Characteristics of the Aging Female Voice

Caractéristiques de la voix féminine vieillissante

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Abstract

This review addresses findings from recent literature pertaining to characteristics of the normal aging female voice. General theories of biological aging are discussed along with the specific effects of the aging process on the anatomical structures and physiologic function of the female larynx. Although age-related changes are noted in the respiratory and the supralaryngeal systems which influence voice production, the present review specifically focuses on biological changes to cartilage, soft tissue, muscular structures, as well as to the neural innervation of the larynx. Measurement of the female voice at physiological, acoustic, and perceptual levels also is summarized to clarify the relationships among the age-related changes observed at all three levels. Results indicate that there are normal differences between male and female speakers due to physiology, differences in the aging process and its relative effects on anatomic structures, and subsequent differences in selected acoustic characteristics of the voice signal. However, studies measuring perceptual features inherent to the aging female speaker are lacking. In order to determine what features can be attributed to normal aging as opposed to disease conditions, it is mandatory that perceptual research with the female population be undertaken. Auditory-perceptual investigations will serve as a first step to understand the aging process on voice production. This knowledge may aid in earlier recognition of age-related voice problems, with potential intervention and improvement in the quality of the life for those individuals who seek treatment.

Abrégé

Cette étude porte sur les constatations présentées dans la documentation récente au sujet des caractéristiques de la voix normale des femmes vieillissantes. On y aborde les théories générales du vieillissement biologique ainsi que les effets spécifiques du processus de vieillissement sur les structures anatomiques et les fonctions physiologiques du larynx féminin. Même si l'on y fait ressortir au niveau des systèmes respiratoire et supralaryngé des changements liés à l'âge qui influencent la production de la voix, l'enquête traite particulièrement des changements biologiques du cartilage, du tissu mou, des structures musculaires ainsi que de l'innervation neuronale du larynx. La mesure de la voix féminine en termes physiologiques, acoustiques et perceptifs est également résumée en vue de clarifier le rapport entre les changements liés à l'âge observés aux trois niveaux. Les résultats révèlent des différences physiologiques normales entre les locuteurs masculins et féminins, des différences au niveau du processus de vieillissement et de ses effets relatifs sur les structures anatomiques, ainsi que des différences subséquentes dans certaines caractéristiques acoustiques du signal vocal. Cependant, les études manquent en ce qui concerne la mesure des caractéristiques perceptives inhérentes au locuteur féminin vieillissant. Pour déterminer quels traits sont attribuables au vieillissement normal comparativement aux cas de maladie, il est impératif d'entreprendre des recherches perceptives sur la population féminine. Des enquêtes de type auditif et perceptif permettront de commencer à comprendre le processus de vieillissement et ses effets sur la production vocale. Les connaissances ainsi acquises pourront aider à la reconnaissance plus rapide des problèmes de voix liés à l'âge et à une éventuelle intervention permettant d'améliorer la qualité de vie des personnes qui se font traiter.

Key words: aging, voice quality, female voice, voice perception, acoustics, laryngeal physiology

The voice is an integral part of that uniquely human attribute known as speech. Beyond carrying words, the voice can also add significantly to a spoken message by adding intonation, reflecting the physical state of a person (i.e., poor physical condition, illness), or by providing an emotional outlet (Rosen & Sataloff, 1997). Parameters of speech and language (e.g., speaking rate, pause time, articulation, vocabulary, syntax), as well as those inherent to the voice signal (e.g., pitch, loudness, voice quality) also may be used to identify a speaker's age. When listeners are asked to describe the vocal characteristics exhibited by individuals judged to be "old" (Hartman, 1979; Hartman & Danhauer, 1976; Ryan & Burk, 1974), such descriptors as "shaky", "squeaky", "weak", and "hoarse" are often used. These age-related features frequently are obvious to listeners and are often bothersome to older speakers. Thus, to differentiate voice changes precipitated by normal aging from those related to physical or emotional abnormalities, it is important to understand the effects of the normal aging process on the voice.

A variety of professionals, including speech-language pathologists and otolaryngologists, are involved in assessing and treating individuals with voice difficulties. It is important that these professionals be familiar with what constitutes "normal limits" so that an older speaker can be counselled appropriately when expressing concern about his or her voice. Such knowledge requires adequate normative data in how normal aging processes affect the human voice, that is, which components of the voice fall within normal limits and which do not (Mueller, 1997). It is vital that a normative database is established and that testing and measurement of the various components of voice are validated (Kent, Kent, & Rosenbek, 1987; Ward et al., 1989), particularly within an increasing and extremely heterogeneous older population (Shadden, 1988). Proper identification, establishment of etiology, and subsequent treatment for voice difficulties require thorough examination. Assessment tools typically include both instrumental (so-called "objective") and auditory-perceptual judgment (or "subjective") methods (Kent, 1996). Although both methods are invaluable in assessment, intervention, treatment, and follow-up, auditory-perceptual judgments often represent the method of final evaluation in clinical decision-making (Kent, 1996) and serve as the approach most often used and valued most highly by clinicians (Gerratt, Till, Rosenbek, Wertz, & Boysen, 1991).

Perceptual studies seeking to characterize the aging speaker's voice are generally limited and, until the late 1980s, data for females were almost nonexistent. Auditory-perceptual study of the aging female voice represents a clearly needed area for research development. With a steady increase of the older population in North America, one can anticipate a growing number of individuals who seek to maintain effective vocal communication for as long as possible. For example, in 1986 about 11 percent of the population in Canada was aged 65 and older (Statistics Canada, 1993). It is projected that the number of older adults will more than double by 2031, equalling almost 24 percent of the total population. Furthermore, projections show that by 2001, women aged 80 and over will outnumber men at a ratio of 2.18 to 1 (Statistics Canada, 1987). Thus, as the number of older women (i.e., 80+ years) increases, it is especially important to address questions surrounding characteristics of the normal aging female voice.

The purpose of the present review is to address studies that identified characteristics of the normal aging female voice. In doing so, it is first necessary to have a general understanding of theories of aging and subsequent biological effects of the aging process on the anatomical structures and physiological functioning of the female larynx. This information is addressed in the following section. Although there are age-related changes in the respiratory and the supralaryngeal systems (Kahane, 1981) which affect voice production, the present review focuses on biological changes associated solely with the laryngeal cartilages, soft tissues, muscles, and neural innervation of the larynx. Next, measurement at the physiological, acoustic, and auditory-perceptual levels is summarized to clarify the relationships among the age-related changes observed at all three levels. Finally, the status of present research and pertinent clinical questions are explored relative to directions for future exploration in the area of the aging female voice.

General Theories of Aging

Effects of the aging process on the human body have been the focus of substantial research by a variety of disciplines for the past several decades. Exploration in the area of "aging" has been due primarily to the explosion of the aging population and the responsibility of health care providers to provide expert care for elderly patients. Biological, psychological, and sociological theories all provide explanations for the aging process but no one theory explains the aging process using an interdisciplinary approach (Linville, 2001). Biological theories are based on research associated with changes in organism function at both the molecular and systemic levels (Sandmire, 1999). Behavioural theories include explanations of how age-related processes affect cognition, attention, and working memory (Cavanaugh, 1999), as well as how aging affects personality and identity. Clearly, factors such as personality and identity play a role in explaining changes associated with the aging process on the voice. For example, differences in personality secondary to increased mood disorders in older individuals (Sataloff, Rosen, Hawkshaw, & Spiegel, 1997) may impair a person's ability to consistently perform vocal tasks.

In contrast, cultural theories provide explanations about how culture-specific ideas affect beliefs about life, independence, death, how society treats the elderly and how stereotypes stigmatise certain segments of the population. Membership in certain ethnic groups may explain some of the variability in voice, although specific effects have yet to be systematically investigated (Linville, 2001). Therefore, the focus of future research should include an integration of these theories such that these multidimensional factors can comprehensively explain age-related processes. As stated by Linville (2001, p.3), "In terms of voice disorders, awareness of the impact of aging on the human body as a whole gives clinicians a broader perspective into which voice production issues can be placed." However, before the specific effects of aging on the voice mechanism are examined, it is important to consider the general characteristics of aging.

