348

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CHAPTER 10

OBSERVATION OF VOCAL FOLD VIBRATION: MEASUREMENT OF EXCISED LARYNGES

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INTRODUCTION

Recent empirical and theoretical studies of laryngeal anatomy, of laryngeal biomechanics, and of glottal aerodynamics have contributed substantially to the development of a detailed quantitative model of phonation. However, progress toward this end has been seriously hampered by the sparcity of detailed descriptions of phonatory vibration patterns, especially in the frontal plane. Studies with excised larynges can help substantially in this regard, since such preparations are accessible for observations and measurements that are not possible with the intact larynx. A particular advantage is that vibrations can be observed from the inferior aspect (Matsushita, 1969, 1975; Baer, 1975) or the medial aspect (Matsushita, 1969, 1975), as well as from the normal superior aspect. Measurements can even be made within the folds, with the aid of novel x-ray techniques (Saito, 1977; also Chapter 8 of this book). An additional advantage is that laryngeal configuration and subglottal pressure can be maintained in steady state for extended durations while the vibrations are studied, and these (and other) parameters may be manipulated systematically and independently.

Usefulness of data obtained from excised-larynx studies is, of course, somewhat limited, since the death of the tissues undoubtably changes their mechanical properties. More significantly, activity of the vocalis muscle, which forms part of the body of the vocal folds and which is normally active during phonation, cannot be adequately simulated. Nevertheless, development of a comprehensive, testable model for the vibratory mechanics of the excised larynx on the basis of detailed data is a useful first step toward the development of a model for the intact larynx.

In the study reported here, an optical technique was used to observe and measure mechanical vibrations from the superior and inferior aspects. Observations from the inferior aspect were made through a subglottal window, which afforded a direct view of the subglottal surface of the vocal folds. Particles attached to the vocal folds were optically tracked throughout the glottal cycle, using stroboscopic illumination while the larynx maintained steady state phonation. By tracking several particles "simultaneously", it was possible to estimate the detailed frontal-plane configuration of one vocal fold throughout a glottal cycle. Canine (rather than human) larynges were used, because human preparations were unavailable. This factor further limits the usefulness of the data as a it applies to human laryngeal mechanics, since there are significant differences between canine and human laryngeal anatomy which are expected to affect their vibratory performance (Hirano, 1975). However, since similar experiments are feasible with live-animal preparations, techniques developed in this study could be extended toward further studies with both excised human preparations and live animal preparations, to investigate the significance of both the canine-human and excised-live distinctions.

METHODS

The method for preparing the larynges in this study was modelled after that of van den Berg, as described in his later publications (van den Berg, 1960). Larynges were stripped of their extrinsic structures, except for a short section of trachea. A small rigid bar was attached to the lamina of the cricoid cartilage, and was then used to fix the cartilage to the apparatus. Three sets of threads were then attached to simulate the activity of the lateral adductor muscles, the interarytenoid muscle, and the cricothyroid muscle. The trachea was clamped to the pseudo-subglottal system.

A schematic drawing of the apparatus is shown in Fig.1. The apparatus contains components for actuating the larynges, for observing them under stroboscopic light, and for measuring the three-dimensional trajectories of individual fleshpoints during phonation.

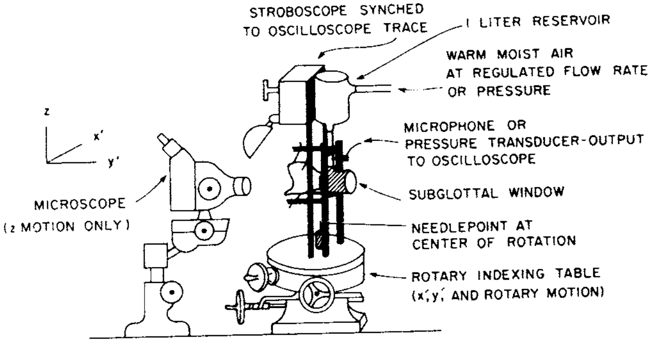


Fig.1. Schematic sketch of the apparatus.

