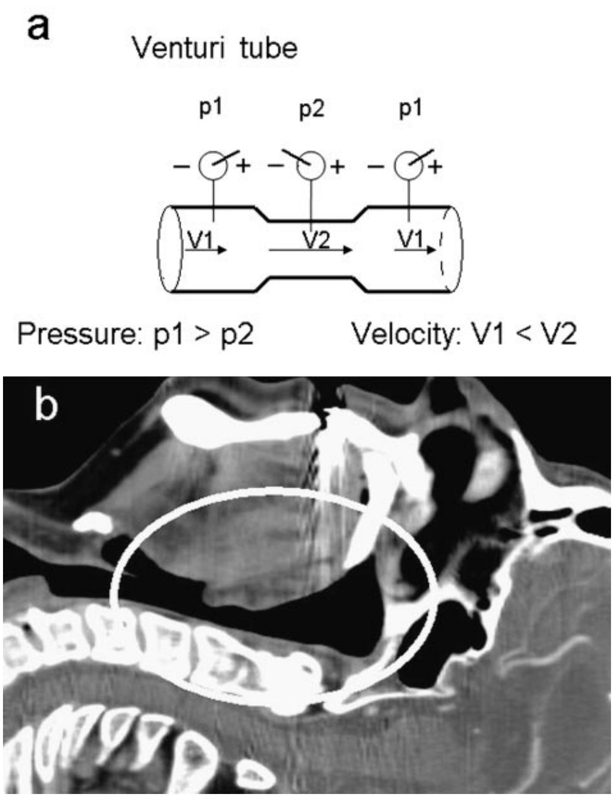

FIGURE 3. *Top*, *a*: Venturi tube demonstrating the Bernoulli principle. *Bottom*, *b*: Similarity of pharyngeal shape to the Venturi tube (circled).

themselves for the development of snoring but they may amplify the loudness of snoring.

The mean cross-section of pharyngeal space was smallest at the level of the soft palate, while the upper retronasal area was larger than the area behind the root of the tongue in all participating persons. None of the sections were significantly different between the snoring and nonsnoring groups. These measurements show that the pharynx shape is similar to a Venturi tube, which can also be seen at a glance from the sagittal CT images (Fig 3, *bottom*, *b*). The similarity of shapes also implies that the pressures in the pharynx are similar to those in the Venturi tube. The upper large part determines the narrowing in inspiration, while the lower enlargement is important in expiration. To confirm the Bernoulli principle in snoring, we compared the snoring and nonsnoring groups by the extent of inspiratory pharyngeal narrowing, which we expressed as the ratio between the nasal area (at the hard palate level) and the most narrow pharyngeal cross-section (behind the soft palate).

The results were highly significant, showing that a greater inspiratory narrowing is characteristic for snoring persons (Fig 4, 5). Furthermore, the narrowing was proportional to the loudness of snoring (Fig 1). The average narrowing was 3.59 (SD, 1.50) for nonsnoring persons (meaning the most narrow area was 3.59 times smaller than the nasal area), 4.71 (SD,

FIGURE 4. CT scans of a nonsnoring person. *Top left*, *a*: Area at the hard palate level (5.75 cm^2). *Top right*, *b*: Area at the most narrow level (1.73 cm^2). *Bottom*, *c*: Sagittal projection of the pharynx. The inspiratory pharyngeal narrowing ratio is 3.3.

