An Aerodynamic Evaluation of Parkinsonian Dysarthria: Laryngeal and Supralaryngeal Manifestations*

L. Carol Gracco,† Vincent L. Gracco, Anders Löfqvist, and Kenneth Marek‡

The speech of individuals with Parkinson's Disease (PD) is characterized by reduced stress, increased rate, monotonic pitch and loudness and imprecise consonant production (see Darley, Aronson, & Brown, 1975 for review). Acoustically, speech has decreased duration of voiced segments, reduced fundamental frequency variations and limited formant trajectories at consonant-vowel transitions as compared to normal age-matched controls (Canter, 1967; Darley et al., 1975; Forrest, Weismer, & Turner, 1989; Logeman, Fisher, & Boshes, 1978; Ludlow, Bassich, Connor, Coulter, & Lee, 1987; Ludlow & Schulz, 1989; Ramig, Scherer, Titze, & Ringel, 1988; Weismer, 1983). Although specific and detailed analysis of Parkinsonian deficits have been limited, existing studies of laryngeal and supralaryngeal structures suggest that the reduction in intelligibility characteristic of Parkinson's disease may be a result of manifestations of this disorder throughout the entire vocal tract musculature. For example, studies of lip and jaw movements have reduced amplitude and velocity (Caligiuri, 1987; Connor, Abbs, Cole, & Gracco, 1989) while cinegraphic studies of laryngeal kinematics in PD (Hanson, Gerratt, & Ward, 1984) reveal a correlation between abnormalities in the phonatory posture of laryngeal structures and voicing deficits. These manifestations may involve the control and coordination of laryngeal and supralaryngeal events. Taken together, these factors result in the overall reduction in speech intelligibility in individuals with PD. Hence, the simultaneous evaluation of upper articulator and laryngeal dynamics may give a more complete analysis of deficit behaviors that ultimately influence intelligibility.

The perceptual significance of aerodynamic events and the utility of aerodynamic measures as a basis for understanding speech and voice articulation has been realized for some time. With few exceptions, however, attempts to associate complex articulatory and phonatory changes with time varying changes in supraglottal air pressure and air flow has seen little progress. Much of the basic and applied literature investigating pressure and flow parameters has focused on differences in peak amplitude as a function of some variable such as vocal intensity, place, and manner of production, or has used peak amplitude to provide measures of glottal resistance. In isolation, peak measures are little more than a description of system output providing limited information regarding the underlying articulatory dynamics.

In a clinical setting, procedures which sample both temporal aspects of laryngeal and supralaryngeal dynamics as well as peak measures associated with various speech motor disorders are regarded as time consuming. This study attempts to provide the basis for a relatively easy and efficient evaluation of laryngeal and supralaryngeal articulation in individuals with Parkinsonian dysarthria. The methodology is based on previous work by Müller and Brown (1980) which illustrated the significance of assessing pressure and flow characteristics correlated with their time varying changes. Laryngeal factors are included in this analysis, reflecting the integration of vibratory characteristics with upper articulator dynamics.

Methods

Subjects. The salient speech characteristics and demographic data for five adult subjects are summarized in Tables 1 and 2 respectively.

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*This work was supported in part by NIH Grant No. DC-00044, DC-00594, DC-00685, and DC-00121 from the National Institute of Deafness and Other Communication Disorders.
Table 1. Summary of Speech Characteristics for 5 subjects with Parkinsonian’s Disease.