The larynx was supported in a horizontal configuration, to facilitate measurements. Tension was applied in appropriate directions to the threads simulating the intrinsic muscles to maintain a stable phonatory configuration. Warm, moist air was supplied to a reservoir and length of flexible tubing which were intended to simulate the tracheo-bronchial tree. In early experiments, this air was delivered at regulated flow rate, but later experiments employed a pressure-regulated source. The effective flow resistance of this source was about 15 to 20 cm H_2O/lps, or roughly ten times that of the human subglottal tract. Thus, improvements in the design of this system would be desirable.

A modified brass plumbing "tee" was used to attach the larynx to the subglottal system. Air was supplied through the flexible tubing to the base of this "tee" and the larynx was clamped to one of the branches. The other branch of the tee was sealed by an optical glass window. Thus, the airway made a right angle turn before entering the glottis, and the window supplied a direct view of the subglottal laryngeal surface. This apparatus was heated to prevent condensation. Because this subglottal fitting did not significantly constrict the airway, the right-angle bend did not affect the patterns of glottal airflow during phonation.

The apparatus for supporting the larynx was mounted on the top of a rotary indexing table. The tabletop could be translated along two horizontal rectangular axes and could be rotated, so that observations could be made from any aspect. Observations could be made either with the naked eye or through a stereo microscope. The microscope's working distance was sufficiently long to focus on the vocal folds through the subglottal window.

As shown in Fig.1, the larynx was illuminated from the anterior-superior aspect by a stroboscope, which was suspended above the specimen. A mirror was placed below and in front of the specimen to improve the illumination of the glottis. The stroboscope could be operated asynchronously, to show the vibrations in apparent slow motion, or synchronously, to stop the motion at an arbitrary phase in the glottal cycle. Synchronization was derived from the output of a pressure transducer coupled to the pseudotrachea.

Small (.08 mm) carborundum particles were placed on the vocal fold surface to serve as landmarks for measurement. In most cases, the particles appeared to move with the tissues throughout the vibratory cycle, rather than sliding across them. Using synchronous stroboscopic illumination, the particles could be apparently stopped at any point along their trajectories, so that their positions could be measured using the microscope and rotary table apparatus. Particle trajectories were measured by repeating this procedure at different phases throughout the cycle.

Measurements of particle position could be made while the tabletop was rotated to any angle convenient for observation, and then referred to a coordinated system fixed with respect to the tabletop. To make these measurements, the microscope and rotary table were both fixed to a rigid base. The microscope could move only in the vertical direction (i.e. along the anterior-posterior axis), as indicated in Fig.1. All other motion was provided by the rotary table, whose translation axes were oriented parallel and perpendicular to the optical axis of the microscope. Measurements were made through only one eyepiece of the stereo microscope, using the highest available magnification. Position along the dimension prependicular to the optical axis was measured with the aid of an eyepiece reticle. Position along the other frontal-plane dimension was measured by utilizing the limited focal depth of the microscope.

Two rectangular coordinate systems were defined. One was the frontal plane coordinate system (X-Y) attached to the tabletop and thus fixed with respect to the larynx. Another, primed coordinate system (X'-Y'), was defined by the translation axes of the table. Both coordinate systems had a common origin, which was fixed to the center of rotation of the tabletop. The angle of rotation, θ, between them, was read from the rotation dial of the table.

The measurement system was initialized by translating the tabletop until its center of rotation was centered in the eyepiece reticle and was also centered within the depth of focus. A telescoping needlepoint was accurately aligned with the rotation axis for this purpose. With the tabletop in this position, the adjustable translation dials were set to zero. The X'-Y' position of any point could then be measured by translating the tabletop until the point was similarly centered in the microscope's field. The coordinates were then simply read off the axis dials. The angle θ was also recorded, and this information was used to transform the measurements to the common X-Y coordinate system. Thus, measurements could be made from any angle for which the point was visible, including through the subglottal window.

Measurement accuracy along the X' (lateral-medial) axis was about .05 mm. Accuracy along the Y' (superior-inferior) axis was limited by the optics to about .13 mm. Measurement accuracy along the X and Y axes then depends on the value of θ, but is not worse than about .13 mm.