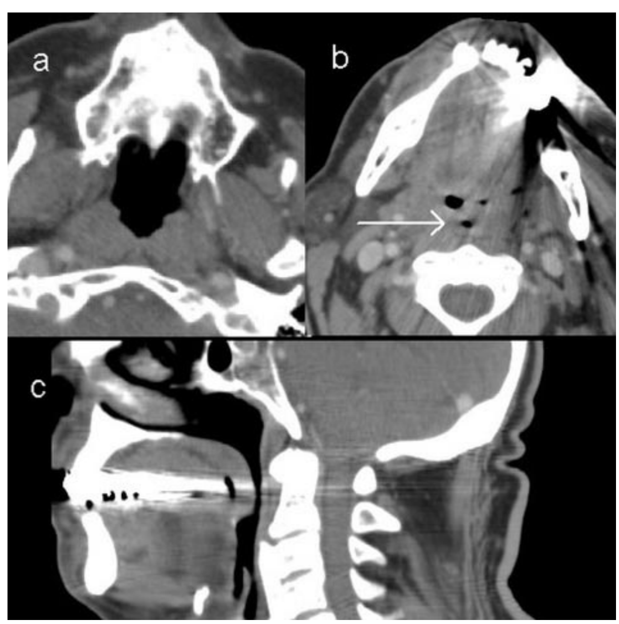

FIGURE 5. CT scans of a snoring person. *Top left*, *a*: Area at the hard palate level (7.26 cm^2). *Top right*, *b*: Area at the most narrow level (0.18 cm^2; indicated by the arrow). *Bottom*, *c*: Sagittal projection of the pharynx. The inspiratory pharyngeal narrowing ratio is 40.3.

1.05) for the moderately loud snoring group, and 8.60 (SD, 6.5) for the loud snoring group. The average narrowing for both snoring groups was 6.65 (SD 4.99).

Increased inspiratory pharyngeal narrowing is therefore quite an obvious snoring characteristic. It is not easily seen on two-dimensional images but must be calculated from the two cross-sections. This supports the Bernoulli principle snoring theory and also shows that the identification of snoring characteristics depends on understanding the snoring mechanism.

For treatment purposes, surgery in particular, it is important to recognize the structure responsible for pharyngeal narrowing. Our study has shown that it is the soft palate or, to be precise, its lower half. The soft palate always confined the most narrow pharyngeal cross-section, even in cases of enlarged tonsils or root of the tongue. These two structures occasionally displaced the soft palate backwards but they were never directly exposed in the stricture.

In the Venturi tube, the negative pressure develops and works on the walls of the constriction only. If the soft palate is the structure that defines the constriction, then it is also the only structure that is retracted by negative pressure and thus responsible for snoring.

The recognition of the soft palate, which with its free lower edge is the most unstable part of all the pharyngeal walls, as the key structure can explain several clinically known reasons for snoring. They all influence the backward displacement of the soft palate and its collapsibility. The most important is sleep and the associated hypotonicity of muscles, which in fact is the basic condition for snoring. Snoring can be triggered or worsened after alcohol and sedative consumption by increased muscular hypotonicity, in the supine position by gravity, and in cases of enlarged tonsils and/or tongue by the direct pressure of these structures on the soft palate. The soft palate is even more prone to retraction if longer and flaccid. In our study, both of these characteristics were confirmed in snoring persons, the first directly by measurements (nonsnoring group, 3.5 cm [SD, 0.6 cm]; and snoring groups, 4.0 cm [SD, 0.6 cm] $p = 0.0173$); and the second indirectly by the age of snoring persons (snoring, 65.5 years [SD, 10.2 years]; nonsnoring, 55.1 years [SD, 20.9 years], $p = 0.04$).

In this study, we confirmed the well-known fact that obesity is significantly related to snoring (see BMI for snoring and nonsnoring groups in the "Results" section). Obesity probably does not influence the soft palate position directly, but the thicker walls reduce the total pharyngeal space and enhance its Venturi tube shape, which in turn increases the suction at the soft palate level.

Why snoring occurs during inspiration in most of the cases and how it develops in mouth breathing are two questions that offer further insight into the snoring mechanism. The absence of snoring during expiration could be logically explained by the obstacle theory. The narrowing at the soft palate (or any other area above it) increases expiratory pressure, enlarges the upper airway space, and prevents snoring by neutralizing the Bernoulli principle negative pressure.

But the absence of snoring in expiration could be explained by the Bernoulli principle alone as well. In expiration, the negative pressure at the constriction is determined by the lower half of the pharyngeal Venturi tube, *ie*, by expiratory pharyngeal narrowing determined as the ratio between area behind the root of the tongue and the most narrow area. The mean magnitude of this ratio did not reach the mean inspiratory narrowing ratio that triggered snoring in snoring groups (see the inspiratory and expiratory pharyngeal narrowing ratio in the "Results" section and Fig 1). Second to the Bernoulli theory, snoring would therefore not develop in expiration even if positive expiratory pressure was not present.