Extrinsic processes that influence aging include smoking, air pollution, a high-fat diet, and side-effects of medications (Novak, 1993). In elderly persons, the effects of smoking coexist with normal changes of aging, by amplifying the effects of aging. Such effects include pulmonary reductions in expiratory airflow (Gregg & Nunn, 1989) and changes in the laryngeal system such as increased vocal fold thickening among smokers vs. nonsmokers (Gilbert & Weismer, 1974). These extrinsic processes, however, can be slowed with changes in the environment, lifestyle, and improvements in technology (Novak, 1993). For example, when an individual ceases to smoke, pulmonary function improves immediately and continues to do so for several months (Buist, Nagy, & Sexton, 1979). Therefore, extrinsic processes of aging are not irreversible or universal to all individuals.

However, unlike extrinsic age-related processes, "true aging" (intrinsic) is said to be universal, decremental, and progressive (Novak, 1993). For example, true aging includes the loss of lung elasticity, the slowing of a person's reaction time, the accumulation of "debris" in aging cells (Novak, 1993), as well as hormonal changes and the increased incidence of hearing loss (presbycusis). It also includes genetic predispositions toward specific illnesses (e.g., diabetes), as well as physical changes such as wrinkling, baldness, etc. Although the rate of change varies depending upon cultural membership (Novak, 1993), among other influencing factors, aging also is said to be universal in that all members of any species show age changes if they live long enough. "True aging" is basic to the organism; the individual is unable to alter or manipulate the rate of this aging process. Further, true aging is progressive and cumulative, gradually leading to decline in physiological function.

Biological Theories of Aging: Implications for Voice Production

The vocal mechanism shares age-related changes with other parts of the body, as well as common molecular and cellular structures. Consequently, a closer look at prominent biological theories of aging is useful as a frame of reference. The theories reviewed herein are not meant to be exhaustive; rather, the reader is referred to other reviews or recent texts for a more thorough explanation (Cavanaugh, 1999; Hayflick, 1994). One of the most commonly proposed mechanisms of cellular aging is free radical oxidation (Chodzko-Zajko & Ringel, 1987). Normal metabolic processes within cells generate free radicals that are then cleared by specialized enzyme systems (Riabowol, 1999). It is suggested that loss of these enzymes might contribute to the aging process, thereby leaving an increase in the number of free radicals to cause damage within the cell (Riabowol, 1999). The damage may be a particular factor in aging when free radicals target special cell types such as nerve cells within the hypothalamus that regulate pituitary gland function (Riabowol, 1999). Among the damage attributed to free radicals are alterations to the structure of collagen and elastin, the destruction of deoxyribonucleic acid (DNA), and a progressive breakdown of the immune system (Chodzko-Zajko & Ringel, 1987). This type of damage is associated with "post-mitotic tissue", the kind of tissue that cannot renew itself (e.g., neuromuscular tissue). In the larynx, the damage is associated with neuromotor control of the vocal folds, and the thyroarytenoid (TA) muscle (Ramig, Drayna, Gray, & Buder, 1999). For example, contraction of the TA muscle decreases the length of the vocal folds and increases cross-sectional area. Contraction of the TA muscle represents one way to lower vocal pitch. Also, contraction of this muscle changes the configuration of the vocal folds themselves, thereby affecting the vibratory pattern (Colton & Casper, 1996). Therefore, disruption of the motor control of the TA muscle influences pitch, loudness, and regularity of the voice.

A second theory of aging is associated with renewable or "mitotic" tissue, and reflects the concept of "telomere-shortening". The process of telomere-shortening can be explained as follows. During cell replication, chromosomes are joined at the telomere. At this time, enzymes function to duplicate the chromosomes. During this process, some of the DNA bases (i.e., those components which make up the chromosome) are lost shortening the telomere (i.e., as the cell ages; Hayflick, 1985). As the telomere shortens due to the loss of DNA bases, the cell does not divide anymore. Hayflick (1985) suggested that cultured human and animal cells exhibit a finite limit with regard to their ability to reproduce. This coincides with the telomere-shortening theory at the genetic level (Riabowol, 1999). For example, senescent (or aging) fibroblasts tend to resist cell death (called apoptosis), thereby contributing to increased susceptibility to developing age-dependent diseases. Older cells also create less energy and produce enzymes more slowly, consequently, they allow waste to fill up inside (Hayflick, 1985), thereby producing deleterious effects. However, the build up of waste only pertains to "mitotic" or renewable tissue (e.g., connective tissue such as the cover and epithelium of the lamina propria of the vocal folds) and not to "post-mitotic tissue" (e.g., neuromuscular tissue).

Theoretically, as different structures (and associated tissue types) involved in voice production are affected by different age-related processes, discriminating measurement tools can be developed to separate the effects from the two different sources (i.e., damage associated with free radicals vs. telomere-shortening). Measuring these effects differentially would aid in marking relationships with known effects on other body structures (i.e., renewable vs. nonrenewable tissues) affected by similar age-related processes. However, even with advanced technology, the ability to separate these processes through current measurement practices remains a focus for future research. Currently, measurement of the voice remains limited to the anatomy, physiology, associated acoustic sound spectrum, and auditory-perceptual correlates of the integrated voice mechanism. In order to review comprehensively age-related processes on the female voice, measurement at all three levels of functioning (i.e., anatomical/physiological, acoustic, auditory-perceptual) is examined in the next section.

Measurement of Age-Related Processes in the Voice

There are three levels of potential study related to examination of voice quality. Firstly, one must examine the voice source and the physiology of the sound-producing mechanism. This includes direct measurement of the structural and functional components of the larynx (e.g., laryngoscopic measurement using endoscopy/stroboscopy; Baken, 1996). Vocal fold measurement by endoscopy is visual-perceptual in nature (i.e., observational). Its value lies in providing data on how the larynx works in concert with the rest of the vocal tract system (Baken). Visualization is extremely important to physicians, as well as to speech-language pathologists, both whom ideally work as a team with individuals who exhibit voice problems. Indirect measurement of the functioning of the larynx and vocal folds is determined through inferred relationships. Examples of indirect measurement of vocal fold functioning include aerodynamic measurements which involve the analysis of air pressure and airflow patterns through the glottis or via electroglottographic (EGG) measurements which examine components of the glottal duty cycle representative of the amount of time the vocal folds are in relative contact or noncontact (Baken, 1996).

The second level of voice measurement includes measuring the acoustical features of the voice signal. The acoustic spectrum of speech is the product of both the vocal source as well as the filter characteristics of the vocal tract. Acoustic analysis provides a method to measure laryngeal functioning as well as articulatory movements. Examples of acoustic measures derived from standard voice analysis systems (e.g., Cspeech; Version 3.1; Paul Milenkovic, Madison, WI; Computerized Speech Laboratory; CSL, Kay Elemetrics, Pine Brook, NJ) include calculations of fundamental frequency, intensity, and various calculations of spectral noise level. These measures are derived commonly from voice recordings of sustained vowels and standard reading passages.

The final level of inquiry involves the salient auditory-perceptual dimensions (i.e., the psychophysical features) that characterize a speaker's voice (Colton & Estill, 1981). Although more information is now available on the effects of aging on the structural components of the larynx, normative data for acoustic and auditory-perceptual features are still insufficient. The finding is especially true for the female voice. A current summary of information related to measurement of age-related processes on the voice is presented in Table 1. Despite a limited number of studies that focus on the aging female voice, a review of known physiological, acoustical, and perceptual normative data associated with normal aging is addressed in the next section.

Anatomical and Physiological Differences between Male and Female Speakers

Differences between age-related effects on male and female voice production are examined in this section. Firstly, normal differences (i.e., unrelated to aging) between male and female speakers are described. Secondly, general age-related effects in both male and female speakers are summarized. After a thorough examination of this information, subsequent differences between aging speakers of both sexes are described. The subsequent sections present this information relative to anatomical and physiological structures, first by examining differences determined by direct measurement tools. The discussion is followed by a summary of differences due to both sex and age-related processes as measured by indirect methods.