RESULTS

General Observations: As noted by others, excised larynges were able to produce vibration patterns typical of normal chest-voice phonation. Falsetto phonation could also be produced, but the ability to vibrate in this mode was dramatically impaired when the larynges became desiccated or when their condition otherwise deteriorated. Thus, the conditions for producing falsetto, more than those for producing chest voice, appear to be constrained by the mechanical properties of the vocal folds. Apparent vocal fry could be produced when both vertical tension and subglottal pressure were low and the vocal folds were fairly tightly adducted. Within the mid range, two distinct modes of vibration were observed, and sometimes there were spontaneous shifts between them. In one mode, the rate of vibration was generally lower, and the amplitude of vibration in the subglottal tissues was greater than in the other. It is still unclear whether these represent intrinsically distinct vibration modes, such as chest- vs. mid-register, or whether the phenomenon results from an acoustic interaction with the subglottal tract.

The minimum subglottal pressure for which phonation was spontaneously initiated was about 3 cm H_2O. However, vibrations could then be sustained as the pressure was reduced to about 2 cm H_2O. The values for both initiating and sustaining vibrations increased as the surface tissues desiccated, and the separation between these values also increased. Thus, the phonatory ability of the larynx appears to be very sensitive to the mechanical properties of the laryngeal cover.

Detailed Measurements: All detailed measurements of vibrations were made during apparent chest-register phonation. In a given run, measurements were all in about the same frontal plane, which was located along the anterior-posterior axis at about the point of maximum vibration amplitude. Some initial measurements were made to determine the envelope of vibrations in this mode. Results are shown in Fig.2. The total vertical extent in the frontal plane of "large" (greater than 0.3 mm) vibration was 5 to 7 mm. However, the vertical extent over which bilateral contact between the folds occurred was smaller (3 to 4.5 mm). The maximum instantaneous depth of closure was, in general, still smaller (about 3 mm). The minimum instantaneous depth of closure usually occurred just before the end of the closed period, and was almost infinitesimally small.

Measurements of particle trajectories in the frontal plane formed the main source of quantitative results in this study. For each particle measured, its position in the frontal plane was determined at 8 phase increments uniformly distributed through the glottal cycle. Because the larynges would maintain a vibratory steady state for only a limited time, the number of particles that could be simultaneously tracked was limited to 2 or, in one case, 3. Some sample results of these measurements are shown in Fig.3. Each part of this figure contains, in addition to the trajectories themselves, an inset showing schematically the gross orientation (in static, non-phonatory condition) of the particles being tracked and a list of notes, including a record of the table angle,

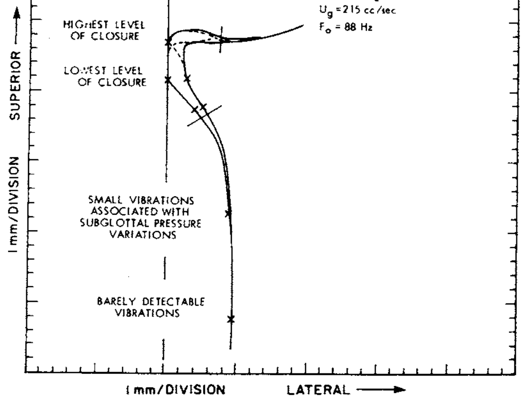


Fig.2. Outline of the frontal section of a vocal fold based on measurements from the inferior aspect. Measured points are indicated by symbols. The estimated envelope of vibrations is indicated by solid lines. Estimated shapes at two instants during the cycle are indicated by broken lines. Two tick marks delimit the region of large vibration amplitude. All subsequent measurements on different larynges were limited to such a region.

θ, for which each measurement was made. An angle of 0° implies measurement from the supraglottal aspect, while an angle of 180° implies a measurement from the subglottal aspect. Thus, these data carry some information about the particles' orientation with respect to the overall vocal fold shape.

In general, the shapes of the particle trajectories were not simple, but could be roughly characterized as elliptical with perturbations. Movement around the main parts of the trajectories was always clockwise in the coordinate system shown, with lateral to the right and superior toward the top of the page. That is, the lateral-going parts of the trajectories were superior to the medial-going parts. Particles furthest from the midline had the flattest trajectories, which most nearly approximated perfect ellipses. Trajectories of particles nearest the midline had the most nearly circular ellipses, but also had the greatest perturbations. General properties of trajectories for particles in three different regions - on the lateral supraglottal surface, near the free edge of the folds, and on the subglottal surface - are described further below, using Fig.3 for examples:

Lateral supraglottal surface (particle 1, Fig.3B); Trajectories are mostly elliptical with relatively small minor axes. The orientation of the major axes are nearly vertical. According to available data, movements are primarily upward during the closed period and downward during the open period.

