AN ATTEMPT OF SWALLOWING FREQUENCY MEASUREMENT BY USING PORTABLE MONITORING SYSTEM

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ABSTRACT
Because a low frequency of swallowing may lead to a worsening of oral aseptic conditions, it is considered necessary to maintain a normal frequency of swallowing to prevent aspiration pneumonia. We have measured the frequency of swallowing during the night using a portable sound recording system consisting of an IC recorder and a piezoelectric microphone. Using this system, the sounds of swallowing from the gular region were recorded from 2 subject and their sleepings. Recording sounds were clear and having little environmental noise. The sound of swallowing was detected using an algorithm employing two digital Butterworth band pass filters. As a result, the frequency of swallowing during sleep was obtained. The developed system shows promise in the non-invasive measurement of the frequency of swallowing.

KEY WORDS
frequency of swallowing, swallowing sound, aspiration pneumonia, time-frequency analysis

1. Introduction

Aspiration pneumonia is one of the main causes of death in the elderly and its occurrence is associated with not only aspiration into lungs but also oropharyngeal colonization and host immuno-resistance [1]. Thus, good oral hygiene is important for preventing of aspiration pneumonia. In normal hosts, the effective clearance of respiratory pathogens in the oropharynx is achieved by salivary flow and swallowing [2-4]. However, reduced salivary flow by medications and dysphagia by aging or diseases lead to decrease in the clearance and alter oropharyngeal flora. Palmer, et al. reported that the clearance in oropharynx was significantly more decreased in elderly institutionalized patients with respiratory pathogens in oropharyngeal colonization than those with normal flora. Other associated factors, such as tube feeding or oral/dental diseases, may contribute to changes of the colonization. On the other hand, sleeping is regarded as a potential factor causing aspiration pneumonia because of microaspirations during sleep. Some studies reported about 50% of healthy subjects without dysphagia had aspirations during sleep [5, 6]. It is believed that bacterias in oropharynx are of the greatest amount during sleep period in the day. Therefore, to prevent aspiration pneumonia, it is vital to maintain a normal frequency of swallowing in day and night.

As a first step in the prevention of aspiration pneumonia by maintaining a normal frequency of swallowing, long-term non-invasive deglutition counting is considered necessary. Although there are several methods for evaluating functional swallowing, current methods are not acceptable for our purpose. Imaging methods employing X-rays are commonly used, but these are invasive, and manometry techniques are also invasive. Non-invasive surface electrode electromyography is possible, but practical long-term stable measurements are difficult to achieve.

We have focused on recording long-term swallowing sounds using a portable IC recorder. In this paper, the design of our swallowing sound recording system is discussed, and the resulting analysis used to detect swallowing from the recorded acoustic data is considered to assess the frequency of swallowing. As a first attempt, the sound from a subject’s larynx occurring during sleep was recorded and analysed to assess the frequency of swallowing.

2. Method

2.1 Measurement system and analysis
The smallest-sized measurement system possible was designed to measure the sound of swallowing without placing a burden on the subject. This used a small IC recorder and a microphone. The recordings obtained from this system were analysed using digital signal processing on a PC.
2.1.1 IC recorder

A commercially available IC recorder (Model DM-1, Olympus Corporation, Japan) was selected for use. The size of this recorder was $109.5 \times 50.0 \times 16.7$ mm$^3$, and it weighed 86 g (size and weight includes the batteries, but excludes the external microphone). The small size of the IC recorder enabled it to be placed in the pocket of a subject's pyjamas. To measure the sound of swallowing during the night, a 128 MB (3.3 V) Smart Media memory card was used to store data temporarily, and two AAA batteries powered the recorder. The recorder could work over a period of about 11 h using the two AAA batteries as a power source. The recorder had two recording modes: short play (SP) and long play (LP). In this study, the LP mode was selected, enabling the recorder to collect data over a period of 44 h 40 min using the available 128 MB of memory. In the LP mode, the sampling frequency used was 8,000 Hz, and the overall frequency response was flat from 300–3,000 Hz.

2.1.2 Microphone

An external microphone was used to record the sound of swallowing. The microphone was connected to the jack socket of the recorder used for external input via a 350 mm long shielded cable. The cable shield was connected to the signal common input. A piezoelectric buzzer (Model PKM13EFPY-4002-B0: Murata Manufacturing Co., Ltd., Japan) was selected for use as a microphone. The case of the piezoelectric buzzer including a piezoelectric device was a cylinder-type with a diameter of 34.5 mm and a width of 9.0 mm. The end of the case had a circular opening (diameter = 6.0 mm) that allowed for the passage of acoustic waves between the piezoelectric device and the outside of the casing. The total weight of the piezoelectric microphone was 7.3 g. The output of the microphone was connected to the recorder without using any further amplification or filtering. Figure 1 shows the recording system used, consisting of the recorder and the piezoelectric microphone.