Inspiratory and expiratory pressures are part of respiration, so we must accept their role in snoring too. If positive pressure prevents snoring, then inspiratory negative pressure should be seen as a generator of snoring or at least as an additional factor in its development. This could be supported by already mentioned association of impaired nasal breathing and loud snoring in the study ($p = 0.029$). Obstacles in the upper airway would thus increase snoring loudness by increasing the negative inspiratory pressure. But are they crucial for the occurrence of snoring as well? Our results show that obstacles are not associated with snoring development itself, and there is another, stronger, clinical argument that supports this statement.

It is common knowledge that most snorers breathe through their mouths while snoring. In these cases, the air stream bypasses all the obstacles at or above the level of the soft palate (which can cause the retraction of the pharyngeal space) and thus excludes them as a possible cause of snoring. And how would Mr. Bernoulli explain the snoring in oral breathing? We were not able confirm it in our study because a low number of participants were breathing through their mouths during the CT examination, but it can be logically assumed. The mouth cavity is larger than the *isthmus faucium*, and during inspiration the two spaces represent the large and narrow parts of the Venturi tube (Fig 6). In snoring, the soft palate is pulled against the tongue in these cases.

From our results and the evidence presented concerning the possible snoring mechanism, we believe that the pressure responsible for snoring is a sum of the

FIGURE 6. Venturi tube shape of the upper airway in mouth breathing. The distances between the lines represent the cross-section sizes of the space.

Bernoulli principle pressure and inspiratory negative pressure since both are present during inspiration. Inspiratory pressure is present throughout the entire airway, increasing gradually from nares to lungs, and depends on lung drive, while the Bernoulli principle pressure develops locally at constrictions and is created by the streaming of the air. The sum reaches a peak at the constriction, and when it is sufficient, the soft palate (unstable constriction) is retracted until complete closure. At this moment, the air streaming is stopped, the Bernoulli principle negative pressure drops, and the soft palate is returned to its starting position by its tonicity. The air stream and the Bernoulli principle pressure are then restored and the whole cycle repeats, thus producing soft palate vibrations and the typical snoring sound. In the course of inspiration, the inspiratory negative pressure is constant and does not influence soft palate closures directly. However, if elevated by an obstacle (stable constriction), it retracts all the pharyngeal walls and amplifies snoring loudness indirectly by increasing pharyngeal narrowing and/or possibly causes a steady closure that might be important in OSA. The Bernoulli principle pressure therefore seems to be essential for the development of snoring, while increased negative inspiratory pressure, if present, can only be seen as an aggravating factor.

Conclusion

The study showed that snoring is associated with typical changes in the upper airway and that they can be presented by CT scanning in awake individuals. We must realize that these are in fact the changes that trigger the real snoring alteration in sleep. They are not very evident and cannot be seen and measured directly from CT images but must be calculated. The increased degree of pharyngeal narrowing determined by the ratio between the area at the hard palate level and the most narrow area (behind the soft palate) is the most important factor. This recognition is possible only by understanding the snoring mechanism in which the Bernoulli principle seems to play a primary role. The key structure responsible for snoring is the soft palate, which is significantly longer in snoring persons. It is directly involved in snoring as it shapes the pharyngeal constriction and is sucked into vibrating by the negative pressure that develops at this site. The soft palate should therefore be the target for the causal treatment of snoring. Obstacles in the upper airway that increase the negative inspiratory pressure could not be identified as important for the development of snoring. They only increase snoring loudness and should be considered as aggravating factors.

The study presented has certain weaknesses. The snoring habits of the participants were not objectively evaluated; their ear, nose, and throat regions were not clinically examined; and the various pressures assumed were not measured. In the explanation of events that may be related and relevant to snoring, clinical observation and basic knowledge of physics were applied along with the evaluation of CT images, which provided the only objective data. Still, the findings offer an acceptable explanation of snoring (and by analogy, all sleep-disordered breathing). We would like to encourage everyone with facilities for making a more objective evaluation to confirm or disprove our findings.

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