<table>
<thead>
<tr>
<th>Subjects</th>
<th>Speech Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>JH</td>
<td>• minimal reduction in intelligibility</td>
</tr>
<tr>
<td></td>
<td>• breathy vocal quality</td>
</tr>
<tr>
<td></td>
<td>• accurate consonant production with infrequent alterations of speech rate</td>
</tr>
<tr>
<td>AD</td>
<td>• minimal reduction in intelligibility</td>
</tr>
<tr>
<td></td>
<td>• breathy vocal quality</td>
</tr>
<tr>
<td></td>
<td>• accurate consonant production with infrequent alterations of speech rate</td>
</tr>
<tr>
<td>HM</td>
<td>• minimal reduction in intelligibility</td>
</tr>
<tr>
<td></td>
<td>• hoarse and breathy vocal quality</td>
</tr>
<tr>
<td></td>
<td>• accurate consonant production with occasional alterations of speech rate</td>
</tr>
<tr>
<td>AB</td>
<td>• intelligibility moderately to severely impaired</td>
</tr>
<tr>
<td></td>
<td>• reduced intensity</td>
</tr>
<tr>
<td></td>
<td>• imprecise consonants</td>
</tr>
<tr>
<td></td>
<td>• accelerated speech rate</td>
</tr>
<tr>
<td>JC</td>
<td>• intelligibility moderately to severely impaired</td>
</tr>
<tr>
<td></td>
<td>• reduced vocal intensity</td>
</tr>
<tr>
<td></td>
<td>• imprecise consonant production</td>
</tr>
<tr>
<td></td>
<td>• inappropriately slowed speech rate</td>
</tr>
</tbody>
</table>

Table 2. Demographic data.

<table>
<thead>
<tr>
<th>Subjects</th>
<th>Sex</th>
<th>Age</th>
<th>Duration PD</th>
<th>H/Ya</th>
<th>UPDRSb</th>
</tr>
</thead>
<tbody>
<tr>
<td>AD</td>
<td>M</td>
<td>74</td>
<td>2</td>
<td>1</td>
<td>19</td>
</tr>
<tr>
<td>JM</td>
<td>M</td>
<td>60</td>
<td>5</td>
<td>2.5</td>
<td>38</td>
</tr>
<tr>
<td>AB</td>
<td>F</td>
<td>50</td>
<td>10</td>
<td>4</td>
<td>82</td>
</tr>
<tr>
<td>HM</td>
<td>M</td>
<td>50</td>
<td>13</td>
<td>4</td>
<td>79</td>
</tr>
<tr>
<td>JC</td>
<td>F</td>
<td>49</td>
<td>22</td>
<td>4</td>
<td>93</td>
</tr>
</tbody>
</table>

Three subjects (JC, HM, and AB) had symptoms involving the speech production mechanism and all extremities. These subjects, each on high and frequent dosages of Sinemet, were characterized as having severe bradykinesia, masked faces bilaterally, and pronounced cogwheel rigidity with tremor. Speech intelligibility was moderate to severely impaired in both female subjects (JC and AB), characterized by reduced intensity, imprecise consonant production and inappropriately slowed or accelerated speech rate. Subject HM showed minimal reduction in speech intelligibility despite the severity of symptoms in the limbs. Vocal quality was characterized as hoarse and breathy, with accurate consonant production and occasional alteration of speech rate. The two remaining subjects, (JH and AD) were mildly impaired, with mild symptoms specific to one upper extremity that were well controlled on low dosages of Sinemet. Vocal quality for these two subjects was characterized as mildly hoarse and breathy.

Tasks and measures. Subjects were instructed to produce a VCV disyllable with V being /æe/ or /i/ and C being /p/ or /b/. Testing was consistently accomplished within 1 hour of a medication cycle. Ten repetitions of each disyllable were obtained at comfortable speaking rate. One utterance per breath was sampled. Subjects were instructed to breath as they would in any normal speaking situation. Four repetitions of sustained vowels /a/ and /i/ of four second length were acquired at conversational pitch and intensity levels. In addition, seven consecutive repetitions of the syllable /pæe/ at the same requested pitch and intensity levels were obtained in single trials.

Laryngeal/supralaryngeal timing. As illustrated in Figure 1, temporal and magnitude measures were made that indicated the following: 1) $T_c$ - duration of the closing phase defined as the time difference between the initial registration of pressure ($P_o$) and the associated timing of minimum air flow 2) $T_r$ - duration of the release phase defined as the time between the onset of the pressure drop (at release) and the return of pressure to baseline. In addition, peak intraoral pressure ($P_p$) and peak air flow ($P_u$) at the instant of release were obtained.

