Development of Laryngeal Stroboscopic Effect With Continuous Light Source

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Background and Objectives Most laryngeal imaging modalities used continuous light source. However, videostroboscopy adopted the unique stroboscopic flashing light triggered externally and is consistent with fundamental voice frequencies. If laryngeal stroboscopic effect could be obtained in the field of continuous illumination, it would be more compatible with conventional video. In this study, we established the mathematical algorithm for stroboscopic effect with continuous light and tried to determine the feasibility of laryngeal stroboscopic effect with conventional laryngoscopy using continuous light in the mechanical model.

Materials and Method The mechanical model of fan motor system was used to validate the present study. Rotational images of the fan motor were captured using conventional laryngoscope with continuous light source.

Results On the basis of the mathematical model, the optimal ranges of the frequency for stroboscopic effect were expected as (multiples of sampling rate [S]/5±(S/5)). In the fan motor model, the stroboscopic effects could be confirmed on the basis of the mathematical model using conventional videolaryngoscopy with continuous light source.

Conclusion Laryngeal stroboscopic effect with continuous light source might be feasible. The stroboscopic effect with continuous light would be expected to provide greater compatibility to integrate with the other imaging modalities for the vocal folds.

Keywords Stroboscopy; Larynx; High speed camera; Continuous light.

INTRODUCTION

The visualization of the vocal folds is important for understanding the physiology of voice production and the pathophysiology of vocal fold disorders [1]. The high-quality static images are able to evaluate the mucosal status and the vasculature of the vocal folds, providing valuable information on vocal fold pathologies [2]. In addition, dynamic images of vocal fold vibrations are important for understanding the physiology of voice production and the pathophysiology of vocal fold disorders [3]. Since Schonharl described the stroboscopic visualization of vocal fold vibrations in 1960 [4], videostroboscopy has been the gold standard for laryngeal imaging, and has been the primary method used to evaluate vocal fold vibrations [5,6].
Currently, in addition to videostroboscopy, various other tools with different mechanisms have been introduced for visualizing vocal folds vibration: videolaryngoscopy, videokymography (VKG), high speed videolaryngoscopy, digital VKG, and two dimensional (2D) VKG [7-12]. As each tool provides unique information to the laryngologists, two or three methods are often used to evaluate the vocal folds in order to differentiate between voice disorders. Each method has its own advantages and disadvantages and is able to complement videostroboscopy. However, the application of multiple modalities could cause discomfort to patients and may require considerable time to complete all examinations. If two or three modalities could be technically joined as one unit, these problems would be improved upon.

Most modalities used a continuous light source, but modern videostroboscopy has adopted a stroboscopic flashing light that is triggered externally by fundamental voice frequencies. This difference of light source would be an obstacle for the integration among the imaging modalities. Also, the flickering light can hinder the examination of tiny lesions, vascular lesions, or suspected malignancies owing to biases in color and brightness. If laryngeal stroboscopy could be implemented with continuous light sources, it would be better for the image quality and the compatibility with other equipments.

Thus, in this study, we established the mathematical algorithm for stroboscopic effect with continuous light and tried to determine the feasibility of laryngeal stroboscopic effect with continuous illumination in the mechanical model.

**MATERIALS AND METHODS**

**Fan motor system**
A frequency-adjustable fan motor (Green Electronics, Busan, Korea) system was designed for the purpose of this study, and was connected to the digital multi-meter in order to measure the rotational frequency. Following this, the letter A and two lines were written on the fan motor. The fan motor is capable of 180 rotation per second (Hz).

**Equipments for laryngeal stroboscopic effect with continuous light**
A full high definition (HD) charge-coupled device (CCD) camera system (USC-700 HD, U-medical, Busan, Korea) was used to capture images of the rotational fan motor and the human vocal folds. A full HD CCD image sensor (1920×1080 pixels) and a global shutter camera were connected. A rigid endoscope (7.2 mm, 70 degrees, 8706CA E, Storz, Tuttlingen, Germany) and a 300 W xenon light source (NOVA 300, Storz, Tuttlingen) were assembled, and the system was used to visualize the vocal folds in their entirety. The camera was used to capture the rotational fan and the entire human vocal folds and the video was recorded at 25 frames per second. The shutter speed of the camera could be adjusted from 1/25 to 1/50000.

**RESULTS**

**Establishment of the mathematical model for laryngeal stroboscopic effect with continuous light source**
In this study, we conceptualized the laryngeal stroboscopic effect using continuous illumination to integrate laryngeal videostroboscopy with other modalities. To theoretically explain this phenomenon, the main author, who is a laryngologist (W. Cha), suggested the mathematical model including sampling rate and fundamental frequency for stroboscopic effects.

1) The movement of vocal fold mucosal waves is a cyclic movement and was hypothesized to be a rotational cycling model to establish a new algorithm for laryngeal stroboscopic effect using a continuous light (Fig. 1).

2) The sampling rates are defined as the rate of image acquisition in a camera, and the frequency of rotation (F) is defined as the number of rotations per seconds in a rotational object:

\[ S \text{(frames/sec)} = \text{Sampling rate} \]
\[ F \text{(Hz, cycle/sec)} = \text{Frequency of rotation} \]

3) The sampling interval is the number of frames divided by sampling rate. A single sampling interval is calculated as the inverse of sampling rate:

\[ \text{Sampling interval (sec)} = \frac{\text{(the number of frames)}}{S} \]
\[ T_1 \text{(sec)} = \text{one sampling interval} = \frac{1}{S} \]

![Fig. 1. The schematic picture of the mathematical model for stroboscopic effect using continuous light.](https://jkslp.org)
4) Phase 0 is defined as the initial phase of a rotating object, and its value is set as 0 degree. Phase T₁ is defined as the phase of the first sample of image, which is 360xF multiplied by a single sampling interval, and could be calculated as 360 multiplied by F divided by S:

\[
\text{Phase } 0 \ (°) = 0 \\
\text{Phase } T₁ \ (°) = 360 \frac{F}{T₁} = 360 \frac{F}{S}
\]

5) Finally, the phasic difference (ΔT₁) between Phase 0 and T₁ is defined as Phase T₁ modulated by 360, or the remainder of Phase T₁ divided by 360 Hz. It can be calculated as 360 Hz over sampling rate, modulated by 360:

\[
\Delta T₁ \ (°) = \text{the phasic difference between Phase } 0 \text{ and Phase } T₁ \\
= \text{Phase } T₁ \mod 360 \\
=(360 \frac{F}{S}) \mod 360 \\
\text{(mod: modulo operation, the remainder after division)}
\]

6) If a minimum of 10 sequential phases were mandatory for realizing the stroboscopic effect, the value of ΔT₁ should range from -36 degrees to +36 degrees. Theoretically, the phasic difference the optimal frequency range is (multiples of S)±(S/10) and the optimal range is S/5 (Hz):

The optimal frequency ranges for stroboscopic effect=xS±(S/10)
(x: integers)

**Validation of laryngeal stroboscopic effect using continuous light in a fan motor model**

On the basis of the mathematical model, the optimal frequency was expected as 25x±2.5 in our setting. The images were acquired with the camera system at various rotational speeds (frequencies) of the fan motor model (Fig. 2). The serial images of the fan, acquired at approximately 99 Hz using continuous light (shutter speed=1/2000; sampling rate=25 FPS), are presented in Fig. 3A. The images of the fan rotated at slow and consistent speeds...
(approximately 17.8 degrees per frame) are presented in Fig. 3B.

**DISCUSSIONS**

It is important to examine the vibrations of vocal fold mucosa in order to understand the mechanisms of voice production, and to diagnose various vocal fold disorders [13,14]. Historically, laryngeal videostroboscopy has been the standard tool for vocal fold imaging in clinical practice. However, it cannot be applied to the movement of vocal folds with irregular phonatory cycles. Various modalities, such as high speed imaging systems, VKG, and 2D VKG have been introduced to complement laryngeal videostroboscopy [8-10]. Imaging modalities for observing vocal fold mucosal movements have their own advantages and disadvantages. Laryngologists sometimes require several imaging tools to visualize the vocal folds in order to diagnose and differentiate various vocal fold pathologies. This also means that patients might have repeated nuisance and painful laryngological examinations. Patient-oriented and user-friendly approaches have recently been trending in medical technology. Several researchers reported the simulataneous uses of two imaging modalities for the clinical convenience [8,15,16]. In clinical practice, the integration of multi-modalities for vocal fold evaluation would be an innovation that could make laryngoscopic examinations more time-efficient for physicians and more comfortable for patients. However, laryngeal videostroboscopy uses a special light source which flashes and flickers [17,18]. It is likely that the light source of stroboscopy is a big technological obstacle when being integrated with other modalities. Thus, the standardization of light sources is assumed to be an essential prerequisite for integrating multiple imaging modalities.

In past, it was difficult to acquire the clear image of vibrating vocal folds due to fast movement. Classically, videostroboscopic systems have adopted the periodic light emission method, synchronizing with the fundamental frequency of vocal fold mucosal vibrations. Since laryngeal videostroboscopy has been developed, the technologies of light sources, optics, and camera systems have remarkably advanced [19]. High power light source and camera technology enables to obtain the clear image within very short period. Thus, we postulated that laryngeal stroboscopic effect using continuous light source would be feasible with the coupling of the fundamental frequency of the vocal folds and the sampling rate of camera. The mathematical model was established for laryngeal stroboscopic effect. Theoretically, if the phonated frequency would not range within the optimal range \((x5\pm5[S/10])\), the images be captured at the unexpected and irregular phases rather than at the slow and continuous serial phases. Our model could explain the phenomenon of irregular stroboscopic effects observed in videolaryngoscopy with continuous lights.

To validate the mathematical model, a rotating fan motor was used. The shutter speed should be shorter than the rotating cycle in order to capture clear images of rotating fans. However, the captured images could be too dark to be distinguished if the light source is weak or the shutter speed is short. Thus, the images were captured on the conditions of various shutter speeds using high power light source (300 W). The optimal shutter speed was 1/2000 s and the camera setting was applied in human experiments. The characters and lines on the fans were fixed in the rotating frequencies (e.g., 75 Hz, 100 Hz, and 125 Hz) of multiples of the sampling rate (25 FPS), and the two aliasing fans were seen in the frequencies (e.g., 87.5 Hz, 112.5 Hz, and 137.5 Hz) between multiples of the sampling rate. Stroboscopic effects could be examined in the rotating frequencies between 97.5 Hz and 102.5 Hz on the sampling rate of 25 FPS. Our mathematical model could explain this phenomenon. On the frequency of 99 Hz, the stroboscopic effects could be seen and the phasic difference of 17.8 degree was measured in the image analysis. This result is approximately identical with the calculated phasic difference (14.4 degrees) by the model.

In this study, we could establish the mathematical model to explain the phenomenon and verify the feasibility of laryngeal stroboscopic effect using a continuous light. This result provides the possibility for the integration of laryngeal stroboscopy with the other modalities using a continuous light. However, in this study, there was the limitation that the effect of stroboscopy could only be observed at specific frequencies (25x±2.5Hz, as calculated with the mathematical model), and auditory feedback was necessary to phonate the targeted frequencies. To overcome this problem, we are currently developing a new camera system that can modify the sampling rate with collaborating engineers. There are two possible methods for better visualizing vocal fold vibrations using continuous light. The first method is to automatically set the optimal sampling rate according to the real-time analysis of the images. We coined this algorithm as ‘internal triggered mode’. The second method, which is the classical method, is to automatically set the optimal sampling rate according to the fundamental frequency obtained with external devices such as a microphone, electro-glottography, and a vibration sensor. This algorithm would be termed as ‘external triggered mode’. Further studies for the system applied with these algorithms will be followed. Moreover, utilizing these mathematical model, we aim to undertake a comparative scrutiny of vocal fold vibration imagery obtained from male and female cohorts using traditional stroboscopic apparatus, thereby elucidating their respective merits and demerits.

In some local ENT clinics, the absence of stroboscopic equip-
ment has prompted exploration into alternative methods for observing vocal fold vibrations, such as adjusting shutter speed and voice frequency. This adaptation may aid in early diagnosis and intervention in various cases. There's potential for flexible endoscopy to replace traditional laryngoscopy and stroboscopy, pending sufficient light sources. This transition could reduce hospital setup costs and offer patients time, cost savings, and greater convenience by eliminating the need for repeat invasive examinations.

**CONCLUSION**

Laryngeal stroboscopic effect with continuous light source might be feasible. The stroboscopic effect with continuous light would be expected to provide greater compatibility to integrate with the other imaging modalities for the vocal folds.

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**Conflicts of Interest**
The authors have no financial conflicts of interest.

**Authors’ Contribution**

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