Normal Anatomical and Physiological Differences between Male and Female Speakers

Many of the normal anatomical and physiological differences between the male and female larynx (i.e., those unrelated to aging processes) are discussed by Titze (1989). Titze found that the male thyroid cartilage is approximately 20% larger than that of the female, and that the membranous length of the male vocal fold is larger than that of the female by approximately 60%. The difference in thyroid cartilage and vocal fold size alone results in a difference in vocal acoustic characteristics of men and women. For example, the increased

Table 1. Summary of selected studies outlining differences in anatomical, physiological, acoustic, and perceptual measurements of the voice mechanism due to age-related processes in males and females.				
Authors	**Participants**	**Physiological/Anatomical Changes**	**Effects on Voice Quality**	
			Acoustic	**Perceptual**
Anatomical/Physiological				
Kahane (1987)	M & F	a) Ossification / calcification of laryngeal cartilages b) Conus elasticus changes c) Thickening in superficial layer of LP For a), b), and c), M > F Increased mucosal edema for F		
Honjo & Isshiki (1980)	20 F 20 M	74 % F - VF edema 58 % F - Inadequate closure	F increasing in age, increasing F_0 M increasing in age, increasing F_0	Hoarseness
Linville & et al. (1989)	20 F 67-86 yrs	16 % - VF edema 25 % - VF bowing 95 % - Inadequate closure	F increasing in age, decreasing F_0	
Acoustic				
Ramig & Ringel (1983)	48 M 3 grps: 25 - 35 yrs 45 - 55 yrs 55- 65 yrs	2 older groups rated as "Good" and "Poor" physical condition Among oldest group (55-65 yrs) "Poor" vs. "Good" condition	Speakers in "good" condition: increasing MPT, decreasing jitter, decreasing shimmer, increasing MPFR Oldest vs. Youngest group: increasing age, increasing shimmer increasing age, increasing perturbation variability	
Linville & Fisher (1985)	75 F, 3 grps: 25-35 yrs,45-55 yrs 55-65 yrs	Identified age: 51 % from sustained vowels, 43% from whispered vowels As age increases, increasing F_0, decreasing F_0SD - discriminators of actual age increasing jitter - not useful for predicting age		
Brown et al. (1989)	25 young F 25 older F	increasing age, decreasing F_0, increasing F_0SD,	increasing reading length	
Perceptual				
Hartman & Danhauer (1976)	46 M 25 - 70 yrs			Older speakers identified: decreasing pitch, decreasing articulation decreasing rate, decreasing quality
Notes: F = female; M = male LP = Lamina propria; VF = vocal fold Maximum phonation time = MPT; fundamental frequency = F_0; Maximum phonational frequency range = MPFR Short-term measures of variability: jitter, shimmer; Long-term measure of variability: standard deviation of fundamental frequency = F_0SD				

mass of the vocal folds in males causes a greater amplitude of vibration in the folds (Titze, 1989). Thus, a greater proportion of the vocal fold, inferiorly to superiorly, vibrates to a greater extent in males than in females. However, this also causes the fold to vibrate slowly (i.e., increased mass = decreased oscillatory rates), which is related to a decreased pitch in males.

Given that the male and female larynx differ anatomically and physiologically, sex-specific aging effects should be examined comprehensively in order to account for differing acoustic and perceptual phenomena. Methodology employed for gathering such data in males and females, however, must remain consistent. Although convincing evidence is not yet available for relating structural changes to functional events, potential indicators for such effects can be examined to direct further inquiry and to make tentative conclusions regarding the association between structure and function (Kahane, 1983). Thus, important trends are described and reviewed in subsequent sections, organized according to tissue type for clarity. Although sub- and supra-laryngeal structures clearly affect the functioning of the voice-producing mechanism, the effects of these processes are not included. The reader is referred to Linville (2001) for a comprehensive review of how age-related processes affect modulation of the voice.

Age-Related Effects on the Male and Female Larynx

Cartilage. The literature shows age-related effects on the larynx relative to structural and functional components (e.g., cartilaginous skeleton, intrinsic muscles, nerve supply, etc.). For example, the cartilaginous framework of the larynx undergoes changes from birth into old age (Kahane, 1987). The principal changes are calcification and/or ossification of the hyaline cartilages of the larynx (Kahane & Beckford, 1991). Most investigators also report earlier and greater ossification in males than females (Kahane & Beckford, 1991). Due to ossification or calcification of the cartilages, structural flexibility is reduced. This reduced flexibility in turn affects the ability to augment fundamental frequency through the compression of the thyroid laminae (Kahane, 1987). The elastic cartilages (epiglottis, apex and vocal process of the arytenoid cartilages) remain unchanged (Kahane).

Articular surfaces. There are age-related changes in the cricoarytenoid joint (Kahane & Beckford, 1991). These changes include thinning of the articular surfaces, breakdown in and disorganization of the collagen fibres in the cartilage matrix, and surface irregularities. These changes may ultimately affect the way the vocal folds approximate one another (i.e., smoothness of adjustments and extent of approximation) and may lead to the escape of air (i.e., a breathy voice quality) during vocal production (Mueller, 1997). Consequently, poor adduction may require an older individual to exert more physical effort in order to generate a vocal signal and resultant speech. Effort would likely translate into increased respiratory force, driving pressure, and volitional concentration in achieving these tasks or manoeuvers. The increase in effort could then translate into increase in fatigue among older speakers, resulting in an increased number of individuals with voice difficulties associated with hyperfunction and decreases in voice quality. In a study comparing three groups (young [23-28 years], middle-aged [40-55 years] and older women [77-88 years]), Fowler (1993) found that listeners' perception of "effort" increased with increases in age. Listeners rated "effort" on a seven-point scale, with one defined as "least effort" and seven defined as "most effort". Significant increases in effort were found between the older female speakers and the two younger groups ($p < .001$), with no significant differences found between the middle-aged and younger female speakers. Fowler's results support the hypothesis that increased effort in aged speakers results in increased voice difficulties, at least in the context of perceived "effort" translating to actual "effort." Other factors such as hearing loss (presbycusis) related to aging would also increase "effort" as individuals may be required to increase attention to not only the sound of their voice, but also to the conversation in which they are engaged. These effects therefore have the potential of fatiguing an older speaker who is involved in conversation for longer periods of time. Further investigation of the relationship between age-related effects and "effort" are clearly a focus for future research.

Blood supply and innervation. Few data support conclusive changes in laryngeal blood supply and innervation due to age-related effects. Linville and Fisher (1985) suggest the possibility of reduced neuromuscular control of the larynx as a function of age. This may relate to decreased control of the vocal folds that in turn might be associated with a "shaky" or tremulous voice. Evidence for aging effects of the posterior cricoarytenoid muscle (PCA; the primary laryngeal abductor muscle) is clearly delineated (Gambino, Malmgren, & Gacek, 1990). This muscle serves as a primary inspiratory muscle (in respiration) as well as a speech muscle (for devoicing). As aging occurs, the neural endplate of the PCA increases in length while the number of terminal axonal branches decreases. The decreased number of axonal branches causes a depression in the input to the PCA. A decrease in input causes the PCA muscle to act less efficiently as the individual ages. In contrast to limb muscles, no evidence exists for early aging effects on the PCA muscle (Gambino, Malmgren, & Gacek, 1990). These data suggest that age-related changes in the PCA may not account for difficulties associated with gradual declines in voice production performance in middle age, but may only be associated with difficulties experienced by the "very" old (e.g., 80 + years).

Glandular supply. There is general agreement that the vocal folds undergo changes that result in accelerated dehydration (Kahane & Beckford, 1991) which in turn could affect the integrity of vocal fold tissue function. Dehydration also may be responsible for the excessive throat-clearing observed in many older speakers and may put the elderly at greater risk for voice disorders. Dehydration may be due to changes associated with the glands that lubricate the vocal cord mucosa (Mueller, 1997). Reduced glandular secretions makes epithelial surfaces more vulnerable to abrasive forces produced during effortful closure. Epithelial changes in turn may adversely affect the leading edges of the vocal folds, causing them to vibrate irregularly, thereby resulting in a "noisy" or "hoarse" voice (Kahane & Beckford, 1991).

Hormonal influences also must be considered when evaluating voice problems in older individuals. For example, thyroid disease is prevalent in both older men and women and can lead to changes in vocal quality, including loss of range, efficiency, and "muffling" of the voice. Further, as women reach menopause, estrogen levels decrease, unless they are on hormone replacement drugs, causing substantial changes in the mucous membranes that line the vocal tract as well as changes in the muscles (Sataloff et al., 1997; see later discussion entitled "Fundamental frequency"). Medications and subsequent side-effects also may contribute to vocal complaints by dehydrating the larynx or laryngeal mucosa (Linville, 2001) as well as producing other physiological side effects (e.g., changes in cardiac performance, respiration, glandular system, hypertension, etc.; Linville, 2001). Medication use increases with advancing age, raising the likelihood of unwanted side-effects . These factors should all be taken into consideration before diagnosing voice disorders related to age (called presbylarynges; Woo, Casper, Colton, & Brewer, 1992).

Vocal folds. Several studies report aging effects on the vocal folds themselves. The vocal folds are composed of a thin epithelial layer, three layers of connective tissue (the superficial, intermediate, and deep layers of the lamina propria), and the vocalis muscle (Hirano, Kurito, & Nakashima, 1983). The three layers of the lamina propria (LP) are essential to vocal fold function during voice production (Hirano, 1974). For example, the cover and transition (epithelial and LP layers) and body (vocalis muscle) of the vocal folds consist of different matrix compositions. The layers of the LP consist of collagenous and elastic fibres that are arranged in several structural arrays and have different mechanical properties. These layers differentially affect the way the vocal folds react to aerodynamic pressures. These multiple reactions, in turn, affect the regularity with which the vocal folds vibrate. The regularity of vocal fold vibration then affects the overall quality of the voice. Examining how age-related processes affect all layers of the vocal fold yields important information on age-effects of voice quality. Age-related effects on the epithelium, LP and vocalis muscle of the vocal fold are summarized in the next section.

Disagreement exists about age-related changes in the epithelium of the vocal fold. Noell (1962) noted that the only age-related change in the laryngeal mucosa was the loosening of the epithelium to the underlying LP. It is suggested that this could reduce the structural support to the cover of the vocal fold, thereby increasing perturbation (i.e., cycle-to-cycle variability) during phonation (Wilcox & Horii, 1980). The increase in perturbation is believed to be caused by the unanchored epithelium that vibrates at a different frequency than the other structures (layers) within the vocal fold.

Mueller, Sweeney, and Barbeau (1985) reported that in postmortem laryngeal specimens of older (mean age 81 years) and younger (mean age 44.7 years) males, age-related features existed among the older group including bowing, atrophy, and cordal sulcus of the vocal folds. These results coincide with observations of Honjo and Isshiki (1980) who noted muscle shrinking (atrophy) and bowing of the vocal folds in male subjects. In contrast, edema of the vocal folds was found in 74% of the 20 females in Honjo and Isshiki's (1980) study. Somewhat differently, Linville, Skarin, and Fornatto (1989) found a 16% prevalence of vocal fold edema among older females. However, like Honjo and Isshiki (1980), Linville et al. (1989) found inadequate glottal closure in females (95% of older females vs. 58% for Honjo and Isshiki's [1980] work; see Table 1). Anatomical changes might reflect underlying changes in the involutions of connective tissues, especially noted in the deep layer of the LP in males (Hirano et al., 1983). Collagenous fibres in the LP of males tend to thicken and lose their linearity (i.e., fibres running parallel to the edge of the vocal fold, as expected in younger individuals; Hirano et al.). The loss in elasticity in the LP of male larynges, increases the relative "stiffness" of the vocal fold. The increase in stiffness is associated with a higher vibrational frequency and is associated with the increase in pitch often observed in older males (Hirano et al.). Another age-related difference between male and female larynges includes changes in the conus elasticus (the fibroelastic layer consisting mainly of elastic fibres) in older males. Changes such as increased edema, thickening of collagenous fibres in the LP, increased stiffness of the VF, etc., yield irregularities in vocal fold vibration that could be perceived as the roughness or hoarseness and/or "breathiness" often observed in older speakers.

Vocalis fibres of the thyroarytenoid (TA) muscle (or the "vocalis" muscle) are the most functionally significant contributors to voice production (Colton & Casper, 1996). Age-related changes that affect the TA muscle include atrophy, degeneration, decrease in muscle fibre diameter, and breakdown in fibrous support of the muscle (Kahane & Beckford, 1991). Kahane (1987) suggests the changes are due to alterations in the blood supply to the laryngeal muscles. Baker, Ramig, Luschei, and Smith (1998) compared the activity of the TA muscle in older speakers when compared with younger speakers. They concluded that reduced amplitudes of TA muscle activity (as measured by electromyographic (EMG) amplitudes) in older speakers could contribute to hypophonia (i.e., reduced loudness) frequently observed in older speakers. This also coincides with an overall "breathy" quality due to a less efficient system in the biomechanics of vocal fold adduction.

Glottal gaps observed between the adducted vocal folds are especially important when describing differences between the anatomy and physiology of men and women of all ages. A glottal gap results from an inability to fully adduct the vocal folds. Women typically exhibit a different pattern of glottal gaps than men. For example, Linville (1996) reported an increased incidence of glottal gaps in male speakers with advancing age. This coincides with laryngeal atrophy in aged male speakers. Different patterns of gaps may be exhibited between both young male and female speakers, as well as between older and younger female speakers (Linville, 1992). Both elderly and young women demonstrate a high prevalence of glottal gaps. Specifically, young women tend to have a gap in the posterior aspect of the vocal folds. Elderly women tend to display an anterior gap; however, there is no significant difference between the two groups for overall prevalence of gaps (Linville, 1992). For example, in young women, glottal gap prevalence estimates range from 70% to 95% of observations whereas estimates for elderly women range from 58% to 90% (Linville). These data are also supported by the findings of Biever and Bless (1989) who reported an incomplete mid-membranous glottal closure of the vocal folds for older women (aged 60 to 77 years) compared to young female speakers (aged 22 to 28 years). Thus, as women age, the pattern of glottal gap changes from a posterior aspect to an anterior one. The pattern suggests that as women age, they 'regain' the ability to close the VFs posteriorly. Given what is known about age-related changes in the larynx, it is surprising that young women demonstrate a posterior chink (or gap) compared with elderly women. Some researchers speculate that young women are physiologically capable of achieving vocal fold closure but fail to do so for functional reasons (Linville, 1992; Sapienza & Dutka, 1996). Linville (2000) suggests that this opening could be an adjustment for economy (i.e., to conserve effort for adductory forces) or to achieve a culturally acceptable voice quality of breathiness. Thus, in this particular example, function (i.e., an "inability" or lack of closure in the posterior area of the vocal folds) may not have "true" anatomic reasons.

Aging Effects on the Vocal Folds as Measured by Indirect Methods

Although data from visual observation (i.e., direct methods) are the gold standard in assessing tissue disorders, much information is provided by measures that do not reveal what the vocal folds actually look like (Baken, 1996). Since direct methods are invasive, costly, and time consuming, simpler methods that rely on correlates of vocal fold action were developed. Although these latter methods cannot substitute for good visual assessment of the larynx, they can generate useful quantitative and qualitative information that may be equally important to assessment and intervention. Such methods include photoglottography (PGG; not discussed herein), electroglottography (EGG) and aerodynamic measures.

Data from aerodynamic studies and electroglottographic measures (Holmberg, Hillman, & Perkell, 1989; Holmberg, Hillman, Perkman, Guiod, & Goldman, 1995; Holmes, Leeper, & Nicholson, 1994; Sapienza & Dutka, 1996) suggest that vocal aging in women does not increase the incidence of laryngeal valving deficits. Several researchers (Linville, 1992; Sapienza & Dutka, 1996) suggest that elderly women may use functional adjustments to close posterior gaps displayed as young adults when gaps begin to appear more anteriorly in the glottis with advanced age. In the case of the older speaker, "bowing" relates to decreased loudness or increased effort to close the vocal folds which may result in strain (Linville, 1996). This hypothesis is supported by Holmes et al. (1994) who found laryngeal airway resistance (RLAW) values were higher for elderly females than males. Holmes et al. also suggested that separate norms need to be established when determining RLAW values for males and females.

Many differences exist between the laryngeal structures of males and females as a part of normal development (Titze, 1989). Overlayed on these normal differences are changes which occur due to the aging process. The age-related structural differences that exist between males and females (see Table 1) yield differences in acoustical and perceptual characteristics of the voice signals. Although the relationship between physiological and aerodynamic measures with acoustical measures is not always predictable, associations between these measures need to be understood and examined in order to explore the route from "production-to-perception". For example, one must examine gross anatomical changes, subsequent physiological changes in functioning of laryngeal muscles and the vibration of tissues, the production of sound, and ultimately, the perception of voice by the listener. The effects of aging on acoustical measures will be examined next as part of the greater "production-to-perception" picture. Again, a review of the literature is required to differentiate between what is normally found in younger male and female adults. The review is followed by a discussion of the effects of "production-to-perception" due to aging.

Effects of Aging on Acoustical Measures

Effects of anatomical and physiological changes in the larynx influence characteristics of the voice. Acoustic features are measured objectively. Specifically, objective measures provide data about physiological events that are affected by vocal fold movement. Studies on age-related effects on the voice include an investigation of the following measures: fundamental frequency (F_o), maximum phonational frequency range (MPFR), short-term microacoustical measures of variability in the glottic signal (e.g., jitter, shimmer, harmonics-to-noise ratio [H/N]) and long-term measures of variability (e.g., standard deviation of fundamental frequency [F_oSD], standard deviation of amplitude [amp SD]), and maximum phonation time (MPT). These measures are not the only ones available for detecting changes in laryngeal function. They do represent, however, measures most commonly found in the literature. As such, a brief summary of each measure and findings related to the aging female voice are presented. Implications for using other measurement variables follow the summary.

Fundamental frequency (F_o). Vocal pitch (the psychophysical or perceptual component) and F_o (the acoustic, physical counterpart) are the vocal parameters studied most extensively related to aging (c.f., Caruso & Mueller, 1997). In general, data show increased F_o in males and a lowering of F_o in females with age (Linville, 2000). More specifically, F_o decreases in males from young adulthood into middle age and then rises again with passage into old age (Hollien & Shipp, 1972; Shipp, Qi, Huntley, & Hollien, 1992). A rise in speaking F_o is observed with advanced age given the muscle atrophy and/or increased stiffness of vocal fold tissue observed in male speakers (Honjo & Isshiki, 1980). The change in F_o among women is less dramatic than that observed among men. Speaking F_o in women remains fairly constant from age 20 until approximately age 50 at which it time drops (Honjo & Isshiki, 1980). The drop in speaking F_o presumably occurs following hormonal changes associated with menopause that result in vocal fold edema (Kahane, 1983). Edema causes increased mass of the vocal folds that contributes to a decrease in F_o. Among the very old (e.g., 90 +), variability of speaking fundamental frequency is quite large. Variability among data sets reflects this heterogeneity (Mueller, 1997).

Maximum phonational frequency range (MPFR). The MPFR is defined as the complete range of frequencies, from lowest to highest, that an individual can produce (Colton & Casper, 1996). Changes occur at both ends of the MPFR in older women, although the age-related changes are not uniform or simultaneous at both ends of the frequency spectrum (i.e., changes at the lower end of the spectrum happen before those changes which affect the upper end of the spectrum, etc.; Linville, 2000). Middle-aged women at menopause display an increased ability to produce lower frequencies than those produced both young adult women and elderly women (Linville, 1987). Changes in frequency production capability that have the greatest impact on total MPFR in women are restrictions which occur at the high end of the range in later life (Linville, 1987). That is, there is a decreased ability to produce higher frequencies (or pitches) as a female ages. The limitation may be associated with weakening of intrinsic muscles, ossification and calcification of laryngeal cartilages, and/or changes in vocal fold mass (Linville, 2000). Later in life, elderly women lose the expanded low frequency range observed in middle age resulting in an overall decrease in MPFR (Linville, 1987).

Results concerning MPFR in men are contradictory. For example, Ramig and Ringel (1983) found that young and elderly men do not differ in MPFR capabilities unless physical condition is considered. That is, for older men in poor physical condition, MPFR capabilities are worse than those of younger male speakers. However, there is no difference in MPFR between the young and older male speakers who are in good physical condition. The loss in MPFR in male speakers, therefore, may not be due to age-related effects, but only to physical condition (see later section entitled, "Health and fitness implications on measures of variability" for further discussion).

Measures of variability. Measures pertaining to the stability of vocal fold vibration (i.e., the regularity of vocal fold vibrations during voice production) are examined often as a function of vocal age because such measures are felt to relate to the regulation and control of voice. Vocal cues that listeners identified as typical of "old" voices suggest increased instability of vocal fold vibration in elderly speakers (e.g., Fowler, 1993; Linville & Fisher, 1985). The instability in vocal fold vibration can be associated with age-related changes in vocal fold tissues (i.e., those associated with changes in epithelium, LP, and the vocalis muscle; Hirano et al., 1983; Kahane, 1987). Measurement of this instability includes both long-term measures (i.e., associated with more gross fluctuations over time) and short-term measures (i.e., cycle-to-cycle fluctuations in vocal fold vibration). A summary of age-related findings measured by both short-term and long-term measures follows.

Short-term measures of variability. Jitter refers to small, cycle-to-cycle changes in the frequency of vocal fold vibrancy, while shimmer refers to cycle-to-cycle perturbations in amplitude (Baken, 1996). At this time, a definitive statement concerning the influence of aging on jitter and shimmer is not possible due to a variety of factors that can interfere with valid and reliable cycle-to-cycle perturbation measurement. Results of current literature reveal several inconsistencies in findings. Factors such as mean sound pressure level (SPL) of phonation (Orlikoff & Kahane, 1991) and mean fundamental frequency of phonation (Orlikoff & Baken, 1990) confound measurements, especially for females. Consequently, results from previous studies examining jitter and shimmer need to be interpreted with caution. For example, Wilcox and Horii (1980) found increased mean perturbation values (i.e., jitter and shimmer) in both older male and female speakers. Linville and Fisher (1985) found that 70- to 80-year old females exhibited higher mean jitter values than younger females. Other studies found no significant differences in vocal jitter values between young and aged women (Brown, Morris, & Michel, 1989). Recent data on age-related changes in jitter and shimmer in male speakers suggest that, as a group, older men display higher levels of both measures when compared to young men (Orlikoff, 1990). The cycle-to-cycle variability in frequency for older male speakers may be associated with the more extensive changes observed in the male larynx as compared with the female larynx (Kahane & Beckford, 1991).

Health and fitness implications on measures of variability. Elderly men exhibit considerably more variability in measures of jitter and shimmer than do young men (Orlikoff, 1990). The increased variability among elderly individuals can be related to individual health and fitness variables. For example, Ramig and Ringel (1983) found significant differences in selected vocal acoustic characteristics between older male speakers of the same chronological age but different levels of physical condition. Level of physical condition was defined by physiological measures of resting heart rate, resting systolic and diastolic blood pressure, percent body fat and forced vital capacity. That is, older speakers in "good" physical condition had significantly better voice quality values (as measured by acoustic parameters) than older speakers judged to be in "poor" physical condition. Further, older speakers in "good" physical condition did not exhibit any differences in jitter values when compared with younger speakers (Ramig & Ringel, 1983). However, older speakers, regardless of physical condition, exhibited higher shimmer values than younger speakers. The differences suggest that shimmer values are not affected by physical condition and may be a good indicator of aging. These results indicate that shimmer values would best be used when compiling normative data on the effects of aging upon the voice (Orlikoff, 1990). Although the effects of fitness level on jitter and shimmer values in female speakers are yet to be explored in detail, Brown, Morris, and Michel (1989) speculated that their inability to find a significant difference in jitter values between young and older female speakers could be attributed to the relatively good physical condition of their speakers. Similarly, Ringel and Chodzko-Zajko (1987) and Sataloff et al. (1997) both suggest that a healthy lifestyle including regular exercise may positively influence laryngeal performance, although they did acknowledge that this association has yet to be definitively established. Thus, effects of physical condition on short-term microacoustical measures (e.g., shimmer) and perceptual measures (e.g., roughness, hoarseness) of the aging female remain a focus for future investigation.

Harmonics-to-noise ratio (H/N). Acoustic measurement of correlates of voice quality involves measurement of the levels of spectral noise in the voice. In this case, spectral noise is defined as the aperiodic noise in the spectra of vowels (Baken, 1996). Spectral noise can be determined using the harmonics-to-noise (H/N) ratio. Normal voices have relatively low levels of noise. Abnormal (i.e., hoarse) voices show greater noise levels compared to normal voices (Baken, 1996). Although there are few data concerning spectral noise in the aging population, Ramig (1983) determined that older male speakers who are in poor physical condition have greater spectral noise (lower H/N ratios) than do older speakers in good physical condition or younger speakers, regardless of physical condition. Fowler (1993) also found a significant difference between older and younger female speakers when comparing H/N ratios.

The utility of the H/N measure to differentiate pathological from normal speakers of young to middle-age was recently demonstrated by Parsa and Jamieson (2000). They found that an enhanced H/N resulted in a classification accuracy of 83.3% (pathological vs. normal speakers). They also demonstrated the usefulness of several other acoustic parameters in classifying overall severity as rated by experienced speech-language pathologists. These parameters include pitch amplitude (PA), the frequency-domain harmonics-to-noise ratio (FHNR; Qi & Hillman, 1997), and the spectral flatness ratio (SFR; Prosek, Montgomery, Walden & Hawkin, 1987), all implemented in a Linear Predictive model as used in the IVANS system (Avaaz, 1997). Older speakers are often rated as having "rough" or "hoarse" voices (e.g., Hartman, 1979). H/N is associated with these perceptual parameters. Therefore, present acoustic methods (Parsa & Jamieson, 2000) may offer a potential way to detect age-related differences, at least for sustained vowel stimuli.

The H/N measure is difficult to apply to connected speech as opposed to voice samples of sustained vowels (Parsa & Jamieson, 2000). However, there are some new methods (Qi, Hillman, & Milstein, 1999) that may aid in obtaining H/N values for more representative speech samples such as conversation and reading. The development of the new methods may make connected speech samples more representative of everyday speech and provide different and more representative acoustic values than those obtained from sustained vowel stimuli (e.g., see Britto & Doyle, 1990 for a discussion of habitual pitch). As such, using methods defined by Qi et al. (1999), the H/N value could be used to determine the effects of aging in samples of connected speech. In summary, H/N measures are associated with "hoarseness" (e.g., Michel & Wendahl, 1971) which is a common characteristic of many elderly voices (e.g., Hartman & Danhauer, 1976). The H/N measure may provide a valuable index of aging effects in both the male and female voice and for providing normative threshold or cut-off values.

Long-term measures of variability. Measures of standard deviation of fundamental frequency (F_oSD) and standard deviation of amplitude (amp SD) are stability measures that reflect more gross fluctuations in vocal fold vibration over time. These measures generally increase with advancing age in both men (Orlikoff, 1990) and women (Linville & Fisher, 1985). Current evidence suggests that F_oSD measures may be a better predictor of vocal age than jitter (Linville & Fisher, 1985; Orlikoff, 1990). Amplitude SD also increases with advancing age in male speakers (Orlikoff, 1990). Longer-term measures predict vocal age more accurately than short-term measures. This pattern suggests age-related processes may be more easily detected in the slowly varying components of the temporal pattern of speech. Slowly-varying components are more prominent in connected speech (Baken, 1996). These are contrasted by the rapidly varying temporal features found in vowel segments (i.e., those segments most often measured by short-term measures such as jitter, shimmer and H/N).

Age-related effects of both subglottal and supralaryngeal systems also influence the regularity of both pitch and intensity measures. For example, variability in vocal fold vibration is affected by alterations in reduced pulmonary function such as reduced vital capacity (Kahane, 1981), reduced reserve volumes (Hollien, 1987), and airflow rates (Chodzko-Zajko & Ringel, 1987). Further, aging effects on the coordination of the oral subsystem with the laryngeal mechanism can have problematic "downstream effects" on damping of vocal fold vibration (Linville, 2001). Therefore, not only are long-term measures affected by changes in vocal fold vibration but they also are influenced by both subglottal and supralaryngeal factors. These effects must be considered when establishing the causal mechanism in how age-related processes are detected by long-term acoustic measures.

Linville, Skarin, and Fornatto (1989) explored the interrelationship among various measures related to vocal function, speech rate, and laryngeal appearance in elderly women (n = 20, age range, 67-86 years). They found that maximum phonation time (MPT) was related to pitch range measures (r = -.36 with high pitch, r = -.35 with semitones in range, and r = .30 with location of modal in total pitch range). They also noted that this relationship could be accounted for by the dependency of both measures on laryngeal functioning. Both values (MPT and pitch) can be affected by age-related changes in the larynx such as muscle weakening, calcification of the joints, etc. Further, Linville et al. (1989) found a relationship between MPT and intensity measures (r = -.48 with minimum intensity, r = .38 with intensity during reading). Both of these measures are dependent on respiratory functioning, which also undergoes age-related changes such as muscle weakening and reduced elasticity of lung tissues (Kahane, 1981). Thus, it is clear that physiological functioning of subglottal and laryngeal mechanisms are related with acoustic measures. Differences are found in physiological functioning of the voice production system between younger male and female speakers. Additionally, differential effects are found due to age-related effects between sexes. Therefore, it is clear that the relationships between physiological and acoustic measures of voice must be explored separately for males and females. Separate explanations will aid in generalizing the effects of the aging process to the whole population, including speakers of all ages and both sexes.

Maximum phonation time (MPT). MPT is measured by having someone inspire and expend the maximum amount of air during phonation of a prolonged vowel (Colton & Casper, 1996). Data indicate that MPT values for both elderly men and women are reduced significantly when compared to those of younger persons (Baken, 1996). For example, based on averaged data, MPT for normal male and female adults is about 30 seconds and 24 seconds, respectively (Baken, 1996). There is, however, considerable variability in maximum performance tests (Kent et al., 1987). MPT values are reduced in older subjects. For example, MPT values range from 14.6 to 18.1 seconds for males, and from 14.2 to 14.6 seconds for females (Linville, 1996). The reduction may reflect the reduced integrity of the glottal valve/vocal folds to impede airflow (i.e., air escapes due to an inability to fully close the vocal folds). It also may reflect reduced respiratory support (lung capacity) associated in normal aging. Unfortunately, MPT does not differentiate between the relative contributions of valve integrity vs. respiratory support (Kent et al., 1987).

Relationship of Acoustic Measures with Perceived Age

Not all acoustic information influences perceived age judgments even though the acoustic values might represent significant differences between young and older speakers. Morris and Brown (1987) investigated the effects of aging on various voice parameters using two groups of 25 women (a younger group, 20-35 years, and an older group, 75 years +). Although they found younger females evidenced a greater intensity range, they also found that conversational intensity was similar for both younger and older speakers. Physiologic changes did not seem to affect performance of an everyday activity, but did influence measures of maximum performance. Similarly, Linville and Fisher (1985) did not find any evidence that jitter is associated with perceived age, even though 70- to 80-year old females exhibited higher mean jitter values than did younger females. Since physical condition was not considered in this study, results must be interpreted with caution. Even though jitter is associated with voice quality features such as "roughness", these results indicate that vocal roughness is not a particularly meaningful perceptual cue to the vocal age of women. However, since shimmer may be a more sensitive indicator of vocal roughness than jitter, this finding suggests shimmer is more meaningful to determine voice quality correlates (Ramig & Ringel, 1983).