Near the midline (particles 1 and 2, Fig.3A; particle 2, Fig.3B): These trajectories are more complex. The "elliptical" parts are more nearly circular, but the perturbations are also more dramatic, sometimes forming secondary loops or more complex shapes. These pertur bations are usually near the most medial parts of the trajectories. When the particle is near the subglottal edge of the glottis (particle 2, Fig.3A), the perturbation occurs near the moment of closure. For these particles, movements are generally upward and lateral during the closed period, downward and medial during the open period. When the particle is near the supraglottal edge (particle 1, Fig.3A; particle 2, Fig.3B), the perturbation occurs near the moment of opening. For these particles, movements are generally lateral and downward during the open period, upward during the closed period. Medial movements may occur during either phase, appatently depending on the particle's distance from the midline.

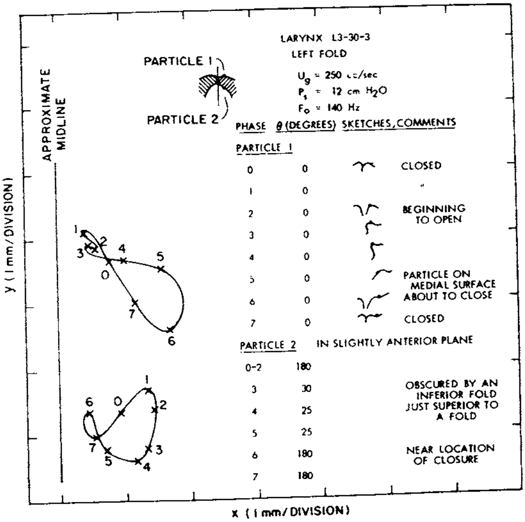
Subglottal surface (particle 3, Fig.3B): Trajectories are again ellipses with relatively small minor axes. The major axes are tilted from the horizontal, and are probably perpendicular to the tissue surface. Movements are generally lateral during the closed period and medial during the open period.

The sketches in Fig.3A indicate a phenomenon that was often noted. Particle 1 was on the superior surface of the vocal fold in the static configuration and during much of the vibratory cycle, but was at an apparent corner at phase 3. In Fig.3B, a more dramatic example of the same phenomenon can be noted. Particle 2 is on the superior surface in the static configuration and during much of the vibratory cycle, but it is actually below the region of glottal closure at phase 2. Thus, the apparent location of the "corner" of the vocal fold seems to change throughout the cycle, due to tissue movements on the superior surface toward the midline. The complex nature of the vibrations can also be highlighted by noting that the trajectories of particles 1 and 2 in Fig.3B intersect each other. These two particles are essentially in horizontal alignment for part of the cycle (e.g., at phases 6 and 0), but they are essentially in vertical alignment at phase 4. A straight line drawn between these particles rotates counterclockwise during the closed period and the early part of the open period, and then clockwise during the remainder of the open period. Such rotations of the tissues near the edge of the fold were often noted.

As the result of vertical phase differences, horizontal excursions of some particles are often greater than the total excursions of "glottal width". For example, the excursion of particle 2 in Fig.3B is from the midline to its position at phase 4. However, at this phase, particle 3 is moving medially, and is already closer to the midline.

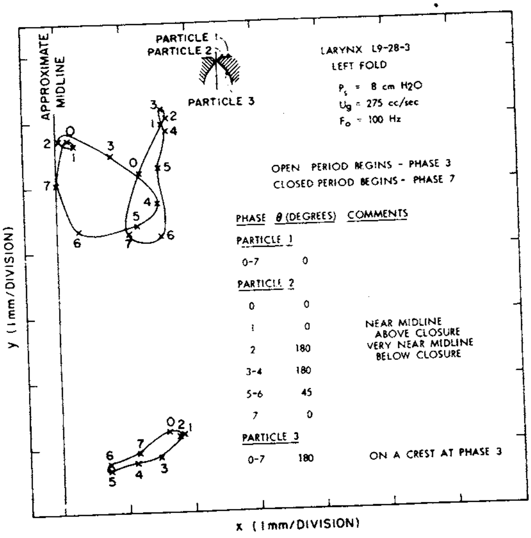
Some aspects of glottal wall vibrations appear to be describable as displacement waves propagating in the superior direction. Propagation velocity was found to be about 1 m/sec, and this is consistent with the phase delays between the horizontal movements of particles at different vertical levels. For example, for the particles in Fig.3A, the vertical separation is about 3 mm, and the phase delay corresponds roughly to 3 msec. Because of the elliptical shapes of the trajectories, the propagating disturbances are presumed to be surface waves. Waves also propagate in the lateral direction on the superior surfaces of the vocal folds, as is often noted in high speed films of normal larynges. Propagation usually begins with the open period of the cycle. The velocity of this wave is smaller - about 0.3 to 0.5 m/sec.

