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Dysphagia

Use of Respiratory Inductance Plethysmography for the Detection of Swallowing in the Elderly

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Abstract. It is essential to have a user-friendly, noninvasive bedside procedure at our disposal in order to study swallowing and swallowing disorders in the elderly in view of the frailty of this age group. In the present work, respiratory inductance plethysmography (RIP) is proposed as an appropriate clinical tool for such studies. An automated process for the detection of swallowing is used involving the derivative of the respiratory volume signal. The accuracy of the automated detection is given by the area under the Receiver Operating Characteristic (ROC) curve and is found to be greater than 0.9. At the optimal threshold, RIP constitutes a reliable and objective bedside clinical tool for studying swallowing in the elderly, as well as being user-friendly and noninvasive. In addition, RIP can be used to monitor swallowing in order to analyze swallowing disorders and put in place medical supervision of swallowing for individuals who might aspirate.

Key words: Swallowing — Respiratory inductance plethysmography — Deglutition disorders — ROC curve — Deglutition.

Dysphagia [1,2] is a frequent problem in the elderly and can have serious consequences [3,4]. In many cases, aspiration results in pneumonia [5] but there is no simple and obvious relation between aspiration and pneumonia [6]. Disabling conditions, as consequences of malnutrition and dysphagia, may result in increased morbidity and mortality when aspiration exists [7]. Loss of independence in eating in institutionalized elderly is associated with increased mortality within six months [8]. Swallowing disorder may result in psychosocial problems such as anxiety at mealtimes and social isolation [9].

To prevent the damaging effects of dysphagia in the elderly, assessments of ingestive skill are imperative. However, ongoing research into swallowing disorders has highlighted inconsistencies in existing clinical evaluation, namely, via the sensory function, the gag reflex, cervical auscultation, and trial swallows using compensatory techniques, as also in instrumental examination decision-making [10]. An ingestive skill assessment framework was devised based on a source of 44 items from a literature review of which only the most meaningful were retained [11]. New clinical tests were elaborated and evaluated for their effectiveness in predicting aspiration: the water swallow test [12] combined or otherwise with the oxygen desaturation test [13], and the association of a water swallow test, a food test, and an X-ray test [14].

The relationship between breathing and swallowing has already been studied in healthy subjects [15–17] and in elderly adults [18,19] using various methods. It has been observed that during swallowing, the airflow is interrupted by a brief closure of the larynx which protects the airway from the aspiration of ingested material [21,22].

The aim of this study was to show that swallowing can be detected through the automated processing of the airflow signals obtained by RIP. If such is the case, RIP affords a user-friendly objective bedside clinical tool for the detection and the analysis of swallowing in the elderly. Its objective nature derives from the use of automated analysis elaborated specifically in this study.

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Methods

Subjects

Fourteen subjects (9 females) were recruited from the Department of Geriatric and Community Medicine of Grenoble after obtaining informed written consent from each subject or their legal representative. Their ages ranged from 75 to 100 years with an average age of 84.6 ± 8.0 years (mean ± SD). Eleven patients suffered from cardiovascular disorder: six from hypertension, four from cardiac arrhythmia due to atrial fibrillation, two from ischemic cardiopathy, one from cardiac insufficiency, and one from cardiac valvulopathy. Five had endocrine system disease: four had diabetes, and two had hypothyroidism. Two had a neurologic disorder: two had suffered a stroke and one suffered from dementia. Two had neoplasms: one was digestive and the other was breast cancer. One had osteoporosis. Seven patients had surgical interventions: five cataracts; two appendectomies, and two hip replacements.

Materials

The RIP system makes it possible to measure respiration via the changes in the cross-sectional area of the rib cage and abdomen [20]. The RIP system used in this study was a computer-assisted Visuresp® (RBI France). The sensor consists of an elasticized jacket easily worn by the patient over their usual clothing. The signals generated by the Visuresp® system are saved in a text file, which is then postcomputed by software developed in the R language (language and environment for statistical computing and graphics).