A comprehensive voice assessment that includes acquisition of both long- and short-term measures may best reflect the overall aging process on the voice mechanism. Long and short-term measures may answer the relative contributions of the two processes of aging (e.g., DNA damage and telomere-shortening) on the structures of the larynx. Determining the differential influences of the two aging processes can be accomplished if: a) differential effects on different tissue types (e.g., DNA damage associated with neuromuscular tissue vs. telomere-shortening effects on connective tissue such as the LP) were definitively established, and if b) functional changes could be definitively associated with structural changes. Additionally, the fact that variable acoustic results are observed for both aging male and female speakers suggests that normative data need to be gathered for both the age and sex of the speaker. Finally, it is critical that the actual perceptual correlates are determined. If an acoustic measurement (e.g., jitter) is not valuable in defining age (Linville & Fisher, 1985), then it is not a sensitive or valid measurement of the aging process for the listeners or speakers. It is most important that the auditory-perceptual features associated with acoustic measures of the aging process on the voice be identified. These features are examined in the next section.

Effects of Aging on Perceptual Measures

A number of factors are reported to affect listener accuracy in perceiving age from voice. Young listeners are reported to be more accurate in their age perceptions than elderly listeners (Huntley, Hollien, & Shipp, 1987; Linville & Korabic, 1986). Female listeners also are reported to be more accurate than male listeners (Hartman, 1979). Other influences such as age and race of speaker may affect age identification (c.f., Linville, 2000). Such factors must be taken into account before determining how accurate listeners can be when perceiving the age of a speaker.

Kreiman, Gerratt, Kempster, Erman, and Berke (1993) proposed a conceptual framework for voice quality perception and suggest that when listeners rate a dimension of voice (e.g., roughness, hoarseness, etc.) they compare the stimulus to internal standards. Internal standards for vocal quality vary according to the listeners' experience with voices, individual perceptual habits, and perceptual biases (Kreiman, Gerratt, & Precoda, 1990; Kreiman, Gerratt, Precoda, & Berke, 1992), and presumably, the overall sensitivity of the dimension being judged. Auditory-perceptual methods may represent the "best" means of assessment (Kent, 1996), particularly if potential sources of error and bias are considered. Factors for consideration include developing a common understanding of perceptual labels (Reed, 1980), consistent use of descriptors and associated scale values, and intra- and interrater reliability (Kearns & Simmons, 1988). However, descriptors for the aging voice are not uniformly accepted. This represents an area of difficulty for comparing the results of studies. This also is a problem with auditory-perceptual study of voice in general, and is not limited to aging effects on the voice. For example, what one study measures as "rough" may not equate with another study of voice which measures "roughness". The lack of descriptors and associated acoustic correlates is especially apparent for studies involving the aging female voice. Scales (e.g., equal-appearing interval scales vs. direct magnitude estimation scales) are often not used appropriately for measuring particular features (c.f., Schiavetti, 1984), yielding results that are often questionable. These factors must all be taken into consideration before interpreting results of past studies and before new research designs are implemented.

Despite much variability between individuals, there are reliable patterns that are known about the auditory-perceptual features of age-related effects on the voice. Most studies of auditory-perceptual features focus on male speakers. For example, Hartman and Danhauer (1976) examined listeners' perceptual repertoires and found that pitch, quality, articulation and rate of speech are predominant features for characterizing the ages of 46 males between the ages of 25 and 70 years (see Table 1). Hartman (1979) examined the perceptual characteristics of the same subjects and found that pitch, quality, articulation and rate of speech are used by judges to approximate an individual's age. Hartman (1979) found that younger male speakers are best identified with rapid rate of speech, high pitch, precise articulation, and clear voice quality. In contrast, low-moderate levels of pitch, precise articulation, and clear quality are used to identify middle-aged male speakers, and low pitch, hoarseness, slow rate, imprecise articulation, breathiness, and long pauses characterized the speech of older male speakers. These findings suggest that listeners are able to differentiate between speakers of different ages based on perceptual features alone.

Other studies also examined listeners' abilities to perceptually identify age from the voices of male speakers. For example, Ptacek and Sander (1966) reported that listeners are 99% accurate identifying old from young speakers from reading passages played forward, 87% from reading passages played backward, and 78% from phonated vowel productions. When asked to judge age directly from reading passages, correlations of perceived age and actual age ranged from 0.88 to 0.93 (Hartman, 1979; Ryan & Capadano, 1978; Shipp & Hollien, 1969). Ryan and Burk (1974) reported that perceptual features such as voice tremor, laryngeal tension, air loss, imprecise consonants, and slow rate of articulation are strong predictors of the perceived age of males who are between the ages of 40 and 80 years. Thus, with adequate perceptual information and carefully selected assessment features, listeners are quite accurate at identifying the age of older male speakers.

In one of the few studies focussing on the female voice, Linville and Fisher (1985) obtained sustained vowel samples from 75 women divided into three age groups: 25-35, 45-55, and 70-80 years. Twenty-three listeners were asked to identify speakers as young, middle-aged, or old. Acoustic analysis was performed on a 1-sec segment from the mid-portion of speakers' vowels and included calculation of the mean F_0, F_0SD, and jitter ratio, as well as the first and second formant frequencies. Listeners were also asked to judge the age of the speaker's sample of a whispered vowel (Linville & Fisher, 1985). Acoustic analysis of the whispered vowel only included formant analysis. Results indicated that older age judgments based on the phonated vowels are significantly associated with higher F_0SD values and lower mean F_0 values (i.e., F_0SD increased and F_0 decreased with age). More specifically, Linville and Fisher (1985) found that listeners are 51% accurate identifying age from phonated vowels and 43% accurate from whispered vowels, suggesting that as less acoustic information is available in the signal and the task becomes more difficult for listeners, accuracy rates drop. Listeners in this study were highly influenced by speaking F_0 to determine perceived age of the speakers. This is evidenced by the higher accuracy rates in judging age from phonated vowels in comparison with whispered vowels. However, it is significant to note that identification is not reduced to a random chance occurrence even when judging age from samples devoid of voicing information, such as whispered vowels. Therefore, in the absence of fundamental frequency, listeners can make use of resonance information (i.e., formant frequencies and relationships between formants), although this information did not provide as much detail as the voiced stimuli (i.e., phonated vowels). In light of the increased accuracy found in perceiving age from longer stimuli such as sentences for male speakers (e.g., Ptacek & Sander, 1966), exploration of these differences for female speakers is not only interesting, but is of extreme clinical importance.

It is clear that a focussed attempt to establish a critical set of auditory-perceptual features for the aging female voice is vital to evaluate comprehensively changes associated with aging. It also is crucial to differentiate this process from psychopathological changes in the voice. However, there first must be agreement among researchers in the use of consistent descriptors of aging voices. Secondly, correlates of acoustic measures must be investigated using representative samples of speech and appropriate measurement scales.

Clinical Implications

There are several conclusions that can be made concerning the literature regarding age-related processes on the voice. Firstly, normal differences exist between males and females due to gross anatomical and refined physiological differences in the laryngeal mechanism. Secondly, there are different effects in the aging process on the laryngeal structures of male and female speakers. Both normal anatomical and physiological changes as well as changes related to the aging process result in unique acoustical and perceptual profiles. These results support the need to develop separate normative databases for both sexes. Finally, sensitive acoustic measures and their potential perceptual correlates need to be established for the female voice because most studies only have focussed on age-related processes for males. The sex-based bias suggests that it is vital that characteristics specifically associated with aging females need to be obtained in order to help clinicians appreciate normal characteristics of the aging female voice. Establishing normative data would aid in clinicians' ability to differentiate voice characteristics associated with the normal aging process from the voice characteristics of those with disease, hyperfunction, or psychopathology. Earlier recognition of age-related disorders of voice also would aid prompt intervention or counselling by a speech-language pathologist, and, in turn, improve the quality of life for the individual affected by age-related dysphonia.