Mean flow rate/laryngeal resistance. Aerodynamic measures were used to evaluate changes in the physiological state of the vocal folds during sustained phonation. One of the consequences of glottic insufficiency or inadequate closure of the glottis is greater than normal mean air flow rate (MFR) (Isshiki & von Leden, 1964; Hirano, 1981; Iwata, von Leden, & Williams, 1972; Shigemori, 1977; Yoshioka, Sawashima, Hirose, Ushijima, & Honda, 1977).

MFR was based on an averaged 50 ms sample from the mid portion of the vowel. In addition, during sustained phonation, laryngeal resistance (defined as the ratio of transglottal pressure to average glottal air flow) during phonation was estimated from simultaneous measures of air flow and intraoral air pressure during repetitions of the syllable /pæe/ based on the method outlined by Smitheran & Hixon, 1981).
Figure 1. A summary of the measurement scheme employed for the analysis of the time-varying pressure/flow variations.

GRAPHIC SUMMARY OF MEASUREMENT SCHEME

AIR PRESSURE (P)

AIR FLOW (U)

CLOSED

RELEASE

Pc - Duration of the closing phase
Tf - Duration of the opening phase
Pp - Peak pressure
Pu - Peak flow at release
Equipment

Aerodynamic events were obtained using a Rothenberg mask equipped with two pressure transducers to sense air flow at the mouth (Microswitch model 163) and air pressure in the oral cavity (Microswitch model 162). A short (approximately 10 cm) polyethylene tube, placed in the oral cavity behind the lips was used to sense the pressure associated with bilabial closure. The acoustic signal was transduced with a microphone at a distance of approximately 15 cm from the subjects’ lips.

All signals were digitized at 5000 Hz. with 12 bit resolution. Once acquired, filtered versions of the pressure and flow wave forms were generated and stored as separate files for analysis. For the calculation of laryngeal resistance, MFR, and laryngeal/supralaryngeal timing, the pressure and air flow signals were software filtered at 80 Hz to remove the fundamental frequency variations.

Results

A number of laryngeal and supralaryngeal sequelae were observed in varying degrees in the five subjects. While the intersubject variability was high, intrasubject variability was generally low. Each subject presented a rather consistent set of behaviors across repetitions and across tasks. Subjects HM and AB represent the extremes for this limited sample and their results will be focused on below. In addition, as a result of insufficiency in the two female subjects, duration of the occluded phase was often not possible to measure and will not be presented.

Amplitude measures / pressure and flow. Figures 2 and 3 summarize the peak intraoral air pressure and peak air flow during bilabial consonant production for the five subjects. All subjects demonstrate a voiced/voiceless difference with voiceless pressures and air flow higher than their voiced counterparts. Peak intraoral air pressure for the voiced and voiceless bilabials ranged from 6 to 8 cm H$_2$O for /p/ and 2 to 5 cm H$_2$O for /b/. With the exception of peak pressure for the voiced bilabial for subject AB (2 cm H$_2$O) these values are within the range found for normal speakers (Subtelney, Worth, & Sakuda, 1966). Peak flow rates ranged from 100 to 1180 ml/sec for /p/ and 40 to 550 ml/sec for /b/. Again, with the exception of the flow rates for subject AB, these values are within the range found for neurologically normal speakers (Gilbert, 1973; Isshiki & Ringel, 1964).

Mean flow rates obtained during the midportion of the vowels /ae/ and /i/ varied for the different subjects. Flow rates for Subject HM were essentially normal, ranging from 150 to 250 ml/sec during the steady-state portion of the vowels. Flow rates for subjects JC, AB, and AD were quite variable, ranging from 40 to 100 ml/sec. Given the presence of adequate peak intraoral pressures it can be assumed that the respiratory driving force was not the major contributor to the reduced flow. Rather, mean flow rates suggest elevated resistance to air flow.

In support of this interpretation were the estimates of laryngeal resistance. Figure 4 represents the mean flow rates, peak intraoral pressure, and derived laryngeal resistance measures obtained during /pae/ repetitions. In general, the laryngeal resistance values obtained were higher than those reported for normal subjects (Hillman, Holmberg, Perkell, Walsh, & Vaughan, 1989; Smitherman & Hixon, 1981) and ranged from 20 to 58 cm H$_2$O/L/sec for the five subjects.
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Figure 4. Mean air flow rates, peak intraoral pressure and derived laryngeal resistance measures obtained during /pae/ repetitions.