Protocol

In a natural but standardized mealtime setting, each subject wore the jacket so that his or her breathing could be continuously recorded and performed four time-marked swallows (TMS): two water TMS, the first static, i.e., no movement of arms (a 20-ml glass of water being given to the subject by the nurse) and the second dynamic (the subject raised the 20-ml glass of water to his/her mouth to drink); and two gelatinous water TMS using the same protocol, except that the glass of water was replaced by a small spoonful of gelatinous water. At our request, each TMS was performed only when a regular respiratory rhythm had been observed. For each TMS, the initial instant (i.e., when water or gelatinous water was placed in the mouth), and the final instant (observed end of larynx movement) were noted.

Measurements

The Airflow Signal

The abdomen and rib cage signals obtained through RIP were combined, with appropriate weighting, to obtain a value of the volume signal. The derivative of the resulting signal, after smoothing using a low-pass filter, has been shown to be a valid estimate of airflow [23]. It is designated by AS. At the beginning and the end of an inspiration, the AS is at zero since there is no airflow, as during apnea or swallowing.

Principle

During swallowing, the airflow is interrupted by a brief closure of the larynx. Identifying TMS thus consists of detecting brief zero values on the AS curve. This detection is achieved by means of a new automated test, which is based on the fact that during a clinical TMS, the value of AS is situated briefly between two horizontal lines, D^+ and D^- (Fig. 1), corresponding to the confidence interval of zero AS value. It should be noted that during this short interval of time, the AS does not simply cross the zero line but varies about zero nonmonotonously.

Test Evaluation

The test is evaluated according to its capacity to detect the clinical TMS from among the automatically detected respiratory cycles. Contingency tables are used. The test is performed for the two sets of respiratory cycles P1 and P2. The first, P1, is made up of elementary events. Each of these is in turn the set of respiratory cycles occurring during one TMS. The second, P2, is the set of respiratory cycles during which there is no TMS.

Definitions Used in the Test

Let $Z(p)$ be the portion of the graph that corresponds to the AS zero-flow confidence interval, totally determined by the value **p** (*p*-cutoff). The test is positive at the *p*-cutoff if and only if the part of the airflow curve within $Z(p)$ for the respiratory cycle concerned is not a monotonous function of time (Fig. 1).

$Z(p)$ is the union of the $Z^+(p)$ and $Z^-(p)$, where $Z^+(p)$ is the positive half-plane portion contained between the straight line $D^+(p)$ and the time axis. $D^+(p)$ is the graphical representation of the threshold for which we obtain **p** percent of the distribution of positive values of airflow data. $Z^-(p)$ and $D^-(p)$ are similarly defined for the negative half-plane. Because the inspiratory period is shorter than the expiratory one, $D^+(p)$ and $D^-(p)$ do not lie symmetrically about zero.

Automated Detection of Respiratory Events

Let p_1 ($p_1 > p$) be the respiratory threshold for this detection. The limits of respiratory cycles are given by the start points of each inspiration. They are roughly localized by the first local positive extrema on the AS curve above the straight line $D^+(p_1)$. Fitting a linear model by weighted least squares onto the increasing part of the AS curve around these extrema enables the start points of respiratory events to be determined on the time axis. In performing this fitting, each point is weighted using the sum of its Euclidean distance from its immediate left and right neighbors to avoid the influence of the data around the extrema.

Statistical Analysis

Sensitivity, specificity, positive predictive value, negative predictive value, concordance rate, and chi squared were computed for the test described above. Its accuracy corresponded to the area under the Receiver Operating Characteristic (ROC) curve [24]. The best zero-AS confidence interval was determined from the best balance between sensitivity and specificity obtained from the ROC curve [24].