Morrison and Gore-Hickman (1986) highlighted the importance of differentiating age-related disorders of voice from voice characteristics associated with disease, etc., with respect to clinical application. Of 1000 patients seen at the University of British Columbia/ Vancouver General Hospital Voice Clinic over a five-year span, 121 patients were 70 years of age or older. Of this group, over half had cancers of the pharynx and larynx. To put this in perspective, carcinoma of the larynx is estimated to account for less than 5% of all malignancies that are identified in the human body (Norante & Rubin, 1978). Thus, the population seen at voice clinics in general (Morrison & Gore-Hickson, 1986; Woo et al., 1992) may exhibit bias in that there is an increased prevalence of disease among older adults who seek voice treatment. These patients typically suffered from dysphonia due to disease processes associated with aging (e.g., neurological disease, vocal fold lesions, inflammatory disorders, laryngeal paralysis, etc.) rather than to normal physiological aging alone (Woo et al., 1992). These results also suggest that due to an increased prevalence of malignancy in older people, there is an increased risk of identifying clinically-significant changes as aspects of normal aging. Findings from both Morrison and Gore-Hickson and Woo et al. support the development of a normative basis of voice to help screen for changes related to aging as opposed to other sources of change (e.g., neurological, malignancies, etc.). Morrison and Gore-Hickman also found that functional dysphonias are mostly the result of misuse and abuse of the voice which may result from compensation for age-related changes. Although Woo et al. (1992) suggest that presbylarynges is not a common disorder (accounting for about 4% of 151 patients aged 60+), they also highlight the importance of ruling out other more serious voice diagnoses. More recently, Hagen, Lyons, and Nuss (1996) found presbylaryngis accounted for 30% of new diagnoses among 47 patients over age 60. These results suggest that this difficulty is more prevalent than previously noted (Woo et al., 1992). However, no matter the actual incidence levels, both Woo et al. (1992) and Hagen et al. (1996) emphasized the need for the "health care professional to tailor the therapeutic goals to the patient needs rather than to an apriori image of 'good' voice" (Woo et al., 1992, p.143).

Additionally, it is critical that the relationships between the laryngeal system and the subglottal and supralaryngeal systems are determined to establish the best approach for intervention. For example, Caruso, Mueller, and Xue (1994) suggested that some articulatory patterns can compensate for and/or offset age-related changes in the voice. However, other therapeutic approaches (e.g., pushing exercises, relaxation, digital manipulation, vocal hygiene, etc.; Mueller, 1997) are more often used for older adults who obtain speech-language pathology services for age-related voice difficulties. The importance of understanding age-related processes also is highlighted by Shadden (1988) who suggests that "communication serves as an important tool in successful adaptation to aging while simultaneously being vulnerable to alteration and decrement due to the same aging processes" (p.10). Both clinical intervention and research must address the communication needs and behaviours of the older adults to promote the overall physical, mental, and social well-being of all individuals in an increasingly aging society.

Challenges for the Future

The main emphasis for studies that focus on the aging female voice is on physiological (e.g., Biever & Bless, 1989; Honjo & Isshiki, 1980; Titze, 1989), and acoustic measures (e.g., Brown et al., 1989; Linville & Fisher, 1985; Linville et al., 1989, etc.). However, caution must be employed when using acoustic measures to establish a normative database due to the extreme performance variability among older adults. For example, Linville and Korabic (1987) examined fundamental frequency stability characteristics in older women, and reported high variability of the F_0SD and jitter measures within the group. The variability also is reflected in acoustical measures of age-related processes in male speakers (e.g., Orlikoff, 1990). Ringel and Chodzko-Zajko (1987) highlighted this characteristic in stating that "one of the most robust findings in aging research is the extreme individual variation with which motor performance decline occurs. Both intraindividual variability (individual inconsistency in performance) and interindividual variability (group heterogeneity) increase with age" (p. 31). Their observation led to additional studies by Ringel and associates (Ramig & Ringel, 1983; Ringel & Chodzko-Zajko, 1987) who addressed the existence of possible relationships between overall physiological status and vocal performance.

Therefore, several measures may be required as part of the standard voice assessment protocol. Further, these measurements must be validated (Kent, Kent, & Rosenbek, 1987) such that the values gathered are truly representative of the performance of older individuals. Thus, comprehensive assessment of the voice requires an approach in which assessment measures multidimensional aspects of voice production. A multidimensional approach also gives the prudent clinician the awareness to resist the temptation to apply all available normative data to all elderly individuals.

Linville and Korabic (1986) noted a difference between different types of vowels used by older subjects in data collection procedures. Different vowels used as stimuli may affect the objective measures of voice. Observed variability in stimulus production may lead to the use of longer and more representative samples, such as connected speech, to establish valid norms. The use of connected speech samples is supported by the work of Ramig (1986) who suggests that listeners are more accurate in their ratings of age from connected speech than sustained vowel phonation, possibly because of the additional physiological and linguistic information provided in a connected speech sample. Britto and Doyle (1990) also suggest that information garnered from connected speech versus vowels can provide more valid measures of habitual pitch. Zeplin and Kent (1996) found that listeners place different importance on perceptual features according to stimulus type (e.g., syllable repetition, passage reading, and vowel prolongation). Therefore, a representative stimulus type must be considered for use in both standard assessment and research protocols. Including both short and longer stimuli and using both short- and long-term objective (and perceptual) measures will produce the best overall measure of aging in the vocal mechanism. Increased sensitivity and validity of these measures (e.g., Parsa & Jamieson, 2000) will ultimately help identify older individuals with and without voice impairments and will help to establish more effective treatment goals and discharge criteria.

Perceptual studies of the aging female voice generally examine relationships between perception and age prediction. However, most studies of the vocal production of older women did not include the description of explicit perceptual dimensions associated with the older female voice, unlike studies which described features for male voices (e.g., Hartman, 1979; Hartman & Danhauer, 1976; Ryan & Burk, 1974). It is vital that perceptual phenomena are linked with sensitive acoustic measures so that clinicians can monitor changes in performance to aid diagnosis and the effectiveness of interventions. It is clear that studies delineating perceptual features in the female voice are crucial to help establish a normative database, as auditory-perceptual cues often represent the final validation in clinical decision-making (Kent, 1996). More critically, common descriptors of aged voices (and all other voice disorders) as suggested by Reed (1980) need to be established so that results can be compared across studies and across treatment centres and clinics.

There is great importance placed on auditory-perceptual judgments in clinical decision-making (Gerratt et al., 1991). It is vital, therefore to obtain perceptual measures that are valid and representative (Kent, 1996). Perceptual changes do not always correlate with acoustic measures. It is important, therefore to examine the variability in both acoustic and perceptual measures to determine which features are actually associated with perceived age estimates. The importance of establishing a normative database using all measures (physiological, acoustical, and auditory-perceptual) in voice quality assessment is highlighted by Colton and Estill (1981) who state that "physiologically, one must examine the source characteristics and the transfer function of the system... It also supposes an adequate description of the significant acoustic features. But it demands first an exploration of the salient perceptual dimensions" (p.319).

With the steady increase in the older population in North America, one can anticipate a growing number of individuals seeking to maintain effective vocal communication for as long as possible. Acoustic and perceptual examination of the characteristics of the female voice are not well explored. They represent areas of great challenge and opportunity for future research. Promoting a multidimensional approach with known anatomical, physiological, acoustical and perceptual data will help provide the best and most appropriate information and health care management to aging females who express concerns about their voice.

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Acknowledgments

I would like to thank Dr. Tony Vandervoort for helping me to understand the broader implications of aging in motor function and for his helpful suggestions in the organization of my paper, as well as for offering his perspective on general theories of aging. I would also like to thank my supervisor, Dr. Philip Doyle, for his support and input into the editing of my paper. I also wish to express my appreciation to Dr. J.B. Orange and those who reviewed an earlier version of this paper for their helpful comments.

Manuscript received May 22, 2000
Accepted December 3, 2000

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