It can also be seen that flow rates are extremely low, averaging approximately 60 ml/sec. Interestingly, it appears that as articulation continues, voicing becomes continuous, and voiceless /p/ becomes the voiced cognate /b/. This is possibly due to increased laryngeal resistance or glottal spasm. It can also be seen that repetition rate for subject AB increases over the five second interval consistent with her tendency toward acceleration.

Figure 5. Pressure, flow and acoustic speech signals for /pae/ repetitions for two subjects. For HM /p/ closures are all associated with laryngeal devoicing while AB tends to continue voicing into the voiceless consonant after two repetitions.

Shown in Figure 5 are examples from seven serial repetitions of /pae/ for subjects AB and HM illustrating the extremes. Laryngeal resistance for this sample for subject HM was calculated at 30 cm H2O/L/sec. As can be seen, flow rates averaged approximately 250 ml/sec and pressures ranged from 7.4 to 9.2 cm H2O. A distinct voiceless interval can be seen during the closure based on the air flow signal. In contrast, laryngeal resistance values for subject AB were much higher, averaging almost 60 cm H2O/L/sec. Peak pressures were much more variable and decline rapidly over the course of the series of repetitions.

Temporal Measures/ Pressure and Flow Variations

Figure 6 is a summary of the duration of the closing phase (Tc) for the lips during voiced and voiceless consonants /p/ and /b/. This value reflects a portion of the change in cross-sectional area at the lips during the oral closing for the stop. The horizontal line in the graph is the average value for this variable reported by Müller and Brown (1980). There was a tendency for all subjects with the exception of JH to display values that are significantly longer than those obtained from
normal subjects. These values reflect, in part, overall rate of articulation such that slow oral closing movements will be reflected as higher $T_c$ values. Of the five subjects in the present study, subjects HM, AD and JH display normal speaking rate while JC and AB display slowed speaking rate and associated slowed lip and jaw movements. However, though the rate of speech of subject AB was decreased, this rate reduction was not as dramatic as that of subject JC. In this case one would not expect to see the greater $T_c$ values for AB as compared to JC. Inspection of the pressure/flow waveforms from subject AB reveal the reason for the longer $T_c$ values. For most of her VCV productions, complete cessation of air flow was not achieved, apparently due to velar insufficiency. As such, $T_c$ values reflect a combination of the closing interval and a portion of the occluded phase of stop consonant production. As noted previously, subject JC also demonstrated apparent velar insufficiency, but to a lesser degree than AB. In this case, occlusion was apparent from the rapid decrease in oral air flow.

earlier than oral closing as evidence by the increase in flow noted by the arrows. In contrast, HM displays a decrease in flow and a rather abrupt cessation in voicing at the moment of pressure rise as the lip area decreases to the minimum value to reflect pressure change. In the case of AB, oral/laryngeal actions appeared discoordinated or slowed. For HM, however the transition was more normal although accelerated.

Figure 6. Mean duration of the closing phase ($T_c$) for the five subjects collapsed across the two vowels. No significant vowel affects were noted ($p > .05$). Horizontal line indicates the average $T_c$ values reported by Müller and Brown (1980).

As suggested above, in the absence of kinematic data, simultaneous examination of pressure/flow interactions can be used to infer laryngeal/supralaryngeal coordination and timing. Presented in Figure 7 are examples from two of the five subjects. During the occlusion phase, flow was noted to decrease due to oral closing and was appropriately timed with laryngeal devoicing (see Figure 1 for example). For the two subjects presented in Figure 7, two different patterns are seen. For AB, laryngeal devoicing begins much

Figure 7. Pressure, flow, and acoustic signals for /æpæ/ illustrating examples of the $T_c$ measure for subjects AB and HM.

Figure 8 presents a summary of the results for the duration of the release phase ($T_r$); the horizontal lines reflect the average $T_r$ values for /p/ and /b/ from Müller and Brown (1980).

For the $T_r$ measure, subjects AB and JC displayed longer than normal durations for the time required for the pressure to return to baseline.

Figure 8. Mean duration of the release phase ($T_r$) for the five subjects collapsed across the two vowels. No significant vowel affects were noted ($p > .05$). Horizontal lines indicates the average $T_r$ values reported by Müller and Brown (1980) for /p/ and /b/.
following oral release of the consonant. Time for release is influenced by numerous factors and reflects not only the release gesture at the point of articulation but the possibility of a superimposed breath pulse as well as any variable that can influence the time constant of the decay rate of the Po such as glottal resistance. In contrast to the results from Müller and Brown (1980) for normal subjects and Gracco and Müller (1981) for a group of spastic dysarthrics, two of the three PD subjects displayed longer Tr values for the voiced stop. The longer Tr values reflect a combination of slowed oral opening movements and higher glottal resistance. Interestingly, the higher resistance is most notable when voicing is maintained during the voiced consonant.

Discussion

The present study constitutes an initial attempt to investigate the laryngeal and supralaryngeal deficits in a group of Parkinsonian individuals based in part on previous work by Müller and Brown (1980). A variety of laryngeal and supralaryngeal impairments were noted. Elevated laryngeal resistance measures may reflect excessive muscle tension either at the level of the glottis or supraglottis, but at the least represent vocal tract constriction. These examples were consistent with limb symptoms of muscular rigidity. That is, for one subject, instances where measured vocal tract resistance was high, limb symptoms of muscular rigidity were also present. For three of the five subjects, vocal tract resistance fell within a range consistent with non-neurologically involved subjects. For these subjects limb rigidity was only mildly present. However, an exception to the limb/bulbar consistency was subject HM. This subject had moderate-to-severe limb involvement; the lower limbs more severely impaired than the upper limbs, and the upper limbs more impaired than the bulbar musculature. However, vocal tract resistance and glottal/supraglottal timing measures were essentially normal.

Supralaryngeal differences were noted in two of the five subjects. Inferences from the time-varying pressure/flow waveforms suggested that oral closing and opening movements were slowed, a finding consistent with previous speech movement studies. In addition, there was some indication of laryngeal/supralaryngeal discoordination.

From this limited sample it is possible to suggest but not to confirm that laryngeal or vocal tract resistance measures may be useful in documenting a variety of the perceptual voice characteristics previously reported for individuals with PD. However, the speech symptoms may not always correlate or correspond to those in the limbs. The time-varying characteristics of the supraglottal pressure and flow waveforms are the consequence of the concomitant articulatory events associated with stop consonant production. Simultaneous recordings and analysis of the pressure and flow events may serve as easily obtained indicators of global system performance aiding in the diagnosis of certain speech related disorders and provide insight into the abnormal articulatory process. For example, the Tr measure or duration of the release phase is defined as the time between the onset of air flow and return to baseline. All of the subjects with one exception showed short Tr values for the voiceless /p/. This measure reflects not only the release gesture at the point of articulation but any variable that can influence the time constant of the decay rate of Po. In the present context, the short Tr values for /p/ may reflect a rapid devoicing gesture perhaps coupled with discoordination of the lips and larynx. For the two most severely involved subjects (AB and JC), the Tr durations for the voiceless /b/ were longer than normal suggesting elevated laryngeal/vocal tract resistance, a slowed release gesture, or the presence on a expiratory breath pulse. Given the low peak pressure values for these subjects, excessive vocal tract resistance seems the most plausible conclusion.

It is especially important to consider that these measures did differentiate subjects within a group of Parkinsonian dysarthrics, though not entirely. Just as there exist subgroups of patients with Parkinson's Disease and various subgroups of Parkinson's syndrome, it appears that acoustic/perceptual and aerodynamic data may be useful in further differentiating these populations. Additionally, pressure and flow information can aid in identifying laryngeal manifestations of pathophysiology affecting phonatory characteristics and glottal efficiency. The preceding dynamic analysis scheme can be used to provide specific information on the general functioning of the speech production mechanism as well as interarticulatory timing from an objective set of data. An analysis scheme of this type in conjunction acoustic and perceptual performance indices, may generate more informed hypotheses concerning the nature of the underlying motor deficit(s) as they affect the speech mechanism.
REFERENCES


FOOTNOTES
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