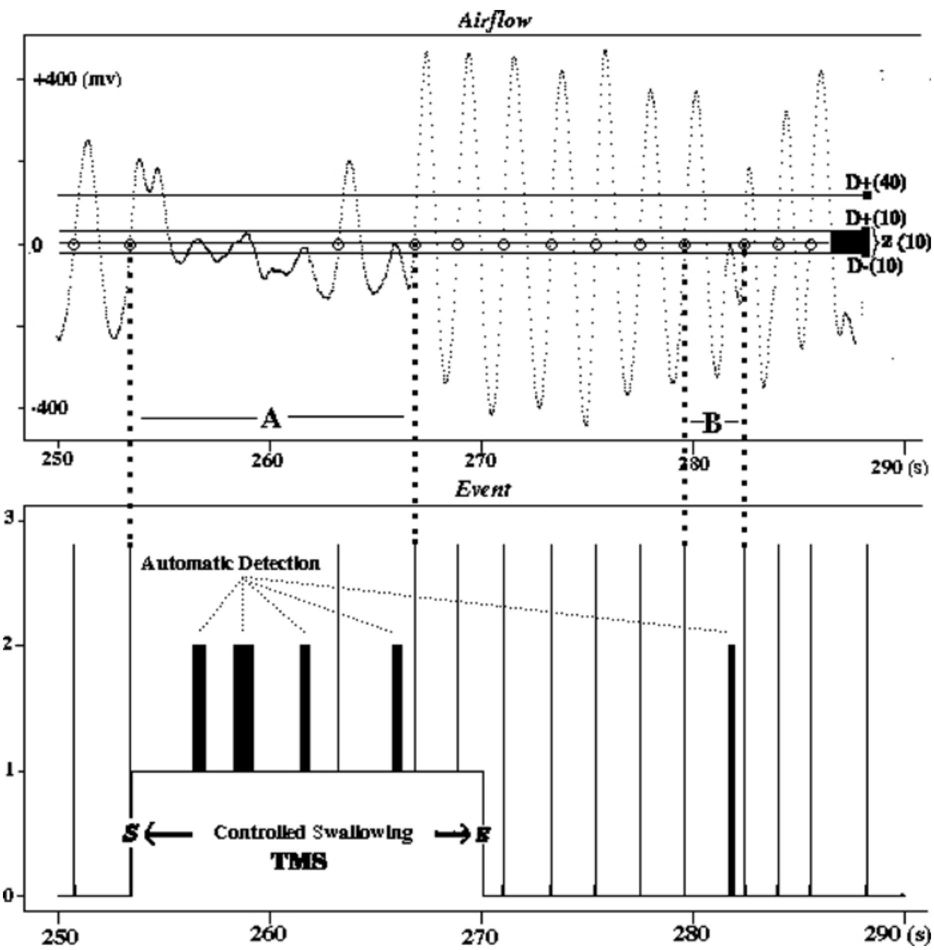

Fig. 1. Airflow and respiratory events. **Top**: The dotted curve represents the recording of the airflow signal (AS) during a swallow of gelatinous water. The straight line $D^+(40)$ corresponds to the threshold used for the automated detection of a respiratory cycle ($p_1 = 40$). $D^+(10)$ and $D^-(10)$ delimit the confidence interval $Z(10)$ of the zero airflow ($p = 10$). **Bottom**: S and E are the beginning and end, respectively, of the clinical swallowing (TMS) located in the time when the patient swallowed. The thin vertical lines represent the start points of each inspiration. The thick vertical lines show the parts of the AS that lie in the confidence interval $Z(10)$ and are not monotonous. Thin and thick vertical lines are automatically computed by software ($p_1 = 40$, $p = 10$). A swallowing (A) is detected if and only if the corresponding respiratory cycles contain thick lines. Furthermore, the software also detects B, which may correspond to a spontaneous unmarked swallowing.

Results

The average recording period for the AS was 351.3 ± 93.7 s, with actual values ranging from 189 to 583 s. Among the 56 TMS, only 51 were analyzed; the other 5 had incomplete data for the swallowing end time. The number of respiratory events automatically identified at respiratory p_1 thresholds of 40% and 50% were 1592 and 1565, respectively. During spontaneous breathing, respiratory events belonging to the P2 set may be considered independent. Results for the contingency tables were all significant [$\chi^2(1, n = 1643) > 100$; $p < 0.001$].

Figure 1 shows an example of automated AS analysis with graphical representation of the parameters introduced above. Respiratory events were automatically identified for a p_1 respiratory threshold of 40% [$D^+(40)$]. The two events A and B were automatically detected with a p-cutoff of 10% [$D^+(10)$,$D^-(10)$,$Z(10)$]: A is the record of a gelatinous water TMS, occurring over two respiratory cycles; B, in our opinion, corresponds to a spontaneous swallow. Figure 1 illustrates the automated detection by the test not only of TMS but also of spontaneous events, which were not time-marked in our protocol.

Figure 2 shows the curves of sensitivity, specificity, positive predictive value (PPV), negative predictive value (NPV), and concordance rate (CR) for automated TMS detection plotted for increasing p-cutoff values from 0% to 40% (the p_1 respiratory threshold was set at 40%). It can be seen that 50% 75%, 95%, and 99% of TMS are automatically detected at p-cutoffs of 2.58%, 7.75%, 18.82%, and 35.49%, respectively.

Figure 3 shows the ROC curve for the test (p_1 set at 40%). The area under the ROC curve (AUC) is greater than 0.90. Furthermore, we notice the independence of the test with respect to the p_1 threshold used for the automated detection of respiratory events: the AUCs for p_1 set at 40% and then at 50% are appreciably identical. The best balance between sensitivity and specificity was computed for these data. It corresponds to M, the closest point on the curve (in Euclidean distance) to the upper-left-hand corner of the graph. The sensitivity was evaluated to be 91.37%, the specificity was 87.20%, and the optimal *p*-cutoff was computed to be 18.05%.

Discussion

The major finding of this study is that RIP provides a noninvasive bedside procedure for detecting controlled swallowing in the elderly. This detection relies on an automated analysis of AS obtained by differentiating the RIP signal. Numerical values can be readily computed. Based on the AUC results, this analysis appeared to be very reliable (AUC > 0.90).

There have been very few studies comparing airflow and RIP-derived signal under physiologic conditions [23]. One such study documented comparisons of time–volume and flow volume components of forced vital capacity [25]. Under physiologic conditions and with varying postures, the RIP-derived signal has been validated as providing an estimation of airflow acquired by pneumotachogram [23].

We modified the water TMS from the water swallowing test [12], which serves as a method of evaluating the swallowing ability of patients. We also varied the type of swallowed food because swallowing disorder may vary according to the texture of the ingested food [14]. We observed that the automated detection of swallowing was not impaired by the use of water or gelatinous water for swallowed food.

We compared static and dynamic (movement of the arm) food intake to ascertain if movement would perturb the RIP signal. We observed that the automated detection of swallowing was not impaired by arm movement.

Assuming breathing cycles to be independent—since they are generated automatically by the respiratory centers—we were able to build contingency tables and compute statistical parameters. Low values of PPV were observed when the *p*-cutoff varied from 0 to 40. This is because of the automated detection of spontaneous swallowing events belonging to set P2. If we included these spontaneous swallows in set P1, the PPV curve would exhibit much higher values.

The present study was performed on only 14 patients. In order to obtain reliable data, the active participation of the patient is required. In addition, the patient should be capable of performing simple tasks. Although the AS analysis was possible with arm movements, it is difficult to carry out the protocol on restless patients.

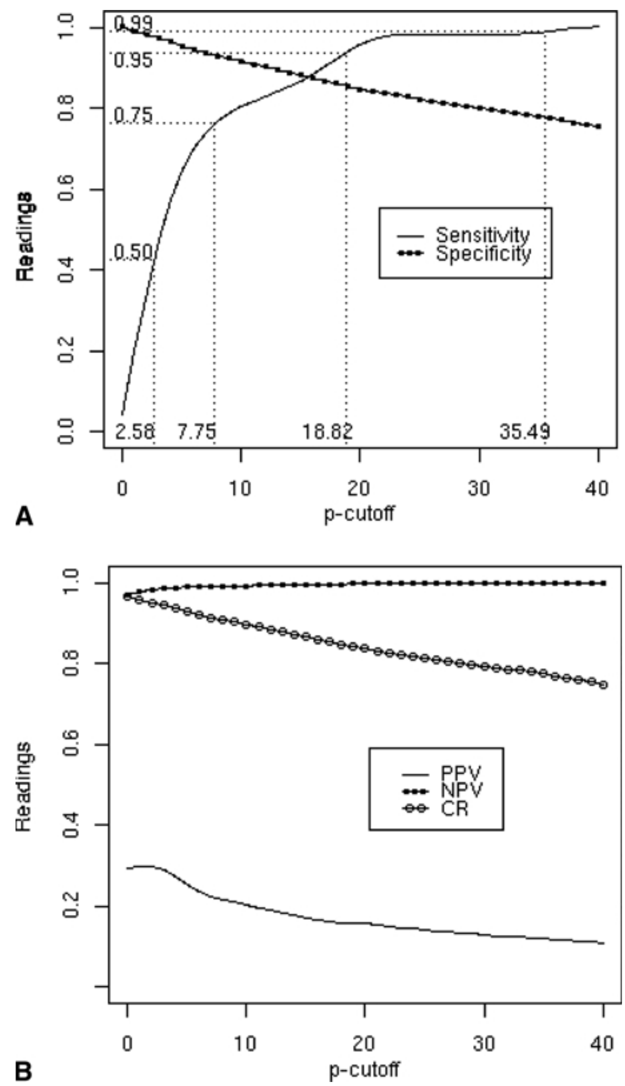

Fig. 2. Analysis of contingency tables. **Top**: The two curves of sensitivity and specificity are plotted for increasing *p*-cutoff values from 0% to 40% (p_1 = 40). The sensitivity curve shows that 50%, 75%, 95%, and 99% of TMS are automatically detected at *p*-cutoff values of 2.58%, 7.75%, 18.82%, and 35.49%, respectively. **Bottom**: Positive predictive values (PPV), negative predictive values (NPV), and concordance rates (CR) are plotted against *p*-cutoff as above. NPV represents high values. CR varies similarly to the specificity. The low values of the PPV may be explained by the automated detection of spontaneous unmarked swallowing.

Being asked to take water or food could possibly induce stress in the patient, which then might affect respiratory events preceding swallowing but not larynx closure during the swallowing. It was for this reason that zero airflow detection was used. This protocol differs from one where swallows were induced by a bolus injection into the oropharyngeal

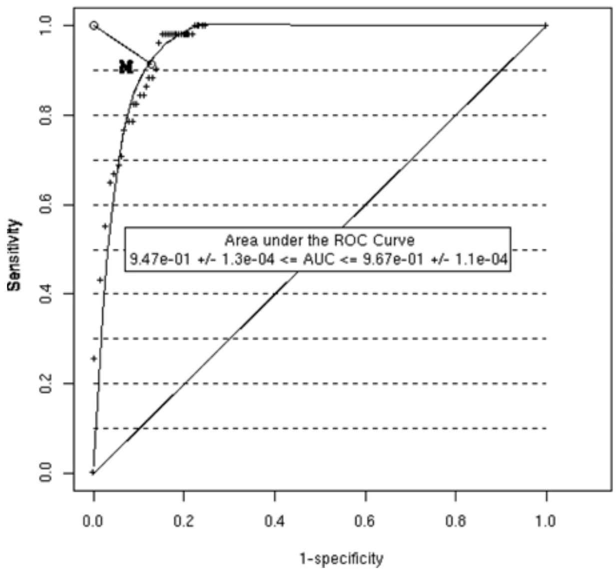

Fig. 3. The ROC (Receiver Operating Characteristic) curves. This curve is plotted from computed points (cross-points) for increasing *p*-cutoff values from 0% to 40% ($p_1 = 40$). The best balance between sensitivity and specificity for these data (the point M) corresponds to an optimal *p*-cutoff of 18.05% with a sensitivity and a specificity of 91.37% and 87.20%, respectively. Another ROC curve was computed for $p_1 = 50$. The boundaries of the area under the curve (AUC) were computed for these two curves. Each boundary is given as a mean ± SD. The results of the automated analysis gave AUCs > 0.9.

cavity, the timing of water injection being randomized [17].

The interplay of swallowing and breathing has been studied using other (and for these frailer patients, often unpleasant) methods involving an electrode attached to the cheek [19], a throat microphone [15,19], a soft polythene tube inserted into a nostril [19], submental electromyography [15–17], or a mouthpiece [17]. The recording procedure used in this study, on the other hand, was well accepted by the elderly because the device consisted of a jacket worn over their usual clothing and the recordings were performed in their usual mealtime environment. Furthermore, the user-friendly nature of this equipment makes this method an appropriate bedside clinical tool. We have no knowledge of the existence of any study of a similar nature.

The detection of swallowing by means of automated recordings and analysis is an essential prerequisite for an objective analysis. The use of the AS, time derivative of the volume signal providing zero airflow detection, made this automation possible.

Although the reliability of the automated detection appears to be sufficiently high in this study, as evidenced by the high sensitivity and specificity at the optimal *p*-cutoff computed, automated AS analysis may be refined by a more precise characterization of the events to be detected. Furthermore, the AS analysis may be improved to:

1. measure the swallowing period, which is manually estimated in common clinical practice. This enhanced precision could help, for instance, in defining more sensitive and reliable criteria for detection of certain swallowing disorders;
2. analyze the AS pattern during swallowing and thus gain information on the quality of the glottal closure;
3. quantify the time needed to recover a resting respiratory rhythm after swallowing. This period of time would probably vary depending on whether swallowing is accompanied by aspiration, as is suggested by oxygen desaturation in individuals who aspirate [13].

Because apneas are not specific to swallowing, the specificity of the detection will be reduced in a different experimental clinical context. Nevertheless, we prefer to attach greater importance to the sensitivity of the automated detection because of the serious, even fatal, consequences of dysphagia in the elderly.

We would tend to think that measurement of airflow could provide a valid method of detecting dysphagia. During swallowing, the airflow is interrupted by a brief closure of the larynx in order to protect the airway from aspiration of ingested material. During aspiration, however, because the laryngeal closure is incomplete, the airflow is not totally interrupted. There is no real apnea and the swallowing will go undetected. Nevertheless, we suspect that when aspiration occurs, the recorded airflow will differ from that of a normal respiratory cycle because of disruption by the ingested material in the airway. Furthermore, we also suspect that the postaspiration airflow will differ in a characteristic way (e.g., postswallowing coughing or sneezing: these are natural defense mechanisms that may be activated by food moving in the wrong direction [2]) and that it will be possible to detect this difference among other physiologic respiratory cycles.

However, as swallowing is only inferred from the respiratory recordings and not directly observed, it is essential for any detected dysphagia to be confirmed by means of a gold standard such as videofluorography.

We also intend to establish one-to-one relationships between the clinical events and the patterns of these events depicted on the AS. This opens up the possibility of monitoring swallowing by recording the airflow with the RIP and using the recordings to reveal indirectly certain swallowing disorders, e.g., by identifying coughing during a meal. Such a tool would be very useful in enabling medical supervision of swallowing to be put in place for acutely affected patients (e.g., recent cerebrovascular accident patients) or those with chronic diseases (e.g., Parkinson's disease) [1] and also for monitoring the effectiveness of therapy for swallowing disorders.

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