Properties of glottal closure were studied. This phenomenon also shows evidence of a propagating wave. After the tissues from the opposite folds first come into contact, tissues at the lower border of this region continuously separate, while tissues at its upper border continue to come into contact. Thus, glottal closure itself



PHASE	θ (DEGREES)	SKETCHES, COMMENTS
PARTICLE 1		
0	0	CLOSED
1	0	"
2	0	BEGINNING TO OPEN
3	0	
4	0	
5	0	PARTICLE ON MEDIAL SURFACE ABOUT TO CLOSE
6	0	
7	0	CLOSED
PARTICLE 2		IN SLIGHTLY ANTERIOR PLANE
0-2	180	
3	30	OBSCURED BY AN INFERIOR FOLD JUST SUPERIOR TO A FOLD
4	25	
5	25	
6	180	NEAR LOCATION OF CLOSURE
7	180	

Fig.3A



OPEN PERIOD BEGINS - PHASE 3
CLOSED PERIOD BEGINS - PHASE 7

PHASE	θ (DEGREES)	COMMENTS
PARTICLE 1		
0-7	0	
PARTICLE 2		
0	0	
1	0	NEAR MIDLINE ABOVE CLOSURE
2	180	VERY NEAR MIDLINE BELOW CLOSURE
3-4	180	
5-6	45	
7	0	
PARTICLE 3		
0-7	180	ON A CREST AT PHASE 3

Fig.3B

Fig.3. Measured trajectories from two different runs. Measurements, indicated by symbols, were made at 1/8-cycle intervals, numbered 0-7. Trajectories are arbitrarily drawn by hand, and midline positions are drawn from

estimates or approximate measurements. The inset to the right of each panel contains additional qualitative information. The schematic sketch at the top shows the orientation of the measured particles on the static vocal fold. Additional notes and sketches associated with individual measurements are tabulated below (see text).
3A: Simultaneous trajectories of two particles.
3B: Simultaneous trajectories of three particles.

propagates upward as a wave. The wavelike nature of glottal closure is emphasized by the fact that closure itself can propagate past a particle. This was noted already in the discussion of Fig.3B. Particle 2 is above the region of closure during the early part of the closed period, but below it at phase 2.

When the vocal folds first come into contact during a cycle, they often form the shape of an inverted V at the subglottis. Just before opening, when the depth of the closure is often almost infinitesimally small, they form a smooth dome (inverted U) shape.

We have noted that several aspects of the vibration patterns seem to be describable on the basis of propagating surface waves. Even the phase delay between the medial parts of the trajectory for particle 3 and the superior parts of the trajectory for particle 1 in Fig.3B could be accounted for in this manner, assuming propagation along the surfaces and past the corner at a velocity of 1 m/sec. However, these same data could be used to argue for the influence of bulk deformations of the vocal folds. If the lateral parts of the trajectories for particle 3 are compared with the superior parts of the trajectory for particle 1, the latency between them is only about 1 msec. Thus, perhaps tissues are displaced laterally from the subglottal surfaces, causing vertical deformations of the supraglottal surface during the closed period. To summarize, some aspects of the vibrations are explainable on the basis of surface waves in the vocal fold cover, while some can also be explained on the basis of bulk deformations of the body. There may in fact be contributions from both mechanisms.

Analysis of Vocal Fold Silhouettes in the Frontal Plane: The data in Fig.3B, along with more general observations of vibration patterns in these excised-larynx experiments, were used to estimate the frontal-plane shape of the vocal fold at each of the eight phase increments. The resulting sketches are shown, both separately and superimposed, in Fig.4. In the sketch for each of the eight phase increments, the three particle trajectories have been superimposed, and the instantaneous position of each of the three particles is indicated by an asterisk. The shape to the left of the midline is not based on separate data, but is a reflection of the shape to the right. The digit in the upper left part of each panel indicates the phase, as numbered in Fig.3B, and the corner in the upper right indicates 1 mm scales along the vertical and horizontal dimensions.

Useful measurements can be made from these sketches that cannot be made on the preparation itself. These measurements include distance along the surface of the silhouette and its area. Measurements of the surface distances between particles 1 and 2 and between particles 2 and 3 from each of the sketches were made. The area of each silhouette was also measured.

The measurements of surface length indicate that the surface tissues are stretched significantly during the cycle. For particles 3-2, the change of distance is about 30% of its average value. For particles 2-1, it is over 50%. In both cases, the waveform showing the surface length as a function of time is near a maximum when the glottis opens and near a minimum when the glottis closes. Therefore, to the extent that vertical stiffness of these tissues is significant, mechanical energy is stored during the closed period and released during the open period.

The area measures show changes of about 20% during the cycle. Because of tissue incompressibility, the area of the vocal folds might be expected to remain constant. This apparent change in area suggests either that there are inaccuracies in the sketches, or that there are additional area variations outside the regions of the sketches.

The superimposed sketches at the top of Fig.4 show a systematic, nearly circular pattern of movements of the vocal fold edge throughout the vibratory cycle. The significance of this pattern is unclear. We have already noted that the edge is not stable with respect to individual particles on the surface tissues. Thus, the apparent movements might be a wave phenomenon or might, alternatively be due to circular (string) vibrations of some underlying fibrous tissues across which the surface tissue slide. Hirano's (1975, 1979) anatomical investigations apparently militate against the latter hypothesis. However, investigations with x-ray stroboscopy (Saito, 1977; Chapter 8 of this book) may help to determine whether the data themselves are realistic, and to elucidate the nature of the vibrations if these results are replicated.

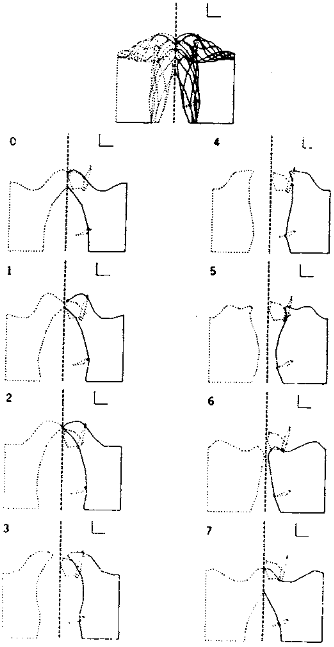


Fig.4. Estimates of the vocal fold shapes based on the data in Fig.3B. The top part shows all eight shapes superimposed. Below are the individual shapes associated with each of the eight phase increments, superimposed on the particle trajectories. The shape to the left of the midline is a reflection of the shape to the right. The scales on the upper right of each part indicated 1 mm in the vertical and horizontal dimensions.

Other Measurements: In another series of experiments, the entire vocalis muscle was unilaterally or bilaterally removed. Excised larynges that had been modified in this way were still able to produce nearly-normal chest-voice vibrations. Trajectories of particles near the superior borders of these vocal folds were similar to those from preparations with intact muscles, except that the major axes of the ellipses were tilted differently. With these preparations, vibration patterns of the vocal fold cover could be observed on the lateral sides of these membranes. Apparent waves, with a propagation velocity of about 1.1 m/sec were observed. This value is similar to that derived for the "intact" excised preparations. These results are especially intriguing, since they suggest that the body of the vocal fold plays a relatively unimportant role in maintaining the vibrations. When the region of the vocal ligament was impaired, on the other hand, phonatory vibrations could no longer be sustained. Thus, this structure seems to play an important role in the phonatory mechanism.

A seemingly counterintuitive result was obtained when falsetto phonation was attempted with these preparations. Falsetto could not be produced. A possible explanation for this result is that the muscle was needed to damp vibrations of the surface tissues at the lower parts of the folds.

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