2.1.3 Data analysis

The recordings obtained using the recorder were stored as digital data in the Digital Speech Standard (DSS) format. After recording, the data was transferred to a PC via a USB cable, and saved on the PC hard drive. The DSS data format was then converted to the WAVE format, using the DSS Player 5 v1.4.0 software package (Olympus corporation, Japan). The WAVE format data was then processed, and computational analysis used to detect the characteristic qualities of the sound of swallowing. The characteristics of the frequency and time domains were considered useful in detecting swallowing. Hence, short-term fast Fourier transform (FFT) time-frequency analysis was employed to detect the sound of swallowing using an algorithm. Matlab v5 (Mathworks, USA) and GNU Octave v2 (freeware) software packages were used to numerically analyse the data. A PC with a 2.0 GHz Pentium 4 microprocessor, and 1GB of memory running was used to analyse the data.

2.2 Experimental

Initial measurements using the developed system were taken on two sleeping subjects. Sleeping was selected because it is a relatively quiet environment in which to obtain data. Using our system, the sound of swallowing from two healthy male subjects was recorded (Subject A was 35 years old, and subject B was 32 years old). These two subjects did not have bruxism, and were not snorers. The subjects willingly agreed to participate in the experiments. The selected measurement site was the subjects’ gular region of the larynx. The piezoelectric microphone was fixed over the larynx using double-sided adhesive tape and a sports tape. The recorder was located in the subject's pyjama pocket, and was fixed using adhesive tape. The subjects were asked to attach the microphone before sleeping, and to commence recording. After waking, the recording was stopped by the subject.

The subjects slept in their own rooms and in their own beds (Subject A slept in a Japanese-style bed). The subjects were asked to follow their regular sleeping patterns and hours. Before and after sleep, the subjects were asked to record a conscious saliva swallowing action two or three times to obtain a standard data record of saliva swallowing. The subjects were also asked to record swallowing 100 ml of water after waking, drunk as fast as possible, to obtain information on the minimum swallowing interval.

Figure 1. The portable sound of swallowing measurement system used. This system contains a commercially available IC recorder and a piezoelectric small and lightweight microphone.
3. Results and Discussion

Data recordings were successfully obtained from each subject. Five recordings during sleep were obtained from Subject A, and two recordings from Subject B. The total recording time of each sleep was 396–475 minutes. In addition, recordings of swallowing 100 ml of water and from swallowing saliva before and after sleeping were successfully obtained. The detection of swallowing 100 ml water and saliva before and after sleeping was so clear that any ambient noise could not be confirmed in each measurement, and the sound of saliva swallowing obviously identified. In addition, clear data was obtained during sleeping, and the sound of swallowing could be easily identified from the recordings.

Short-term FFT analysis was carried out on the standard saliva swallowing recordings (i.e., the recordings taken before and after sleeping), and on the recordings taken on swallowing 100 ml of water. These were performed to establish a sound of swallowing detection algorithm. Figures 2(a) and 2(b) show typical examples of a short-term FFT analysis displayed as a spectrogram. From the spectrograms obtained, it was confirmed that the power distribution of the sound of swallowing was wide, with the higher frequencies at 1,000–3,000 Hz. By observing the obtained spectrograms, we were able to find two characteristic traits in the sound of swallowing saliva and water in the frequency domain and in the time domain. The first characteristic in the frequency domain was from \( f = 1,000–1,500 \) Hz, and a second characteristic was from \( f = 2,000–3,000 \) Hz. In each saliva swallowing, higher orders of those frequency ranges were observed. The characteristic in the time domain was related to the minimum interval of swallowing from data obtained from swallowing 100 ml of water. In the data obtained from swallowing 100 ml water, two or four swallowing periods were observed, with the minimum interval between swellings being >1 s.

By observations of the recording waveforms, several periods having continuous larger magnitude of sound were confirmed. By hearing those periods, it was confirmed that subjects soliloquised before sleeping, talked in their sleep or had a coughing fit in those periods. This periods did not have any swallowing. One of the important characteristics of swallowing that we confirm is that one swallowing must be isolated in time domain. Before and after swallowing must be silent during at least 1 s.

From these observations, we attempted to design a swallowing detection algorithm by combining envelope curve detection, two Butterworth digital filters and the dead time. At first, in order to avoid soliloquising, talking in their sleep and having a coughing fit, the envelope curve of sound recording was calculated and periods having larger value of envelope were neglect from analysis. Because, those periods was considered as having no swallowing. Next, to detect higher powers of the two frequency ranges quickly, an Infinite Impulse Response (IIR) digital filter was introduced to reduce the calculation time as much as possible. Two 30th order Butterworth band pass filters were prepared. The first filter had its band pass from 1,000–1,500 Hz, and the second filter had its band pass from 2,000–3,000 Hz.

Figures 2(c) and 2(d) show examples of the filtered sound of swallowing waveforms. From observing these waveforms, it was thought that both filtered waveforms have higher amplitudes of the swallowing period. Hence, a set value for detecting swallowing was considered for each waveform: the set value used for the band pass of \( f = 1,000–1,500 \) Hz was 0.19, and the set value used for the band pass of \( f= 2,000–3,000 \) Hz was 0.09. A time duration of 0.1 s in which both filtered waveforms had values > each set value was considered as a possible point of swallowing. After detecting these possible points using the information in the frequency domain, the time domain information was applied to extract swallowing incidents. The dead time between swallowing was considered for this. Since the minimum interval between swallowing was >1 s, the dead time was set to \( t = 1 \) s. Then, the possible points of swallowing that were within 1 s the possible swallowing points were eliminated, and the final estimated swallowing points were extracted.

The developed algorithm was first applied to the standard recordings of saliva swallowing and swallowing 100 ml of water. In those cases, all the swallowing actions could be detected. Next, the algorithm was applied to
recording taken during sleeping and the automatic
detection of swallowing was attempted. The automatic
estimated frequency of swallowing was in the range of
36–100 times a night for the two subjects. The
computational time for the calculations was almost linear
with recording time, and the maximum computational
time employed was 240 min for data lasting 475 min.

Figure 3 shows examples of swallowing profiles
recorded during the night. In Figure 3, the x-axis shows
the time from the start of the recording process, and the
y-axis shows the cumulative sum of swallowing actions.
As can be seen from Figure 3, the cumulative sum of
swallowing in the night exhibited a tiered pattern rather
than a straight-line behaviour. The swallowing profile in a
night consisted of periods where the subject swallowed
successively at short intervals (these periods are indicated
by the almost vertical sections in figure 3), and periods
where the subject did not swallow for long intervals (these
periods are indicated by the near horizontal sections in fig.
3). These periods alternated. From each recording, there
were periods where the subject did not swallow for more
than 40 min. The maximum interval of swallowing
measured was 76 min.

The sound of swallowing has been studied by
many researchers [7, 8]. The significant advantage of
methods that detect the sound of swallowing is that they
are non-invasive. In many studies, the sound was only
able to be recorded using a small microphone or an
accelerometer placed on a subject’s neck. For recent
example, Lazareck and Moussavi showed the possibility
of swallowing sound segmentation by using one of the
type of fractal dimension analysis and fast fourier
transform [9]. Although many researchers have attempted
an acoustic analysis of the sound of swallowing to
establish objective evidence in the detection of
swallowing disorders, it has been difficult to obtain

Figure 4. Examples of swallowing profiles and frequency of swallowing obtained over a single night: (a), (b) and (c) are
data obtained from Subject A, and (d) is from Subject B.
clinical criteria using these sounds. Logemann [10] has reviewed the sound of swallowing methods, and has identified the parameters that limit these sounds. We agree with Logemann in that the functional assessment of swallowing disorders requires that the sound of swallowing method must be substantially developed.

However, in this study, we have focused on the limited data obtained from swallowing, namely the frequency of swallowing. Although the quality of swallowing (i.e., whether the swallowing is good or not) may not be evaluated by our method, we assert that information on the frequency of swallowing can be valuable.

Lear et al reported on the frequency of adult deglutition over a 24 h period [11], and this paper is the only report on the long-term frequency of swallowing. The system used by Lear et al was not described in detail. However, it is almost certain that they used a system composed of analog circuits, and that the measurement system was not ambulatory (at least within the present meaning). Our method can be thought of as a modern version of Lear’s method, in having refined digital devices and utilizing digital signal processing. Although an assessment of the frequency of swallowing was suggested, this assessment was not attempted. We consider that the reason for this is a lack of the use of an automatic procedure for such an assessment. Because we developed and used an automatic procedure to count the frequency of swallowing, we were able to provide such an assessment using this automatic technique.

The method developed was non-invasive, was portable, had ease of handling, and had an automated analysis. Therefore, it is a promising technique for obtaining the frequency of swallowing as an index of oral clearance. Currently, we are carrying out experiments using elderly subjects and paralysis patients to establish an assessment protocol for oral clearance in high-risk aspiration pneumonia groups.

4. Conclusions

To assess frequency of swallowing as a non-invasive index of oral clearance, a portable measurement system was used to detect the sound of swallowing, and a swallowing detection algorithm was developed. The measurement system consisted of a commercially available portable IC recorder and a piezoelectric microphone. As a first experiment, the frequency of swallowing from two subjects was measured during sleep using recordings obtained from the subjects’ necks. The obtained acoustic recordings were analysed using short-term FFT, and the characteristics of the sound of swallowing were defined. Digital filters were designed from the insights obtained, and the dead time rule was applied to extract the sound of swallowing. As a result, acoustic data was clearly obtained, and the swallowing detecting algorithm could detect swallowing during the night. The estimated frequency of swallowing was 33–96 times a night. The swallowing profile during the night consisted of periods where the subject swallowed successively at short intervals, and periods with no swallowing. Periods with no swallowing occurring for > 40 min were observed in each recording. The developed system shows promise in the non-invasive measurement of the frequency of swallowing.

Acknowledgements

Authors acknowledge for voluntary subjects of this study. Authors also acknowledge for Dr. Kazuo Takakuda, Institute of Biomaterials and Bioengineering, Tokyo Medical and Dental University, for discussion about material of microphone casing.

References: