DESIGN OF AN INTRAORAL ARTIFICIAL LARYNX SYSTEM FOR THE SPEECH REHABILITATION OF TOTAL LARYNGECTOMEES

by

İmran Göker

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APPROVED BY:

Doç. Dr. Mehmed Özkan ....
(Thesis Supervisor)

Doç Dr. Fikret Gürgen ....

Doç. Dr. Yasemin P. Kahya ....

DATE OF APPROVAL:

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ABSTRACT

The cancer of larynx is treated with a surgical method called total laryngectomy whether it is diagnosed in the later stage of the disease. In this procedure, the larynx and the vocal cords are removed. Consequently, these patients are loosing their voice and their ability of speech production.

The aim of this study is to establish an intraoral artificial larynx system that will produce vibrations at the fundamental frequency of the vocal cords and which will be worn easily as a dental prosthesis to provide a speech rehabilitation method to the laryngectomees.

The circuit of this system is first setup on a breadboard. A prototype of that system is manufactured using micro-components and mounted in a dental prosthesis.

To establish clinical studies and to compare with electrolarynx, two other prototypes individual to each patient are manufactured and applied to two total laryngectomees. These patients are trained to perform exaggerated articulation while using the intraoral artificial larynx system. Audio records are taken while the patients are reading text materials using both electrolarynx and the system. These records are listened by twelve testers which, are requested to write what they understood on a form prepared for this purpose. According to the results gathered from the testing process, the average success percentages are calculated for both system to compare both of them.

This study shows that even though the performance of that system is lower than that of electrolarynx, it may be used as a speech rehabilitation method provided that some technical improvements are accomplished.

Keywords: Speech Rehabilitation, total laryngectomy, laryngeal cancer

TOTAL LARENJEKTOMİLİ HASTALARIN SES REHABİLİTASYONU AMAÇLI BİR İNTRAORAL YAPAY LARENKS SİSTEMİ DİZAYNI

ÖZET

İleri evrelerde tanısı konmuş larenks kanseri vakaları, total larenjektomi adı verilen bir cerrahi yöntemle tedavi edilmektedirler. Bu cerrahi işlem sonucu larenks ses telleri tamamen çıkarılmaktadır. Bunun sonucunda hastalar konuşma yetilerini kaybetmektedirler.

Bu çalışmanın amacı, ses tellerinin temel titreşim frekansında sesler üreten ve hastalar tarafından kolayca bir diş protezi gibi kullanılabilecek ve total larenjektomili hastalara ses rehabilitasyonu sağlayabilecek bir intraoral yapay larenks sistemi oluşturmaktır.

Sistemde kullanılan elektronik devre bir deneysel montaj kartı üzerine kuruldu. Daha sonra devre elemanlarının mikro komponentleri kullanılarak bir prototip imal edildi v bir diş apareyi içine monte edildi.

Klinik çalışmalarda kullanılmak ve elektrolarenks metoduyla karşılaştırmak için iki adet yeni hastalara özel, prototip imal edildi. İki adet total larenjektoımili hastaya uygulandı. Bu hastalar söz konusu sistemi kullanırken uygulamak üzere abartılı artikulasyon yapmak için eğitildiler. Hastalar hem elektrolarenksle hem de söz konusu sistemle metinler okurken ses kayıtları alındı. Daha sonra bu kayıtlar on iki kişilik bir dinleyici grubuna dinletildi ve bu amaçla hazırlanmış bir form üzerine anladıklarını yazmaları istendi. Bu test aşamasından elde edilen sonuçlara göre hem elektrolarenks hem de söz konusu sistem için ortalama başarı yüzdeleri hesaplandı.

Bu çalışma sonucunda elektrolarenks göre az bir farkla düşük performans göstermesine rağmen bu sistemin teknik bir takım iyileştirmelerden sonra bir ses rehabilitasyon metodu olarak kullanılabileceği öngörüldü.

Anahtar sözcükler: Konuşma rehabilitasyonu, total larenjektomi, larenks kanseri

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A	Cross-sectional area of the vocal tract
B_n	Bandwidth of frequencies of resonance for each vocal cavities
c	Velocity of sound in air
C_a	Acoustic Compliance
CLK	Clock
CT	Cricothyroid Muscle
CTJ	Cricothyroid Joint
DLI	Depressor Labii Inferior Muscle
EL	Electrolarynx
ES	Esophageal Speech
f_0	Fundamental Frequency of the Vocal Cords
F_n	Frequency of each resonance of vocal cavities
G_a	Acoustic Conductance
GG	Genioglossus Muscle
H(s)	Acoustic Transfer Function of the Vocal tract

HPV	Human Papilloma Virus
IA	Interarytenoid Muscle
IAL	Intraoral Artificial Larynx
IC	Inferior Constrictor Muscle
IL	Inferior Longitudinal Muscle
L_a	Acoustic Inertance
LCA	Lateral Cricoartenoid Muscle
MAS	Masseter Muscle
MC	Medial Constrictor
OO	Orbicularis Oris
PCA	Posterior Cricaarytenoid Muscle
R_a	Acoustic Resistance
s	Complex frequency Variable
SC	Superior Constrictor Muscle
SL	Superior Longitudinal Muscle
SMD	Surface Mounting Device
TA	Thyroarytenoid Muscle

TEM	Temporalis Muscle
TEP	Tracheoesophageal Prosthesis
VC	Vocal Cords
Z_a	Acoustic Characteristic Impedance
η	The ratio of specific heat at constant pressure to that of constant volume
λ	Thermal Conductivity
μ	viscosity of air
ρ	Density of air
σ	Real part of the complex frequency variable
ω	Frequency

1. INTRODUCTION

Speech is the principal means of communication of human beings. It also distinguishes them from the other life forms and is dispensable to accomplish social interactions with other people [1].

Cancer of larynx is a malignant disease considerably encountered in the Head and Neck Surgery clinics. Radiation therapy may be effective for the earlier stage lesions with a little destruction in voice quality [2]. Total laryngectomy (i.e. surgical removal of the larynx), however, is inevitable in all malignant tumors which, do not respond to conservative laryngeal surgery or radiation therapy due to their positions or extensions for the survival of the patients [3], [4]. Unfortunately, the patients lose their abilities of speech production and, therefore, the possibility of vocal communication. Since language expressed through speech is a fundamental characteristic of human communication, the loss of vocal communication severely disrupts normal patterns of interaction with others and results in serious social and psychological changes, which lead to social isolation [5]. For this reason, many different methods have been developed for the postoperative voice rehabilitation since Billroth established the first laryngectomy in 1873 [6], [7].

There are several methods developed and applied to provide voice restoration of the patients after total laryngectomy, and to meet their communication needs. Current applications are mainly focused on:

i) Esophageal Speech

ii) Tracheoesophageal Prosthesis (TEP).

iii) Electrical and pneumatic artificial larynges [2], [5], [8], [9].

Although it provides the laryngectomees to generate natural sound during speech production, esophageal speech requires the patients a long -training time to master with it. Moreover, since they use esophagus as an air reservoir [10], that has very small volume compared to the lungs, the laryngectomees have difficulties to achieve a continuous speech with esophageal speech. So, most of the patients do not prefer that method.

Tracheoesophageal Prosthesis (TEP) provides also a fluent speech with natural sound. On the other hand, due to the humidity of that medium, fungal colonization that disturbs the function of the prosthesis occurs. Therefore, these prostheses have to be replaced by the new ones with a period of three months [11]. In addition, some clinical problems such as granulation formation, hypopharyngeal stenosis, dysphasia may be encountered [12].

Patients who cannot develop esophageal speech usually prefer to use the electrolarynx that is a battery-powered vibrator [13]. The major problem with this method is to find correct location to achieve an efficient speech [2]. On the other hand, since these electrolarynges are hand-held, the laryngectomees cannot use both hands during the speech production with this method. There are also pneumatic devices using expired air in order to vibrate a reed such as the "Tokyo Artificial Larynx" [9]. However, they are not commonly used [2].

The aim of this study is to design a prototype of a sound generator device which will be mounted on a dental prosthesis and which may be worn easily without going to an outpatient clinic. After the design and the setup stage, the system will be applied to the laryngectomees and will be compared with an accepted speech rehabilitation method such as electrolarynx to test the performance of this Intraoral Artificial Larynx.

2. ANATOMY OF THE SPEECH PRODUCTION

2.1. Anatomic Structures Playing Role in Speech Production:

The human vocal system may be divided into three components according to their functions as shown in Figure 2.1.

1) The subglottal system
2) The larynx
3) The supralaryngeal vocal tract [14].

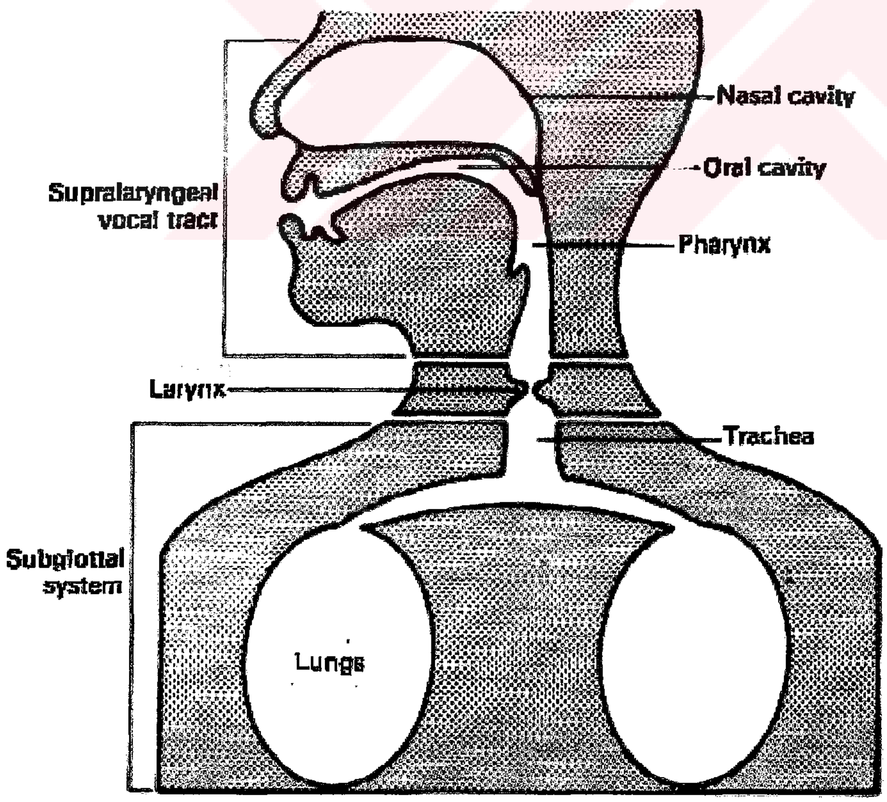


Figure 2. 1. The Physiologic Components of human speech production

2. 1. 1. The Subglottal System:

The subglottal system which, has also the respiratory functions, consists lungs and trachea (windpipe). The intercostal muscles and the abdominal muscles that, are illustrated in Figure 2.2. are the auxiliary structures. They expand the rib cage both in speech production and respiration [14]. The trachea connects the subglottal system to the larynx [14], [15].

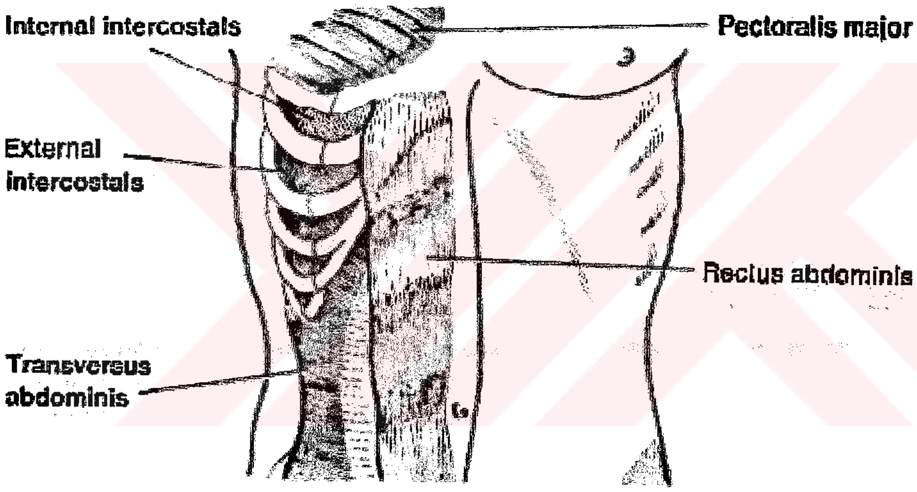


Figure 2. 2. The auxiliary structures of the respiratory system

2. 1. 2. The larynx:

The larynx that is also called " vocal box " is located between the level of fourth and sixth cervical vertebra. The upper part of the larynx is connected to lower part of the pharynx (laryngopharynx) and attached the hyoid bone. The lower part of the larynx is connected to the subglottal system via the trachea. The anatomy of larynx is sketched in Figure 2.3. [15].

The main task among the three important laryngeal functions is to provide an airway. It also acts as a switching mechanism to lead air and food into the convenient channels such as trachea and esophagus [15]. Due to the fact that it houses the vocal cords, the third function of the larynx is voice production to accomplish the phonation [15], [16].

The larynx is a complex musculocartilogenous structure [17], [18]. Its framework is mainly made of nine cartilages connected by membranes and ligaments: thyroid cartilage, cricoid cartilage, epiglottis, and pairs of arytenoids, cuneiforms and corniculates. These pairs of cartilages constitute the posterior and the lateral walls of the larynx [15], [18]. Thyroid cartilage or Adams's apple being the largest cartilage of the larynx is prominent in adult human males [18], [19].

Epiglottis being located between the posterior part of the tongue and the anterior part of thyroid cartilage is important to accomplish the second function of the larynx. While swallowing, the larynx is pulled superiorly and epiglottis tips to cover the laryngeal inlet in order to prevent the food to pass to the respiratory system [15]. These structures are illustrated in Figure 2. 3.

Since they produce sounds via their vibrations, the vocal cords or the vocal folds are playing the main role in phonation. They consist of opposite ligaments forming a constriction where the trachea is joined to the lower part of the vocal tract [15], [20]. These ligaments forming the core of the vocal cords are under the laryngeal mucosa and attach the arytenoid cartilages to the thyroid cartilages [14], [15]. These ligaments are composed of elastic fibers. The cover of the vocal cords is composed of elastin and fibers.

On the other hand, the body of the vocal cords is made up by the muscle fibers of thyroarytenoid (TA) muscles [14], [19], [21].

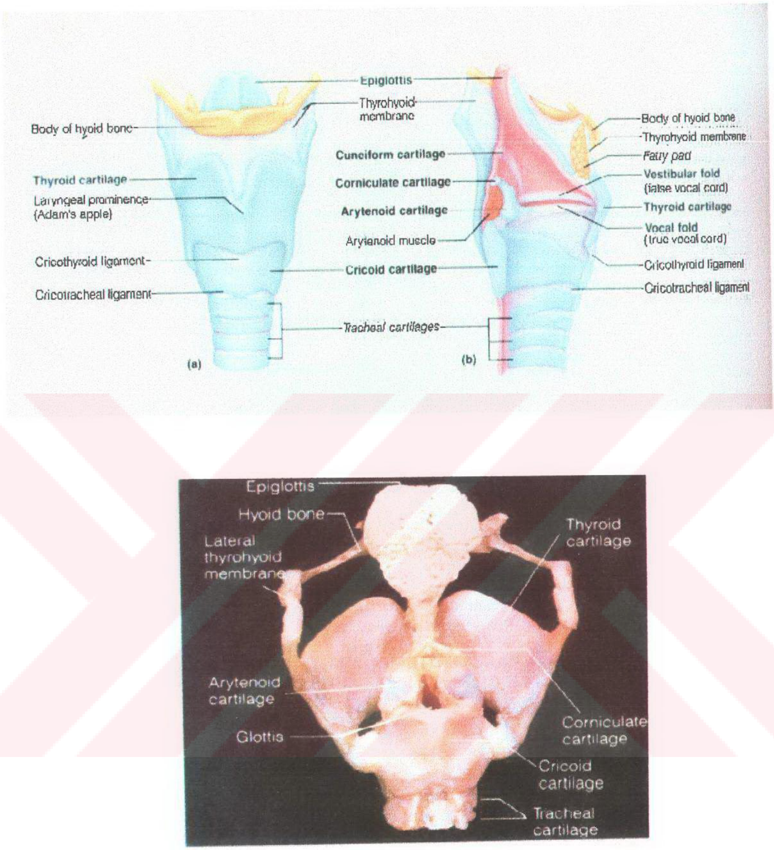
The medial opening between the vocal cords where the expelled air passes is a slit-like orifice and called "rima glottidis" or "glottis" [14], [15], [18], [20], [22]. The opening and closing procedures of the glottis and the adjustment of the vocal cords are achieved by the contraction of the intrinsic muscles of the larynx shown in Figure 2. 4. during the phonation [23].

The thyroarytenoid muscles (TA) extending from the inner surface of the thyroid cartilage to the lateral surface of the arytenoid cartilage constitute the body of the vocal cords via its medial fibers [14], [19], [24]. While contracting, they pull the arytenoid cartilages to the thyroid cartilage, and then the tension of the vocal cords is decreased [14], [24]. The thyroarytenoid (TA) muscles are playing role in the adduction of the vocal cords [25].

The posterior cricoarytenoid (PCA) muscles lying between the posterior surface of the cricoid cartilage and the arytenoid, are the only abductors of the vocal cords. They are also only muscles that open the glottis [14], [19], [24], [25], [26].

The lateral cricoarytenoid (LCA) muscles go between the arch of the cricoid cartilage and the muscular process of the arytenoid cartilages. When they are tense, they apply a medial compression to adduct the vocal cords. As a result, the vocal cords are moved toward the midline to close the glottis [14], [19], [24].

The interarytenoid (IA) muscle, which is the only unpaired intrinsic muscle of the larynx, is lying between the arytenoid cartilages. When it contracts, the arytenoid cartilages are brought together. It functions in combination with the LCA muscles to adduct the vocal cords. Thus, the glottis is closed [14], [19], [24].



(c)

Figure 2. 3. Anatomy of the larynx : (a) anterior superficial view. (b) Sagittal view, anterior surface to the right. (c) The cartilaginous framework of the larynx, posterior view

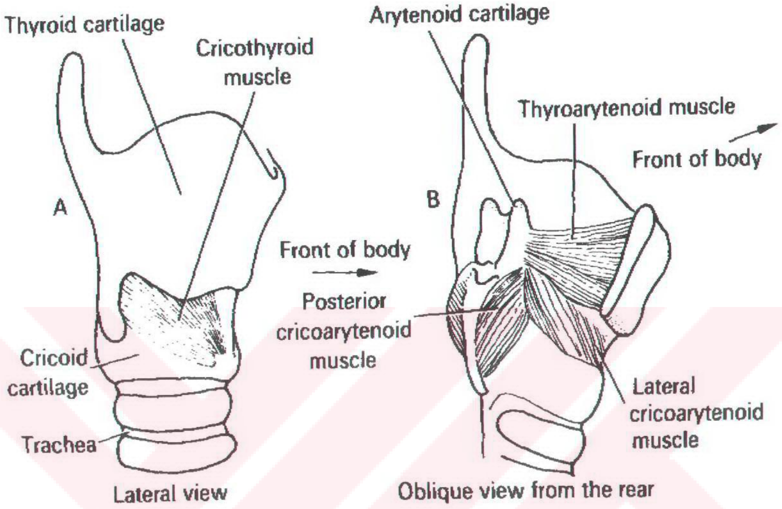


Figure 2. 4. The muscles of larynx playing role in speech production

The cricothyroid (CT) muscles extend from the arch of the cricoid to the lower border of the thyroid cartilage. The activity of the CT muscles causes a movement at the cricothyroid joint (CTJ) that brings the cricoid and the arytenoid cartilages together [24], [27]. This activity increases the longitudinal tension of the vocal cords [14], [24], [28].

2. 1. 3. The Supralaryngeal Vocal Tract:

The supralaryngeal vocal tract illustrated in Figure 2.5. lies between the vocal cord constriction and the lips. It consists of some resonant cavities such as pharynx, oral and nasal cavities and the articulators such as lips, tongue, velum, and jaw [22].

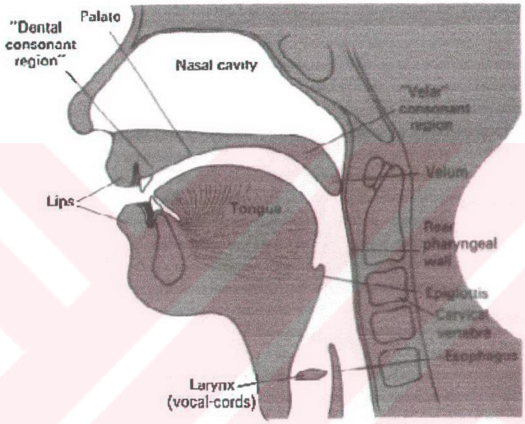


Figure 2. 5. Supralaryngeal Vocal Tract

The pharynx is extending from the base of the skull to the sixth vertebra. It connects the nasal cavity and mouth to the larynx inferiorly. It serves as a common pathway for food and air [14], [15]. The pharyngeal constrictor muscles; superior constrictor (SC), medial constrictor (MC), inferior constrictor (IC), are playing role not only during swallowing but also in the production of the wovel sounds like [a] [14]. Figure 2. 6. illustrates these muscles.

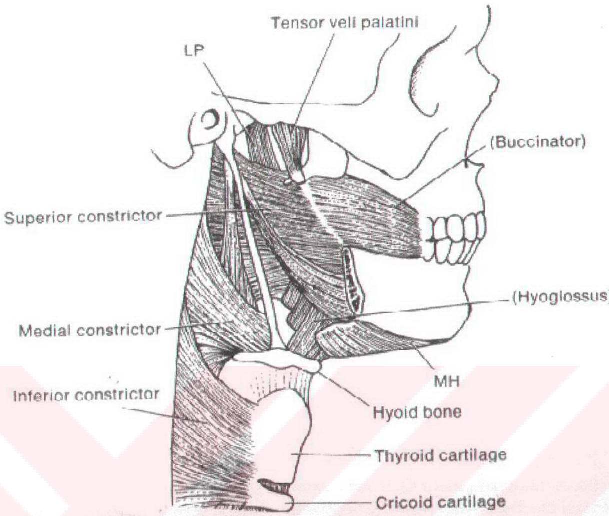


Figure 2. 6. The pharyngeal constrictor muscles.

The palate forming the roof of the mouth has two distintc parts. The hard palate being located at the anterior part of the palate is made of bones. It provides rigid surface against the forces of the tongue either in speech or chewing. The posterior part of the palate is the soft palate or velum, which consists of skeletal muscle. During the respiration, it falls downward to connect the nasal cavity to the pharynx and the larynx. During the speech production, it moves upwards to seal the nasal cavity from the oral cavity to generate oral sounds [14], [15].

The tongue occupying the floor of the mouth is an articulator in speech production. It does not only contribute the production of consonant sound by accomplishing constrictions but also helps to adjust the harmonics of the voiced sounds via its ability of humping in different configurations [14], [15]. The muscles controlling the movements of the tongue are shown in Figure 2. 7.

The jaw contributes speech production as an articulator by moving downwards and upwards by means of the muscles shown in Figure 2. 8.

The lips are at the end of the vocal tract. They also play role as an articulator in speech production through their ability of changing their shapes via some fascial muscles shown in Figure 2. 8. They contribute to wovel and plosive consonants production. [14], [22]. All the muscles playing role in speech production are grouped in table 2.1.

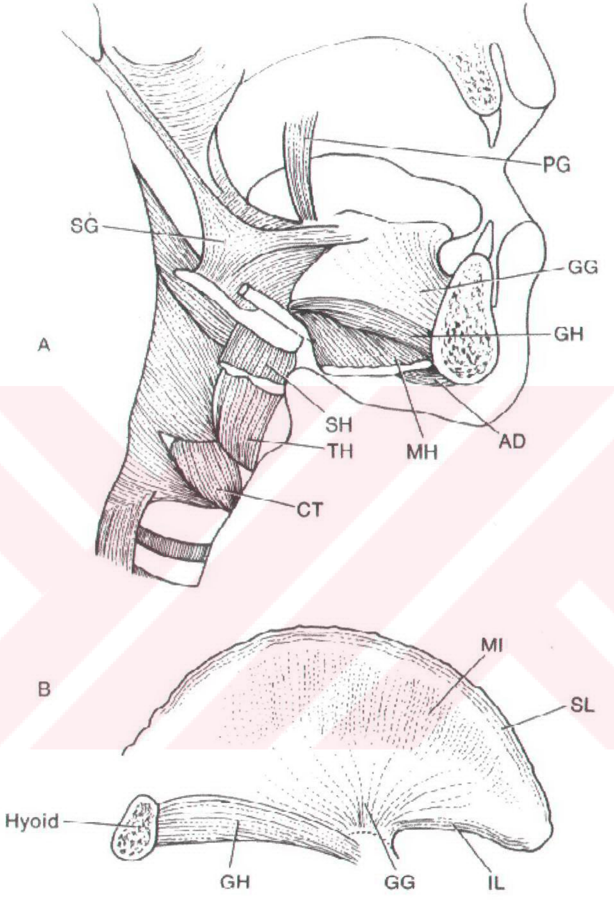


Figure 2. 7. The Muscles of the Tongue.

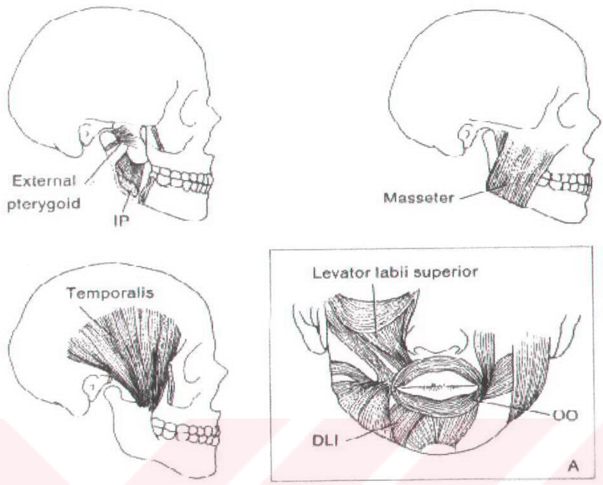


Figure 2. 8. The facial muscles playing role in jaw and lips movements.

Table 2. 1.

The Muscles of Speech Production

Muscles	Figure Reference	Function
	Larynx	
Thyroarytenoid (TA)	Figure 2. 4	Vocal cord tensor; forms the body (TA) of vocal cord; is active during f_0 change
Posterior Cricoarytenoid (PCA)	Figure 2. 4	Opens the glottis for either breathing or the production of voiced sounds
Lateral Cricoarytenoid (LCA)	Figure 2. 4	Adducts the vocal cords; applies medial compression; is active during f_0 changes; active in setting phonation neutral position
Cricothyroid (CT)	Figure 2. 4	Applies longitudinal tension to vocal cords; is active during f_0 changes
Interarytenoid (IA)	Figure 2. 4	Adducts the vocal cords; applies medial compression ; may be active in setting neutral position
	Pharynx	
Superior Constrictor (SC) Medial Constrictor (MC) Inferior Constrictor (IC)	Figure 2. 6 Figure 2. 6 Figure 2. 6	Constrict the pharynx;active during swallowing and in the production of sounds like the vowel [a].

	Tongue	
Superior Longitudinal (SL)	Figure 2. 7	Turns up the tip of tongue
Inferior Longitudinal (IL)	Figure 2. 7	Turns down the tip of tongue
Transvers (MI)	Figure 2. 7	Narrows the tip of tongue
Vertical (MI)	Figure 2. 7	Flattens the tip of tongue
Genioglossus (GG)	Figure 2. 7	Pulls tongue body forward; depresses the tongue body Is active in production of sounds like [u] and velar consonants
Styloglossus (SG)	Figure 2. 7	Pulls tongue body towards styloid process; is probably active in production of sounds like [u] and velar consonant
	Jaw	
Masseter (MAS)	Figure 2. 8	Closes the jaw
Temporalis (TEM)	Figure 2. 8	Closes the jaw; pulls lower jaw backwards
	Lips & Face	
Orbicularis Oris (OO)	Figure 2. 8A	Close the mouth; puckers the lips; acts to close and round lips in sounds like [u]
Depressor labii inferior (DLI)	Figure 2. 8A	Opens and retracts lips; active in release of sounds like [p] and [b]
Lavatory labii superior	Figure 2. 8A	Open lips; sometimes active in release of sounds like [p] and [b]

3. PHYSIOLOGY OF SPEECH PRODUCTION

3. 1. Physiological Role of the Subglottal System in Speech Production:

The subglottal component of the vocal system consisting of lungs, thoracic and abdominal musculatures functions as a power supply during speech production [22], [29].

The lungs are not attached to the rib cage. There is an enclosed volume that is called pleural space between the lungs and the chest wall. As the volume of the pleural space is increased by the contraction of the inspiratory muscles, the elastic lungs are expanded. Air, therefore, is filled into lungs. During the inspiratory process energy is stored in elastic expansion of each lung. During the expiration much of the force is provided by the elastic recoil of lungs to push the air out of the lungs through the trachea, larynx and supralaryngeal vocal tract [14]. In addition, the thoracic and abdominal muscles also play role in expiration and, then in speech production to maintain subglottal pressure P_s by a steady contraction [22].

The expired air flowing out from the lungs furnishes the force necessary to generate speech sounds [29]. As a conclusion, the vibration of the vocal cords are maintained and initiated by the respiratory driving force [16], [23].

3. 2. Physiological Processes in Larynx during Speech Production:

Larynx is the component of the vocal system that coordinates the respiratory system and the articulators of the supralaryngeal vocal tract [27]. It converts steady flow from lungs into a series of puffs of air [14], [29]. This is accomplished via a pulsating jet formed by the air passing through the opening and closing glottis which is three-dimensional space deforming dynamically during phonation and acting as a dynamic valve to create pulsative air [16], [30].

The primary functions of the larynx are the control of phonation, the control of fundamental frequency f_0 and the control of intensity of sound [31].

Phonation may be defined as the mechanism of human voice production achieved by the vibratory action of the vocal cords and used for vowel and voiced consonant generation. It is, therefore, the result of the vocal cords movements generated by the alternating forces depending on the pulmonary air pressure [14], [16], [22]. Its source is located within the larynx. It is initiated via the muscular compression of the rib cage and thereby increasing lung pressure and forcing a flow through the glottis [20], [22]. In addition, laryngeal muscles swinging the arytenoid cartilage contribute also to the initialization of the phonation [14].

The adductor muscles LCA and IA act on the glottis to preset it 0.5 seconds before the phonation. All these muscular events accompanied by aerodynamic forces provided by the lungs are referred as the prephonatory adjustment phase 50-100 msec later, before the initiation of the expiratory air flow, the vocal folds begin to move towards the midline.

Therefore, as it is implied in the myoelastic-aerodynamic theory of phonation, the vocal folds are the self-oscillating systems (i.e. their vibrations are not determined by the neural impulses) controlled by the aerodynamic stresses applied to the surfaces of the vocal folds and by the myoelastic forces generated by the tissues [32]. According to the myoelastic-aerodynamic theory, one cycle of the vibratory action of the vocal folds has the following stages:

i) The vocal folds are adducted and medially compressed by the action of the adductor muscles LCA and IA to preset the glottis 0.5 seconds before the phonation. These muscular events accompanied by aerodynamic forces provided by the lungs are referred as prephonatory adjustment phase.
ii) Air is forced through the vocal tract from the lungs

iii) The negative air pressure generated by the Bernoulli force, which is a result of the increased speed of the airflow, pulls the vocal folds together. Consequently, the vocal folds are sucked together. This stage is called simultaneous vocal attack. When the vocal folds are sucked together, although the flow through the glottis stops, the air flow from lungs continues and, subglottal pressure rises beneath the vocal folds. This stage is the hard glottal attack.

iv) When the subglottal pressure is greater than the medial compression of the vocal folds generated by the adductor muscles, the folds are pushed apart by aerostatics forces (lateral displacement). A puff of air is released into the supralaryngeal vocal tract. All these events occur in the breathy (aspirate) attack.

v) The subgottal pressure begins to fall

vi) The vocal folds return to neutral position by means of the restoring forces of the laryngeal muscles and of the elasticity of the vocal folds.

vii) The following cycle begins [14], [29], [31].

The vibratory cycle of the vocal folds being illustrated in Figure 3.1. has three phases:

i) The opening phase : Lateral displacement of the vocal folds is achieved by subglottic pressure and then, the glottis is opened

ii) The closing phase : The vocal folds are pulled towards the midline by elastic recoil and suction of the aerodynamic forces

iii) The closed phase: The vocal folds remain in neutral position for a brief portion of time.

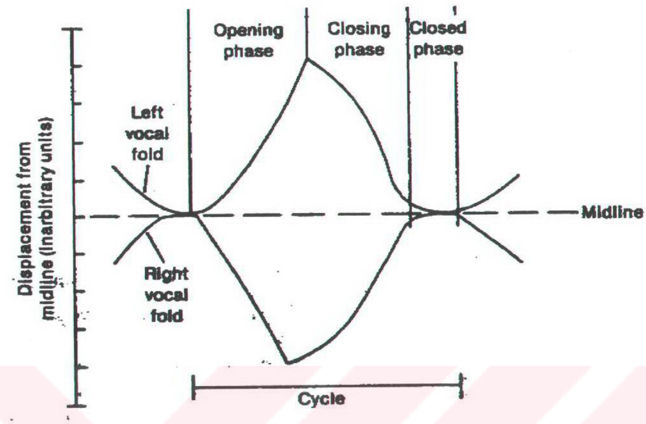


Figure 3. 1. The Phases of the Vocal Cord movements

The opening and closing movements of the vocal folds that are shown in Figure 3.2. may be described in the following stages [14], [31]:

(1) The vocal folds are approximated. There is a higher impedance to airflow created by the synergistic activity of TA and CT muscles and a subglottal pressure is built up beneath the vocal folds.

(2) While subglottal pressure is increasing, the lower portions of the vocal folds are blown apart. The upper parts, however, are pushed inward due to the incompressibility of the folds and due to the changes in transglottal pressure. A vertical phase difference results in the difference of timing between the movement of the upper and lower portions of the vocal cords. That phase delay is significant to create wave-like movement of the folds and essential for efficient energy transfer between the air and the tissues [21].

(3) The subglottal pressure continues and seperates the upper edges of the vocal cords.

(4-5) These edges are pushed aside and the glottis are completely opened. As a result, the opening phase is completed and a puff of air is released.

(6-8) The lower portions of the vocal cords begin moving towards midline and the upper portion is following the former. Elastic recoil and a sudden transglottal pressure drop help the glottis to return neutral position. All of these events occur during the closing phase.

(9-10) The vocal cords remain in neutral position for a short-time which is the closed phase.

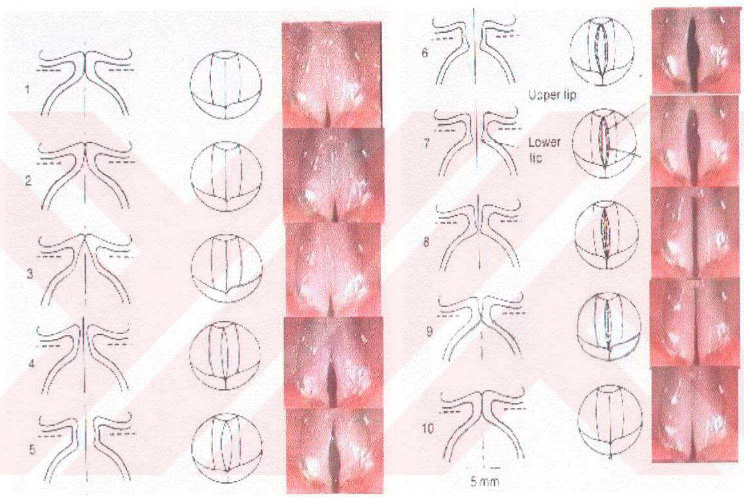


Figure 3. 2. One cycle of vocal cord vibrations: view in coronal plane (left), from above (middle) endoscopic photographs (right).

The number of cycle of vibration of the vocal folds is referred as fundamental frequency (f_0) or pitch [31]. It is determined by the opening and closing rate of the vocal folds [14]. It is controlled either by laryngeal muscle activity or by subglottic pressure, or both of these factors which are usually correlated [2], [14], [29], [33]. The sternohyoid (SH) muscle plays role in shifting from the low f_0 mode to the high f_0 mode or vice versa [33].

In the low f_0 mode, the SH lowers the larynx. Therefore, the vocal folds become, short, thick and lax and more sensitive to subglottic pressure. On the other hand, in high f_0 mode, the deformation forces of the intrinsic laryngeal muscles are dominant in the control of f_0 [21], [33], [34].

The laryngeal muscle activity controls the physical factors such as mass, length, tension of the vibratory structures that regulate the frequency of vibration [29]. The forces of these muscles act in one direction: longitudinal, mediolateral and vertical [2]. Due to their decreased mass per unit length, long vocal folds being also thin, have high f_0. They are lengthened and stretched by the CT muscle which, is the principle pitch-raising muscle. TA, however, shortens the vocal cords making them tenser. These longitudinal forces are achieved by the rotation of the thyroid and cricoid cartilages around the CTJ [27], [31], [35].

The mediolateral tension made by medial compression of adductor muscles, the LCA and IA increase f_0 by raising glottic impedance. Vertical tension is made by the extrinsic muscles of the larynx such as Sternothyroid (ST) which lowers the f_0, and the Genioglossus (GG), playing role in raising pitch [31].

Fundamental frequencies in phonation lie in total range of 60 to 500 Hz. For men the f_0 is approximately 120 Hz, for women 225 Hz, and 265 Hz for children [28]. During the puberty Adam's apple being prominent in Adult males and which is the anterior part of the thyroid cartilage grows disproportionately [14], [15]. The anteroposterior length of this cartilage is 20% longer in male than that of female [36]. As a result, since the males' vocal folds elongate and thicken, they vibrate more slowly and their pitches lower [15]. So, the adult males' fundamental frequencies are less than those of females are.

Intensity that is also referred as "loudness" is controlled almost by the same mechanisms as the pitch. The essential factors that the intensity depends on are the laryngeal muscle tension, the duration of the closed phase, the magnitude of the subglottic pressure and the airflow [2]. To obtain an increased intensity at low pitches, an increased glottal resistance created by a greater laryngeal muscle tension is necessary. The LCA and

TA muscles are contributing to change the intensity in this case [31], [34]. At high pitches, since the vocal cords are already tense, the intensity is controlled by the airflow pushed from lung [31], [34].

A greater subglottic pressure that means a higher peak value of pressure within each glottic cycle caused by a longer closed period increases the intensity. The airflow through the glottis, which depends on either the work done by the respiratory system or the cross-sectional area of glottis, is affected by the subglottic pressure. Thus, both increased airflow and increased subglottic pressure are necessary to obtain a greater intensity. As a conclusion, greater intensity may be established by either increased work done by the respiratory system at constant vocal cord resistance or increased vocal cord resistance at constant airflow [31].

For a male, the intensity may be approximately 75 dB. For a female it may be 65 dB. Whisper has an intensity value of 40 dB where as loud speech has an intensity value of 90 dB at least [31].

Voice quality that enables the listener to identify the speaker is determined by the changes in the glottal waveform. These changes related to the ratio of the open to the closed phase of the vibratory cycle affect the f_0 and amplitude of the glottal waveform [29]. The supralaryngeal vocal tract also plays role in shaping the voice quality through the resonant cavities beside the vocal folds [15], [29].

3. 3. The Supralaryngeal Vocal Tract in Speech Production:

The supralaryngeal vocal tract with a length of 17 cm begins from vocal fold constriction and is terminated by the lips [1], [22]. It plays role not only in shaping voice quality also in forming phonemes. Supralaryngeal regions playing role in speech production and consisting of resonating cavities such as pharynx, oral and nasal cavities, and articulators such as the lips, jaw, tongue and velum may be described as follows:

i) pharynx,

ii) the variable constriction of velum and the nasal cavity,

iii) narrow passage formed by the humped tongue,

iv) large oral cavity,

v) radiating ports by the mouth and nostrils [15], [22], [38].

The cross-sectional area is varied by the movements of these articulators from zero (i.e. complete closure) to about 20 cm^2 [1], [20].

The vocal tract exhibits different behaviors in respect for the production of vowels and consonants. The vowels are controlled by the physiological parameters such as vocal-tract length, position of the tongue, and configuration of the lips. The vocal-tract length is affected by the interactions between larynx, mandible and lips. Furthermore, the changes in the shape of the lips are important in the differentiation of sounds of vowels. The tongue is the determinant of the vocal tract shape. It contributes to the vowel production by deforming the cross-sectional area via its humped position [22], [37].

The consonant production is established by forming a complete constriction at a specific location of the vocal tract by a specific part of articulators. The tip of tongue or lips must contact the palate or teeth [37]. As a result, these sounds radiate from the mouth to outer space.

4. ACOUSTICS OF SPEECH

The vocal tract and the structures contributing to the speech production are functioning as system converting the mechanical energy of the airflow exhaled from the respiratory system to the acoustical energy.

4.1. The Role of the Respiratory System :

The respiratory system including the lungs being associated with respiratory muscles acts as a power supply for the vocal tract and provides a steady flow [14], [22], [29]. Therefore, the subglottal pressure P_s may be assumed analogous to the voltage of the power supply in the electrical transmission line model [39].

4.2. The Larynx and Its Acoustic Function in Speech Production:

The vocal cords located in the larynx are vibrated by the expelled air flowing through the glottis and acts as a relaxation oscillator. It converts the steady flow into the discrete puffs of air [14], [22].

The volume of expired air from the respiratory system is modulated by opening and closing movements of the vocal cords during phonation. The cords vibrate periodically at a certain rate called fundamental frequency f_0 [40]. Fundamental frequency is related by the muscle activities of CT and TA muscles and the subglottal pressure P_s [41]. As a result the quasiperiodic broad-spectrum pulses that excite the vocal tract are produced due to the interrupted flow of the exhaled air. The waveform of these pulses are illustrated in Figure 4. 1.

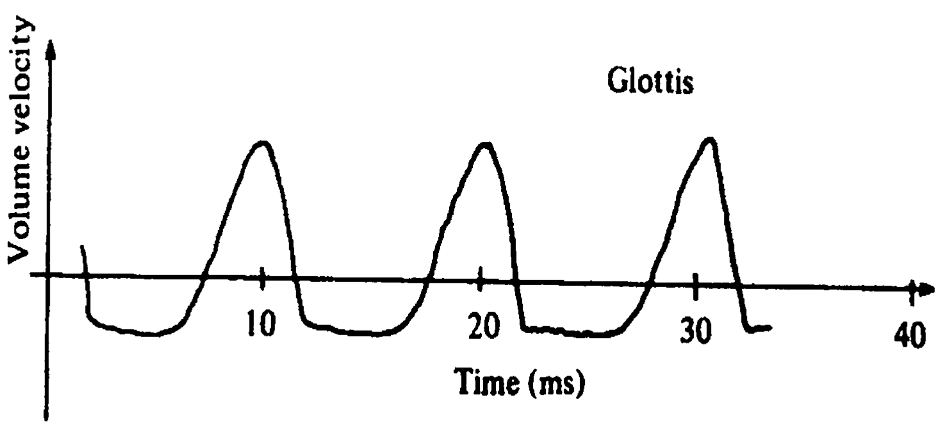


Figure 4. 1. Time vaweform of volume velocity pulses at the glottis

4.3. The Function of the Vocal Tract:

The vocal tract that may be considered as an acoustical transmission system, is a bent tube of complex geometrical shape where the sound radiates to the outside air from the mouth opening [42]. Such an acoustic tube being non-uniform in cross-sectional area lies between the vocal cord constriction at the top of the trachea and the lips [1], [22].

In adult male, the length of the vocal tract is about 17 cm. The cross-sectional area of the vocal tract in its forward portion may be varied from zero (when complete closure is accomplished) to 20cm^2. The shape of the vocal tract is deformed in cross-sectional area by movement of articulators such as lips, jaw, tongue, and velum [1], [22].

According to the assumptions about the acoustic models of the vocal tract, it is made up four cylindrical sections representing the throat cavity, the constriction caused by the hump of the tongue, the mouth cavity and the constriction due to the lips [43].

4.3.1. The Acoustic Properties of the Vocal Tract:

The vocal tract is considered as a lossy cylindrical pipe consisting of different sections of different length and of cross-sectional area. It has some physical properties depending on the physical behavior of the air.

4. 3.1.1. The Acoustic Inertance (L_a):

Because of its mass, the air in the pipe has an inertance opposing acceleration. In other words, the mass of air contained in the unit length of the vocal tract is defined as "the acoustic inertance L_a" which is expressed as follows:

$$L_a = \frac{\rho}{A} \tag{4. 1}$$

where ρ is the density of air and A is the cross-sectional area of the tract [22], [44].

4.3.1.2. The Acoustic Compliance (C_a):

The compressibility of the volume of air contained in the unit length of the vocal tube is called "the acoustic compliance or capacitance C_a"

$$C_a = \frac{A}{\rho c^2} \tag{4. 2}$$

Where A is the cross-sectional area, ρ density of air and c the velocity of sound in air [22], [44].

4. 3. 1. 3. The Acoustic Resistance (R_a):

Another assumption in the acoustic model of the vocal tract is that it is a hard-walled smooth tube where energy losses should occur at the wall due to the viscous friction. So, "the acoustic resistance R_a" represents the power dissipated in viscous friction, which is expressed as follows:

$$R_a = \frac{S}{A}\sqrt{\frac{\omega\rho\mu}{2}} \tag{4. 3}$$

where S is the circumference of the tube, A is the cross-sectional area, ρ is the density of air, μ is the viscosity of the air.

4. 3. 1. 4. The Acoustic Conductance (G_a):

The shunt conductance providing a power loss proportional to the square of the local sound pressure arises from heat conduction at the walls of tube. The acoustic conductance G_a is as follows:

$$G_a = \frac{S(\eta-1)}{\rho c^2}\sqrt{\frac{\lambda\omega}{2c_p\rho}} \tag{4. 4}$$

where S is the circumference of the tract, η is the ratio of specific heat at constant pressure to that at constant volume c_v (For air in normal condition $\eta = c_p / c_v = 1.4$), λ is thermal conductivity, c_p specific heat [22], [44].

4. 3. 2. Electrical Analogous of Vocal Tract:

The vocal tract acts as a time-varying acoustic filter for vowels that shapes the frequency spectra from the voice being produced at glottis and operates as a multiresonant filter due to the air cavities located in the vocal tract [40], [42].

According to the source-filter theory of speech production, since the frequency spectrum produced by the vocal folds is different from the spectrum at the mouth, it is assumed that the glottal source and the vocal tract filter are linearly separable [45], [46]. This is explained by the behavior of the glottis as a high-impedance source [47].

While constructing a model for speech production, the vocal tract has been assumed as a hard-walled, smooth tube. Since the plane wave propagation in such a tube exhibits behaviors being analogous to those of electric wave along a transmission line, the vocal tract may be considered as a system analogous to an electrical transmission line [22], [44]. Therefore, the acoustic theory of speech production is based on elementary electrical theory and equivalent circuit concept. Each shape of the vocal tract being regarded as a tube with its acoustical properties may be modeled in terms of an electrical network [40], [48]. This model is illustrated in Figure 4. 2. The acoustical parameters of the vocal tract, therefore, are analogous to the electrical parameter. The sound pressure is considered to be analogous to the voltage and the volume velocity to the current. There is also analogy between the air mass inertia and the inductance, the air compressibility and the capacitance, the viscous loss and the series resistance, the heat conduction loss and the shunt resistance. [22], [39], [44]. These analogies are indicated in table 4. 1.

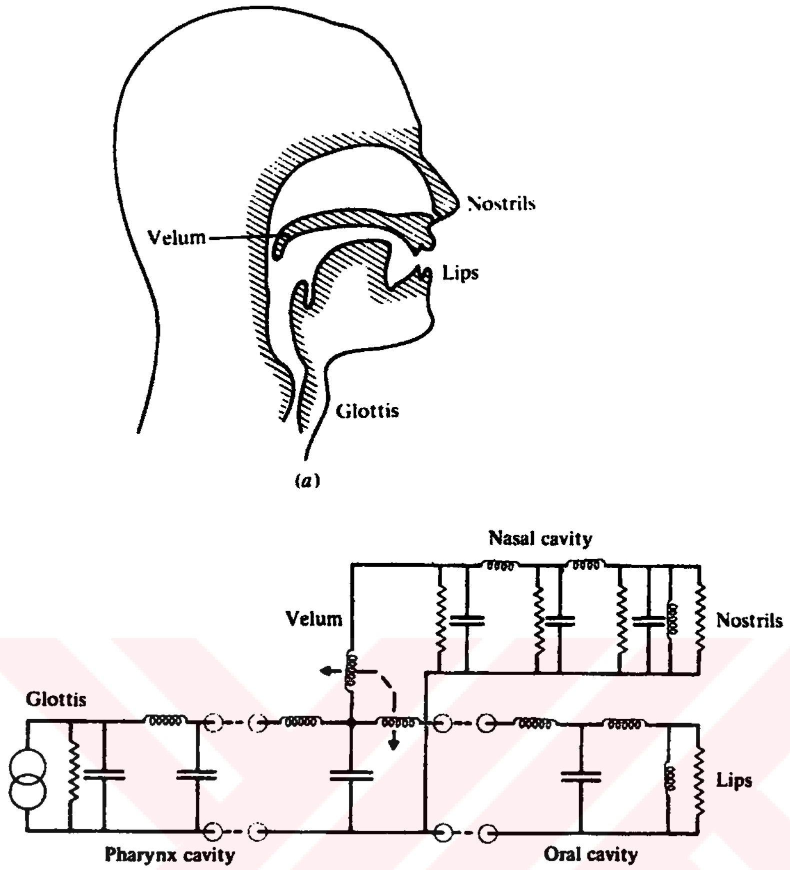


Figure 4. 2. Transmission line model of the supralaryngeal vocal tract

Table 4. 1.

Table of Acoustical/Electrical Analogues

Acoustical Parameter	Electrical Parameter
Pressure	Voltage
Volume velocity	Current
Air Mass Inertia	Inductance
Air Compressibility	Capacitance
Viscous Loss	Series Resistance
Heat Conduction Loss	Shunt Resistance

Another important concept for the vocal tract in that transmission line model is the acoustic characteristic impedance being expressed as follows;

$$Z_a = \sqrt{\frac{R_a + j\omega L_a}{G_a + j\omega C_a}} \tag{4. 5}$$

4.3.3. Transfer Function of the Vocal Tract:

Since the vocal tract being a multiresonant acoustic filter can be modeled in terms of an electronic network, any speech sound is considered as the output of such a network. The characteristics of any sound segment include those of the source and those of the network. The former is referred to as the source function and the latter to as the vocal tract transfer function or filter function [40], [48].

In terms of line spectrum, the relationship between sound coming from the excitation source (the glottis) and the sound radiated from any point in the vocal tract is expressed as follows:

$$|P(f)| = |S(f)||H(f)| \tag{4. 6}$$

where $|P(f)|$ is the function of the sound radiated any point along the vocal tract, $|S(f)|$ is the function of the source volume velocity and $|H(f)|$ is the vocal tract transfer function [45]. For an idealized vowel, the transfer function defined as the ratio of the volume flow at the radiation port (i.e. lips), to the volume flow at the glottal end. The transfer function for the first vowel of the word 'about' is shown in Figure 4. 5

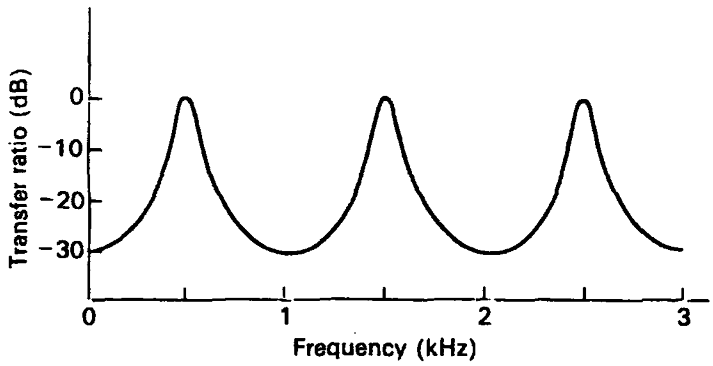


Figure 4. 3. Transfer function for the first vowel of the word about

According to the acoustic model of speech production, the vocal tract consists of cylindrical sections represented by a T-network or Π-network owing their transfer function. The transfer function of whole vocal tract is the product of those of the cylindrical sections [49], [50].

In terms of Laplace transform, the characteristics of speech sounds are expressed as:

$$P(s) = S(s)H(s) \tag{4. 7}$$

where *P(s)* is the radiated sound function, *S(s)* is the source funtion, *H(s)* is the vocal-tract transfer function, and $s = \sigma + j\omega$ is the complex frequency variable.

Mathematical expression for this transfer function, which is an all-pole product at a distance l cm from the source, is;

$$H(s,l) = \frac{s}{4\pi l} \bullet \frac{1}{\prod_{n=1}^{z}(1 - s\hat{s}_n)(1 - s\hat{s}_n^*)} \tag{4. 8}$$

where $\hat{s}_n = \sigma_n + j\,\omega_n$ $\quad \hat{s}^*_n = \sigma_n - j\,\omega_n$ [40], [50]. The poles of this function are related with the transmission maxima of that filter function, which are the results of the acoustic resonances (formants) of the vocal cavities. These formants are represented in terms of their frequencies F_n and bandwidth B_n. The relationship between the F_n, B_n and complex poles of $H(s)$ may be described as follows;

$$F_n = \frac{\omega_n}{2\pi} \qquad\qquad B_n = \frac{\sigma_n}{\pi} \tag{4. 9}$$

where n is the number of the formant [1], [40].

The formants are the result of the variations in the cross-sectional area and, in the length of the vocal tract. The arrangement of formants is responsible for the differences of vowels. Each vowel may have four or more formants. The relationship between the first and second formants for english vowels is illustrated in Figure 4. 4.

These arrangements are achieved due to the alterations in the configuration of the tongue. When the body of the tongue moves backwards and forward, the length of two sections or acoustic tubes are altered in order to change the resonances. When the tongue moves up and down in the mouth, it also contributes to change the resonanaces by varying the cross-sectional area.

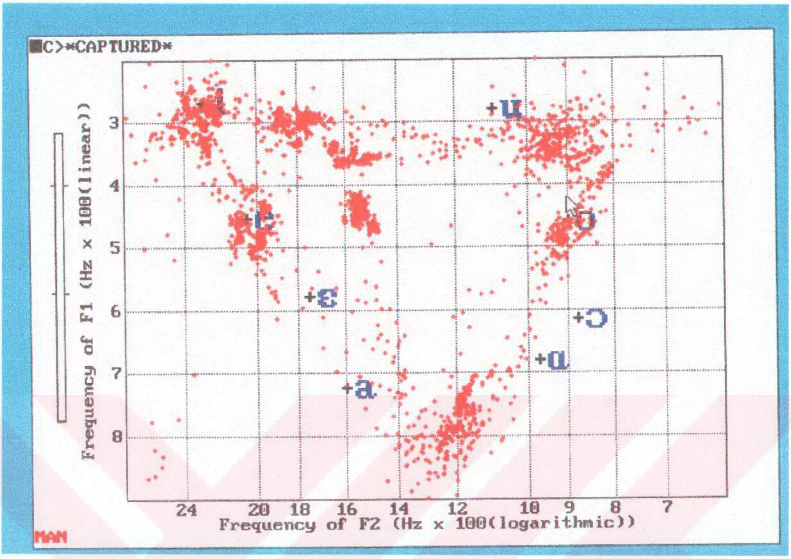


Figure 4. 4. The plot of the first and second formants of the English vowels

These arrangements are achieved due to the alterations in the configuration of the tongue. When the body of the tongue moves backwards and forward, the length of two sections or acoustic tubes are altered in order to change the resonances. When the tongue moves up and down in the mouth, it also contributes to change the resonanaces by varying the cross-sectional area. The vocal tract spectra for the vowel [a] and [i] and the alterations in the vocal tract shape are shown in figure 4. 5.

The lips also contribute to adjust formants through their varying shapes not only by varying the cross-sectional area but also by lengthening the vocal tract [29].

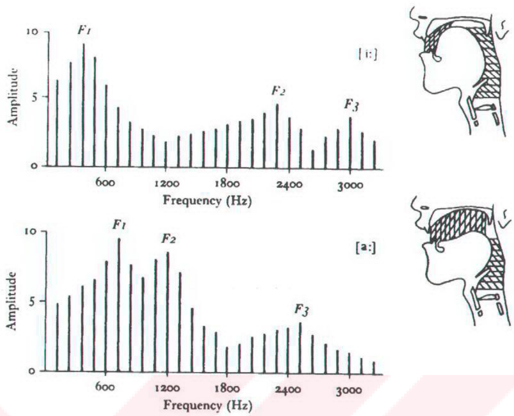


Figure 4. 5. Vocal tract shapes and the spectra for vowels [a] and [i].

4. 4. Generation of Unvoiced Sounds:

The unvoiced sounds or consonants are produced either from an incoherent noise excitation or transient excitation of the vocal tract.

The noise generation is achieved by the turbulent airflow at some point of constriction as in the case of fricative sounds. That can be considered as a random noise generator in the electrical transmission line model of the vocal system.

The transient excitation occurs via a complete closure that builds up a pressure behind the constriction. This pressure is released by an abrupt opening of that closure. The plosive sounds are produced by this kind of excitation of the tract can be considered as a voltage source with a step function [22].

5. THE CANCER OF LARYNX

The cancer of larynx is a malignant disease, which disrupts the physiological process of the larynx in speech production. Moreover, it may have fatal consequences at the later stages provided that it is not cured.

5. 1. Epidemiology of the Laryngeal Cancer :

5. 1. 1. Incidence and Mortality :

The cancer of larynx is the second malignant disease in incidence following the thyroid cancer, when compared with the other head and neck malignant tumors [51]. According to the National Cancer Institute records, there exist approximately 11,000 cases of laryngeal malignancy per year within the United States with a mortality of 4,000 cases per year due to that malignancy [51].

The occurrence of the laryngeal cancer is more common in males than in females. The generally cited male to female ratio is about 10 to 1. The ratio for laryngeal cancer is 2.3 per cent of all malignant tumors in males, whereas 0.4 per cent of all malignant tumors in females [51], [52].

Since the cancer of larynx is encountered in elderly people, the peak age that the laryngeal cancer occurs is sixth and seventh decades with vast majority of cases seen between 40 and 69 years [51].

5. 1. 2. Etiology and Environmental Risk Factors :

The risk factors for the development of laryngeal cancer are considered as tobacco, alcohol, industrial exposure and laryngeal papilloma.

Tobacco consumption is the major factor for the occurrence of the laryngeal cancer. Some prospective studies have shown that there is a correlation between the daily consumption of cigarette and the mortality [51], [52].

Heavy alcohol intake significantly increases the risk of laryngeal cancer. The combination of smoking and drinking alcohol enhances the risk 50 per cent over the expected incidence [51].

Industrial exposure is considered as the chemical substances that have been thought to be related to laryngeal cancer. They include asbestos, mustard gas, wood dust, refinery products, and certain mineral oils and nickel compounds. It has been shown that asbestosis increases the risk twice [51], [52].

HPV viruses cause laryngeal papillomatosis. The conversion of laryngeal papillomatosis to the malignant tumors is especially seen in the patients that have received radiation therapy in the past [51].

5. 2. Pattern of Spread of Laryngeal Cancer :

Since the cells exhibit an irregular and uncontrollable increase of number in laryngeal cancer like the other types of cancer, they tend to spread to adjacent tissues from the beginning focus.

The laryngeal cancer usually begins from the glottic region. That infiltrative lesion may invade the intrinsic muscles such as LCA, IA, PCA causing vocal cord fixation. Other structures invaded are the cricoarytenoid joint and thyroid cartilage [52].

At the following stages, the lesion may spread extralaryngeal regions. Afterwards, it might reach to the cervical lymph nodes.

At the later stages, the malignant cells will reach to other organs through the lymphatic circulation and form new malignant focus. This process is called distant metastasis. The metastatic malignancies that can be seen following the laryngeal cancer are in kidney, breast, lung, prostate, and gastrointestinal tract [52]. It is almost impossible to survive the patients at that stage.

5. 3. Diagnosis and Assessment :

Inasmuch as the earlier detection of the malignant tumors of larynx enhances the success of the therapy, diagnosis is very important in the management of the laryngeal cancer.

5. 3. 1. Symptoms :

Hoarseness occurring more than four weeks is evident symptom of the laryngeal cancer. It occurs due to the narrowed air passage by tumor or the restricted movement of the vocal cords. Every patient with hoarseness should be examined, and if indicated, the larynx is biopsied [51], [52], [53].

Dispnea may be seen due to the narrowed air passage at glottis. That symptom may also be the result of the secondary infections due to the blocked airway secretions by the tumor [51].

Dysphagia, or difficulty in swallowing may be observed, if the tumor is spread to the supraglottic or hypopharyngeal regions [51], [52].

Throat pain and fullness produced by direct tumor invasion through the laryngeal cartilage or more commonly by a metastatic cervical lymph node [51].

5. 3. 2. Indirect Mirror Examination :

Indirect mirror examination using a headlight and mirror is the classic method of examining larynx. This is the first step in the examination. This method allows the physician to see the lesions in the majority of case [51], [52], [53]. That method should be used after the history of hoarseness or throat pain, or both. This examination is used to observe the appearance of the mucosa, to check the mobility of the cords, and the condition of the airway [51].

5. 3. 3. Endoscopy (Direct Laryngoscopy) :

Even though mirror examination provides the best color and depth perception, it may be supplemented by evaluation with a flexible laryngoscope. The patients with an intense gag reflex require supplemental examination [52].

Biopsy specimens should be taken by means of the fiber-optic flexible scopes during the examination for histopathologic observations to evaluate the malignancies of the lesion [52], [53].

5. 3. 4. Radiological Diagnosis Techniques :

Computerized tomography (CT) being as a reliable method is widely applied especially in determining the extensions, cartilage invasion and extension into soft tissue. It is complementary to clinical examination and to laryngoscopy [51], [52].

Preoperative assessment of advanced malignancies is further clarified with computerized tomography [51].

Magnetic Resonance Imaging (MRI) is also applied in the diagnosis of laryngeal cancers. Like CT, MRI is helpful to detect extensions and cartilage invasions [52].

5.4. Therapy of the Laryngeal Cancers :

5. 4. 1. General Principles of Therapy :

The principle in treatment is to apply the convenient therapy that provides higher recovery chance with the lower adverse effect. The therapy in laryngeal cancers is based on surgery and radiotherapy. In small lesions, surgery or radiotherapy is applied alone. In bigger lesion, the combination of radiotherapy and surgery must be applied.

Nowadays, the main principle for the treatment of the small lesions is to apply radiotherapy alone. Nevertheless, partial laryngectomy is preferred in some case such as differentiated infiltrative tumors, patients living in rural areas which are difficult to follow [51].

5. 4. 2. Partial Laryngectomy :

It may be also called as conservative surgery. The purpose of the partial laryngectomy is both to survive the patients with laryngeal cancer and to protect their voice as possible as for speech production. However, it can be applied in case of early diagnosis. The partial laryngectomy is contra-indicated in the existence of invasion of thyroid and cricoid cartilages, of laryngeal fixation, of spread to the root of the tongue. That surgical procedure is preferred if the vocal cord movements are affected by the tumor [52].

5. 4. 3. Total Laryngectomy :

Total laryngectomy is a surgical removal of whole larynx. Since the patients lose their abilities of speech production, either the patients or the physicians do not prefer it. On the other hand, total laryngectomy becomes inevident to apply for some patients. Indications for total laryngectomy are as follows:

1. Advanced glottic carcinomas having vocal cord fixation
2. Advanced tumors with cartilage destruction and extralaryngeal extensions.
3. Bilateral vocal cord lesions
4. Interarytenoid (IA) involvements
5. Tumors with normal vocal cords mobility but a degree of subglottic extension beyond the limits of conservation surgery.
6. Advanced tumors of certain histologic types that are incurable by endoscopic resection or radiotherapy.
7. Radiotherapy and partial laryngectomy failures [51], [52], [54].

6. AVAILABLE VOICE REHABILITATION METHODS

The patients that have malignant tumors of larynx are usually cured by the total laryngectomy (i.e. surgical procedure to remove the larynx and surrounding tissue). To prevent food to pass to the air passage through the laryngeal area, a new air passage is constructed that allows the patient to breathe through an opening called tracheostomy stoma in the neck as shown in Figure 6. 1 [55], [56]. After this surgical procedure, supralarygeal resonance regions and phonemic articulation remain unimpaired whereas,

(a) **(b)**

Figure 6. 1. a) Normal larynx b) Status after total laryngectomy

expiratory breath and cord oscillation is disrupted. The expiratory breath functioning as a power supply for the whole vocal system in healthy individuals is deviated outwards through the tracheostomy after the laryngectomy. The patients, therefore, cannot produce a fundamental tone [3].

After the total laryngectomy, even though they are cured, the patients face an important problem about how to communicate with the others and to meet social needs without voice [10]. Furthermore, since it depends on some factors such as psychosocial, medical, and surgical factors, to find a convenient voice rehabilitation method for each patient individually may be another difficult problem to solve. Current clinical applications are as follows:

i) Esophageal speech

ii) Tracheoesophageal Prosthesis (TEP)

iii) Artificial Larynx

6. 1. Esophageal Speech

After laryngectomy, a pharyngo-esophageal (P-E) segment is constructed. The laryngectomees use the body of the esophagus as air reservoir to provide air supply to the upper portions of the vocal system [10], [57]. The esophagus must be charged with air by the patients.

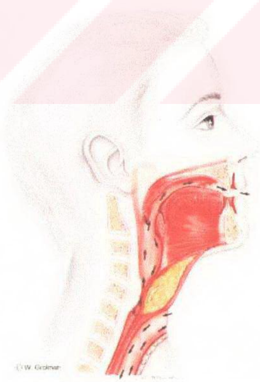


Figure 6. 2. Esophageal Speech

They swallow boli of air into esophagus and then regurgitate this air into vocal system as shown in Figure 6. 2 [10], [55], [56], [58]. The cricopharyngeus portion of the inferior constrictor muscle of the pharynx acts as a vibrator. The vibrations are achieved by virtue of air expelled from the esophagus. The resonating systems and the articulators, which remain unchanged, help the patient to articulate this sound into intelligible speech [10], [57].

The esophageal speech can sound natural and fluent and may be a good substitute for lost voice. The average patient must spend three to twelve months for the intensive training to become proficient in the technique [55], [56].

Although some laryngectomees can master this method, one third fail to acquire useable speech [1], [10]. Success of the patients depends on their ability in developing over muscles of the pharynx [55]. For successful patients being able to master with this technique, it is not possible to achieve a continuous speech. The speaker becomes tired after a short time [56]. Due to the small volume of air trapped in the esophagus and the small velocity of airflow, sound intensity is low [55].

6. 2. Tracheoesophageal Prosthesis (TEP):

In this method, the prosthesis is inserted into the fistula constructed between the trachea and the posterior wall of the esophagus [2]. During the expiration, the air flowing through the tracheoesophageal (TE) fistula of the P-E segment via the prosthesis causes vibrations as seen in Figure 6. 3. Then these vibrations are transmitted by the vocal tract and are modulated by the patients' articulators such as tongue lips etc. [7], [60], [61], [62].

There exist different types of TEP. The Groningen, Provox and Blom-Singer prostheses possess valve mechanism that close the TE fistula when speech does not occur in order to prevent food and saliva to pass to the lungs [63]. On the other hand, the Nidjam Voice Prosthesis (VP) has not such a valve mechanism. The barrier mechanism is created by the

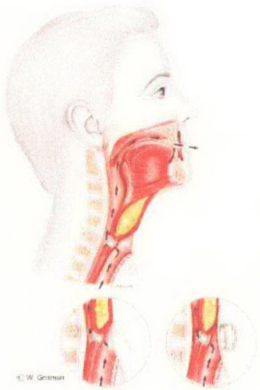


Figure 6. 3. Speech with Tracheoesophageal Prosthesis

umbrella-like hat of the prosthesis that covers the TE fistula on the esophageal site. During the expiration and speech production, the esophageal flange of the Nidjam VP is deflected; the esophageal mucosa is deformed to provide a TE opening for air exhaled from the lung [62], [64].

Since the patients are utilizing pulmonary air, tracheoesophageal prostheses provide them fast and spontaneous voice rehabilitation [65]. And also, with respect to voice quality, pitch, loudness, intelligibility, rate of speaking, lingual representation, tracheoesophageal prostheses may be considered superior to esophageal voice [6]. Due to the fact that the laryngectomees use the physiological air reservoir in the lungs, these prostheses enable them to achieve more sustained phonation than in the case of esophageal speech [58].

Due to the humidity and heat of the medium, fungal colonization of candida may cause valve or barrier dysfunction resulting in leakage fluids through the prosthesis [6], [11], [12]. So, the tracheoesophageal prostheses have limited lifetime, they have to be replaced periodically (on average approximately every five months) in an outpatient clinic. These procedures are neither time-effective nor cost-effective and they restrict the quality of life of the patient [7], [60], [61], [62]. In addition, these prostheses cause local complications such as granulation tissue and hypertrophic scar tissue formation [7].

6.3. Electrolarynx:

A number of the laryngectomees who cannot succeed to acquire esophageal speech after total laryngectomy prefer to use artificial electrolarynx (EL) [67], [68]. This is an hand-held, battery-powered device that is pressed against the neck [13], [55]. It possesses low-frequency oscillator with a vibrating diaphragm [59]. When the electrolarynx is placed against the neck and energized, the diaphragm is acted by the electromechanical vibrator. The vibrations created by the vibrator pass through the neck tissue into the pharynx. Then, they are modulated into speech by oral cavity and by the articulators such as tongue, lips as illustrated in Figure 6. 4 [55], [56], [57].

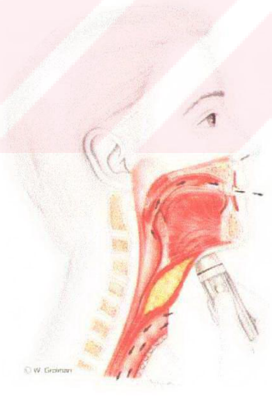


Figure 6. 4. Speech with Electrolarynx

Since it is easier to learn how to use it, EL may be considered as an alternative method for voice restoration after total laryngectomy. Nevertheless, it has a number of drawbacks; For an efficient sound transmission, a pocket of skin that covers the vibrator head is necessary. However, in some cases, since the neck tissues are thickened, edematous and inelastic due to the post surgical swelling after a radical surgery, it is not possible to find such a suitable location for a good acoustic transmission. In addition, formation of bands of scar tissue occurred during the healing of fistulae due to the pre-operative radiotherapy reduces also the acoustic energy transmitted through the neck tissue [69], [70]. Therefore, the laryngectomees must wait until the healing process of tissues becomes completed before introducing EL [56].

Each time that the laryngectomee intends to use EL, he or she has to place the head of the vibrator on the right and the same location on the neck [55], [56], [70]. So, that does not seem to the patient very practical.

The throat may be anaestetic after the surgery. The patient has difficulties to find exactly the right place to hold the head of the vibrator for an efficient acoustic transmission [70], [71].

While talking, the patient must hold the device using one of their hands because of the design of EL. Therefore, one hand is incapacitated during the speech production [72], [73].

7. DESCRIPTION OF THE SYSTEM

A method that will be used for voice restoration must produce vibrations which are virtually the same as the fundamental frequency f_0 of the vocal cords. An electronic circuit that generates pulses and converts them into the audible sounds at that frequency by means of a speaker may be used for this purpose. The whole circuitry must comprise a power source, a signal generating circuit, an audio amplifier, an intra-oral sound source and tongue activated controls associated with a flip-flop. All of these components may be placed in a dental prosthesis that will protect them from the moisture of the oral cavity. The block diagram and the circuit diagram of that circuitry is represented in Figure 7. 1 and in Figure 7. 2 respectively

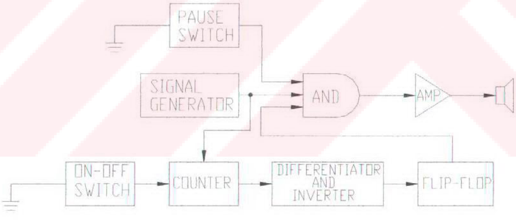


Figure 7. 1 Block Diagram of the System

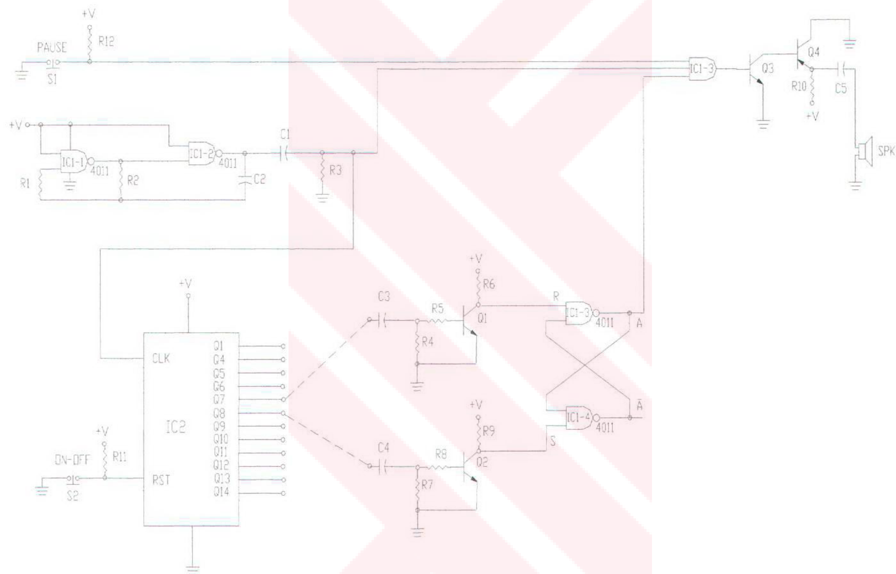


Figure 7. 2. Circuit Diagram of the System

7.1. The Signal Generating Circuit:

The signal generating circuitry includes a square-wave signal generator and differentiator. This square-wave signal generator comprises an astable multivibrator generating a signal with a frequency of 130 Hz. Two of four NAND gates of IC-1 (MC14011) is used for this purpose. The logic diagram and the input and output pin connections of MC4011 are shown in Figure 7. 3. R1, R2 and C2 determine the frequency of that signal.

The output of the signal generating circuit is differentiated in order to obtain spikes that corresponds to the frequency and amplitude of the square waves by a first order differentiator consisting of the resistor R3 and the capacitor C1. These spikes are separated by long near-zero voltage time period with duty cycle of about 0.85%. Thus an audio flicker effect is obtained to have signals to be audible.

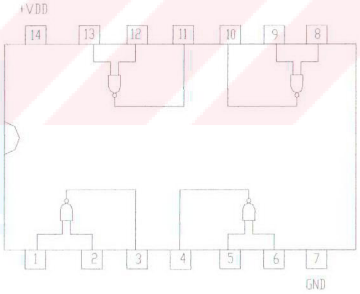


Figure 7. 3. Logic Diagram of MC14011

7.2. The Controlling Switches:

The system is controlled via a tongue activatable intraoral switching device to activate or deactivate the system. These functions are achieved through a timing means. An on-off switch made of two adjacent silver contacts controls the timing device comprising a counter. The timing closure is accomplished by a completion of a ground path through contacts. Bridging between adjacent contacts with the tongue does this grounding. The counter IC2 (MC14020B) counts in response to the output (CLK) of the signal generating circuit when contacts of the on-off switch are grounded by holding the tongue against the contacts. The counter is inhibited if the contacts are not grounded and do not count the output of the signal generating circuit. As a result, the user must hold his/her tongue for a preselected period of time after which an output signal is sent to differentiator and inverter.

The user may remove the tongue when he/she hears the sound from speaker. So, the flip-flop will remain "on" position. This switching circuit prevents also accidental activation or deactivation of the system.

The pause switch including two silver contacts is used to temporarily disable the system by momentarily deactivating the amplifier and speaker. Under normal conditions, these pause contacts are open. The signal going to "AND" gate through R12 is high in order to permit the impulses coming from the differentiator of the signal generating circuit to pass to the amplifier and then to the speaker provided that the signal coming from the flip-flop is also high.

7.3. The Counter :

The Counter circuit that is used to adjust on-off times comprises IC2 (CD4020BE). It is a 14– stage binary counter and is used in this system as a frequency dividing circuit. The logic diagram of MC4020B is shown in Figure 7. 4. When the grounding is established in on-off switch, the voltage at the node where R11 and Pin 11 of IC2 being the Reset (RST) of that integrated circuit are connected, drops to zero. So, the impulses coming from the differentiator of the signal generating circuit are permitted to come to the Clock of IC2 (CLK) as inputs. IC2 includes R-S type flip-flops and buffered outputs can be obtained from stage 1 (Q1) and Q4 thru Q14. In every stage the frequency of the signal generator output is divided by 2. In this system, in order to accomplish a regular switching function that the user can easily profit, the outputs are taken from Q7 and Q8. So, the output frequency of the signal generating circuit is divided either by 2^7 or 2^8 and the resulting frequencies are approximately 1 Hz, and 0.5 Hz. The duration necessary of holding the tongue on the silver contacts to switch on the circuit is 1 second, and that to switch off the circuit is 2 seconds.

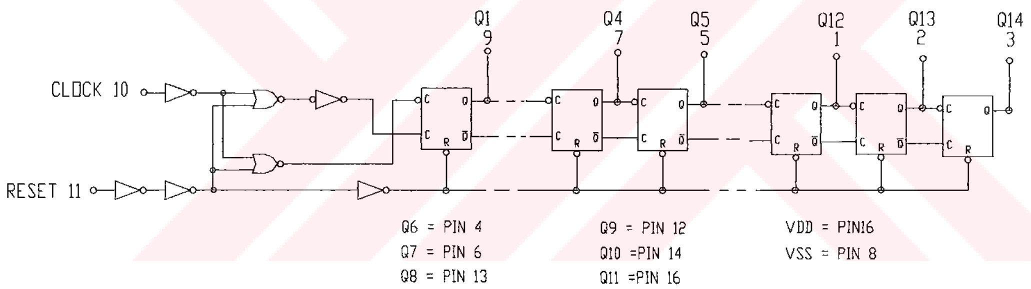


Figure 7. 4. Logic Diagram of MC14020B

7. 4. The Differentiator and The Inverter:

The outputs of IC2 are square wave signals of frequencies of 0.5 Hz and 1Hz. They are differentiated either by the differentiator consisting of C3 and R4 or by those consisting C4 and R7 to obtain impulses. So, the flip-flop is driven is driven by these impulses via the inverter. When the impulse comes to the bases of the transistors either Q1 or Q2 in the inverter, the current passing through either R6 or R9 is lead to the ground. Therefore, the voltage at the nodes where Q1, R6, IC1-3 or Q2, R9, IC1-4 are interconnected drops to zero.

7. 5. Flip – Flop:

That circuit is a bistable multivibrator device. It is set up using two of four NAND gates of IC1 (MC4011B). When the voltage at the node where *S* input is connected drops to zero, the input *S* of flip-flop becomes low level signal. Since $S = 0$, the output *A* of IC1-3, becomes 1 whether the other input of IC1-3 is 1or not. On the other hand, $R = 0$ and the other input of IC1-4 which is connected to *A* output is equal to 1. The output $\bar{A}$ of IC1-4 which is also the input of IC1-3 becomes 0. The flip-flop is on position to provide a high level signal to the AND gate.

When the voltage at the node where *R* input is connected drops to zero, a low-level signal is provided to IC1-4 as input. The output $\bar{A}$ of IC1-4 which is also the input of IC1-3 becomes 1. As a result, *A* becomes zero and a low level signal to AND gate. This is the off position of flip-flop.

7.6. The AND Gate:

The AND gate used in this circuitry should have three input and one output. For that purpose one of three AND gates of IC3 (MC14073) is used. The logic diagram of MC14073 is illustrated in Figure 7. 5. The inputs are connected to the differentiator of the signal generating circuit, to the pause switch and to the output of flip-flop. The output is connected to the amplifier.

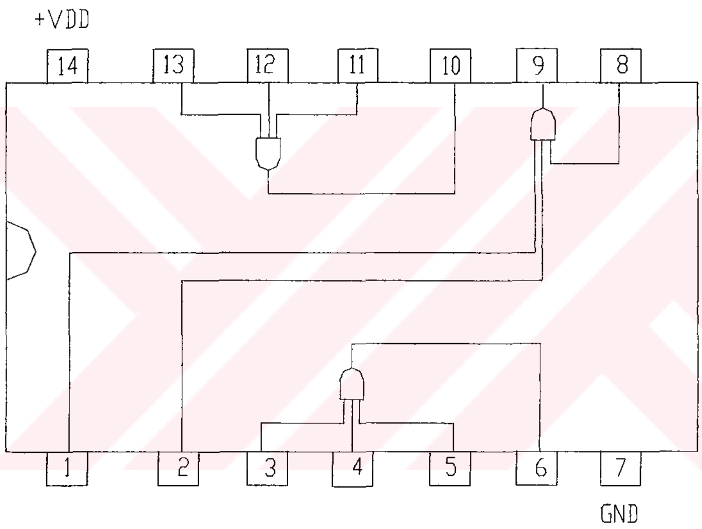


Figure 7.5. Logic Diagram of MC14073B

Provided that the pause contact is not grounded and if the output of the flip-flop is a high level signal when it is on position, the AND gate permits the impulses of the signal generating circuit to drive the amplifier. Thus, the speaker begins to generate sound.

If the pause switch is grounded, the voltage at the node where one of the inputs and R12 are connected drops to zero. So, the output of the AND gate becomes zero. The circuit stops to generate sound.

If the bistable multivibrator is off position, it provides to the AND gate a low level signal. The output of the AND gate becomes again zero in order to switch off the circuit.

7. 7. The Amplifier :

The impulses being allowed to pass through the AND Gate come to the amplifier of the system. The output of the AND gate is connected to the base of the transistor Q3. When a high-level impulse comes to the base of Q3, the collector has a negative polarity. Then the base of Q4 is triggered and this transistor begins switching function. As a result, power amplification is achieved due to the gain of the transistors Q3 and Q4. The amplified impulses of frequency of 130 Hz are the converted to the audible sounds by means of a speaker connected to the output of the amplifier.

7. 8. The Power Supply of the System:

Due to the constraint of place, it was necessary to use a power supply being not only as small as possible in size but also powerful enough to satisfy the energy requirements of the system. Two lithium batteries of type CR1220 that are appropriate in dimension were used. They have voltages of 3 volts. So, they could provide 6 volts to the system when they are connected in series. A battery-pack with contacts establishing connection in series to obtain of the batteries is manufactured and mounted to the dental prosthesis.

7. 9. The Setup of the System:

The aforementioned circuit was setup experimentally on a breadboard as illustrated in Figure 7. 6. At the following stage, in order to manufacture a circuit that can be placed in a dental prosthesis, a printed circuit board (PCB) suitable in size was designed and prepared using the serigraphy method. The micro-components of the resistors, of the capacitors and the transistors and the SMD components of the integrated circuits that were used in the experimental setup were soldered on this PCB. These components are described in table 7.1.

The circuit board, the speaker, the control switches and the battery pack are mounted in a dental prosthesis as shown in Figure 7. 7. Finally the circuit was coated with acrylic to protect the system from the moisture of the mouth

Table 7. 1. The Description of the Components of the System

Component	Description	Component	Description
R1	Resistor 2.2 M	C1	Capacitor 0.0018µF
R2	Resistor 270 K	C2	Capacitor 10nF
R3	Resistor 18 K	C3	Capacitor 10nF
R4	Resistor 1 M	C4	Capacitor 10nF
R5	Resistor 1 M	C5	Capacitor 10nF
R6	Resistor 100 K	Q1	BC 107 NPN Transistor
R7	Resistor 1 M	Q2	BC 107 NPN Transistor
R8	Resistor 1 M	Q3	BC 107 NPN Transistor
R10	Resistor 2.7 K	Q4	BC 177 PNP Transistor
R11	Resistor 10 K	IC 1	MC4011B Quad 2-input NAND Gate
R12	Resistor 10 K	IC 2	MC4020B 14-Stage Binary Counter
SPK	Buzzer	IC 3	MC14073 Triple 3 input AND Gate

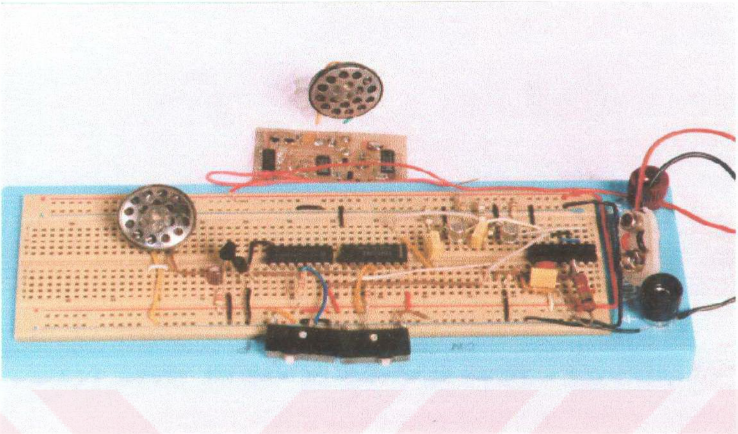


Figure 7. 6. The Experimental Setup of the IAL System

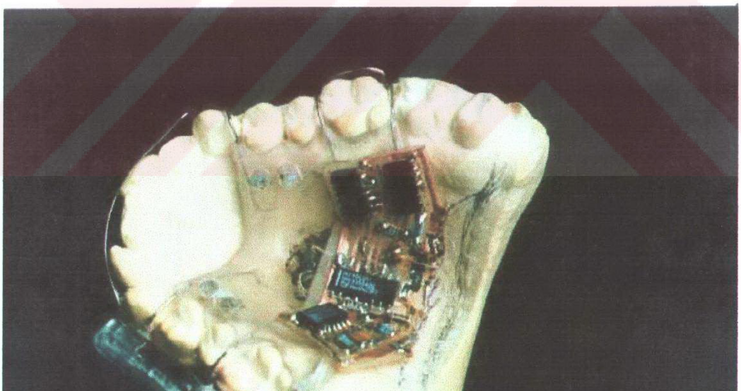


Figure 7. 7. The Circuit Mounted on a Dental prosthesis

8. CLINICAL STUDIES

8. 1. The Aim of the Clinical Studies:

After the setup of the prototype of the Intraoral Artificial Larynx (IAL) system, in order to test the performance of the system, to clarify the aspects that must be improved of the system, a comparative study with an accepted speech rehabilitation method such as electrolarynx (EL) was decided. The clinical application was planned to use two patients. The reason of choosing EL is due to its nature of sound similar to that of IAL.

8. 2. The Patients:

Two laryngectomees operated in Izmir Ataturk Devlet Hastanesi were chosen for this study. One of the patients being sixty-five years old was operated fourteen years ago. He had tried to perform ES but since his coughing reflex is provoked while swallowing boli of air into the esophagus. He, therefore, gave up to use this method. The other patient being sixty-four years old could not also be successful in performing ES.

8. 3. The IAL Systems Used in the Clinical Studies:

Two circuits are manufactured for this study. Two dental prostheses individual to each patient are prepared in a dental clinic. The appropriate places are digged on these prostheses to embed the circuit boards, the cables, the speaker, the battery pack and the switches. They are coated with acrylic.

8. 4. Training of Patients:

Due to the fact that the gag-reflex is provoked easily, the speaker is cannot be placed at a location being over the hard palate. Therefore, it is not possible to profit the acoustic transfer function of the whole vocal tract efficiently. So, this problem might be solved by exaggerated use of the articulators. The patients should be trained to gain the skill of exaggerated articulation.

According to the speech therapists advises working in İzmir Ataturk Devlet Hastanesi, a training program was prepared.

In the first stage of the training, the pronunciation of Turkish vowels and consonants is trained respectively using the protocols below:

[a]: The teeth must be open. The tongue must be moved backwards. The jaw must be moved downwards.

[ı]: The teeth must be closed. The mouth must be pulled both to the left and right side. The tongue must be moved backwards.

[o]: The mouth must be rounded. The jaw must be moved downwards. The tongue must be moved backwards.

[u]: The lips must be supershaped. The tongue must be moved backwards.

For [e], [i], [ö], and [ü], The same articulatory gestures must be performed as [a], [ı], [o], and [u] in exception with The position of the tongue being forwards.

[b]: The lips must be closed tightly. The mouth is filled with air. Then the air is released with a moderate force.

[p]: The same gestures as [b] must be applied. However, the explosive release of air must be performed.

[m]: The lips are closed, but they are not brought together tightly as in case of [b] and [p]. The air taken into the mouth is released slightly.

[f]: The upper teeth are touched to the lower lip. The air released vigorously.

[v]: The same gestures must be applied as [f]. However, the air must be released vibrating the lips.

[t]: The tip of tongue is hold between the teeth. A forward force must be applied from the root of the tongue. A strong release of air must be performed.

[d]: The same gestures as [t] must be performed. But the air must be released slightly.

[l]: The tip of tongue is pushed toward rear part of the upper teeth while releasing the air.

[ç]: The hump of tongue is pushed toward the palate, while releasing the air strongly.

[c]: It is pronounced as [ç] with exception of releasing air softly.

[s]: The tip of tongue is touched to the palate slightly. The air is released slightly from the left and right sides of the tongue.

[ş]: Almost the same gesture of tongue is established as [s]. The tongue is pulled toward the root of the tongue. The tongue is widened toward the left and right. The air is released vigorously.

[z]: The tip of tongue is hold between the upper and lower teeth. The tongue is widened to the left and right sides in the mouth. The tongue is touched slightly to teeth when the air is released.

[j]: The same gestures as [ş] in exception of rounding the mouth.

[y]: The tongue is pulled backwards from its root. The jaw is moved downwards. The mouth is widened to both right and left sides.

[n]: The hump of tongue is pushed towards the palate, while releasing the air.

[h]: The mouth is open. The tongue is pulled backwards. The jaw is moved downwards. the tip of tongue is touched to the lower teeth. The air is released vigorously.

[k]: The tongue is pulled backwards from the root. The jaw is moved downwards. The tip of tongue is touched to the lower teeth. The air is released vigorously.

[g]: The same gestures must be performed as [k]. The air is released vigorously.

[r]: The tip of tongue is vibrating when it touches to the palate.

In the second stage of the training, the words used by the patients in their daily life are chosen. The patients are required to pronounce these words with the exaggerated articulatory gestures taught in the first stage using the IAL system.

In the third stage of the training, the patients are trained to read sentences and paragraphs chosen from the newspapers and magazines.

8. 5. The Records:

Two sets of reading materials are prepared individual to each patient consisting of five paragraphs meaningful in context and one paragraph consisting of twenty-five independent Turkish words.

Audio records are established while the patients were reading their reading materials on an audiocassette in a place having relatively less background noise. Both EL and IAL are used during the records. These records are transferred to a recordable CD in order to prepare testing materials in a PC.

8. 6. Testing Process :

To prevent the testers to be biased, the reading materials read by the patients are distributed successively according to the system used. For this purpose, two categories of testing materials are formed using Cool-Edit Program.

Twelve testers are used for this purpose. Each category was listened by six of twelve testers. Each paragraph was listened by twelve testers, so that each paragraph read by using IAL was listened by six of twelve testers, and the same paragraph read by using EL by the other six testers.

Each paragraph was divided into sentences using Cool-Edit Program. Each sentence was listened five times by the testers. The testers are requested to write what they perceived and understood on a form prepared for this purpose (See Appendix A).

The testing process is established in the PC laboratory of the Institute of Biomedical Engineering having relatively less environmental noise.

8. 7. Evaluation of the Data Acquired in the Testing Process:

The success percentage of each sentence of each paragraph was calculated using the rates of correct perceived words to the total number of the words in a sentence for each tester, for each system, for each listening session. The average of success percentages of the sentences included in a paragraph is computed to find the success percentage of each paragraph.

For the sixth paragraph, the success percentage was calculated using the rate of the numbers of correctly understood words to twenty-five which is the total number of words of the sixth paragraphs. The averages of success percentages are calculated for each patient, for each system, for each listening session. These success percentages are represented in bar charts for each patient, for each system, for each listening session.

8.8. Results:

The average success percentages of each paragraph of the first patient for each listening session are tabulated in table 8.1. According to this table, five different bar charts are drawn to illustrate and to compare the success percentages of IAL and EL.

Table 8. 1.

The average success percentages of IAL and EL for each paragraph of the first patient (H1) for listening sessions L1 through L5,

H1	L1		L2		L3		L4		L5	
	IAL	EL	IAL	EL	IAL	EL	IAL	EL	IAL	EL
P1	34	47	45	62	53	57	76	49	60	40
P2	20	83	31	71	25	78	30	84	20	80
P3	19	76	47	53	37	87	42	89	30	70
P4	35	74	32	77	29	68	29	78	30	70
P5	29	68	55	66	40	70	45	77	30	60
P6	21	31	24	30	31	31	20	30	29	33

The average success percentages for the first patient for the first listening session (L1) are illustrated in Figure 8.1. for each system. According to this chart, the success percentages of EL are higher than those of IAL.

According to the chart represented in Figure 8. 2., the success percentage of IAL is increased significantly for the first, third, fifth, and sixth paragraphs in the second listening session L2.

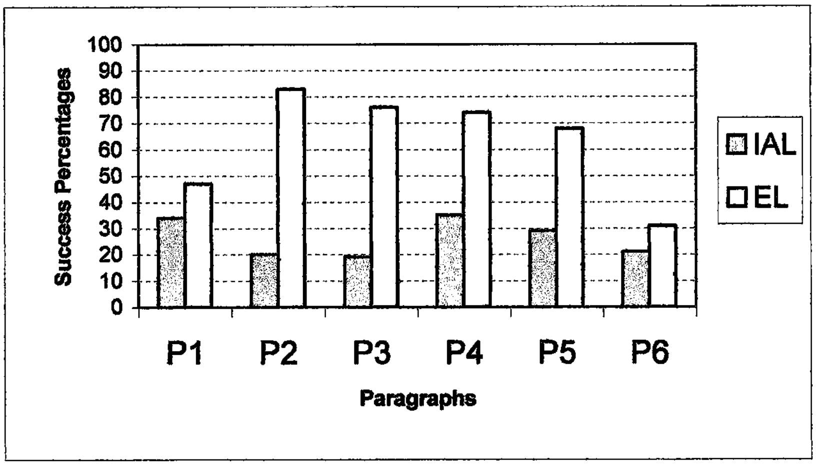


Figure 8. 1. The average success percentages in the first Listening session (L1) for the first patient (H1)

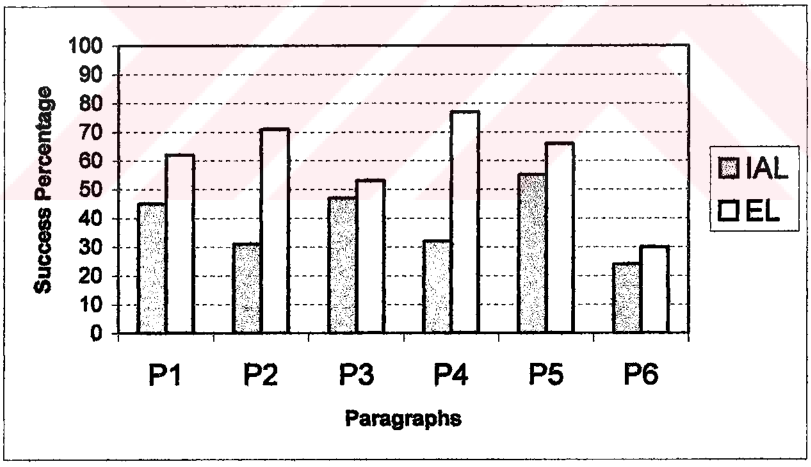


Figure 8. 2. The average success percentages in the second Listening Session (L2) for the first patient (H1)

In the third listening session as shown in Figure 8.3. there is no significant differences between EL and IAL for the first paragraph, in contrary to other paragraphs. For the sixth paragraph the performance of both system is the same.

In the fourth listening session that is represented in Figure 8. 4., there is a significant increase in the performance of IAL for the first paragraph. And also it has higher success percentage than that of EL for that paragraph. On the other hand, EL seems to have higher performance for the other paragraphs. In the sixth paragraph, EL has a higher percentage. But that difference is moderate.

In the fifth listening session being illustrated in Figure 8. 5, the same situations are occurring as the fourth listening session. Furthermore, the difference between the performances of both systems in sixth paragraph is decreased.

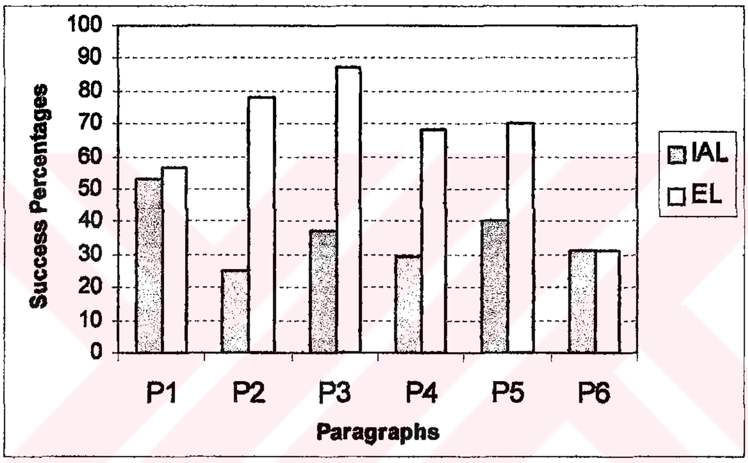


Figure 8. 3. The average success percentages in the Third Listening Session (L3) for the first patient (H1)

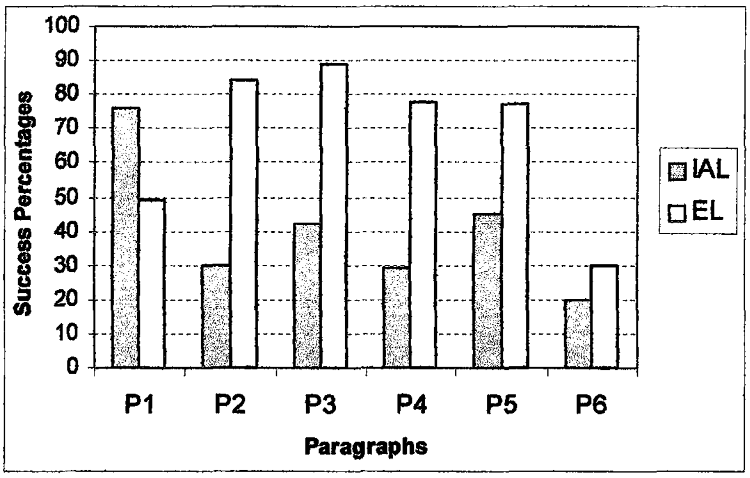


Figure 8. 4. The average success percentages of EL and IAL in the Fourth Listening Session (L4) for the first patient (H1)

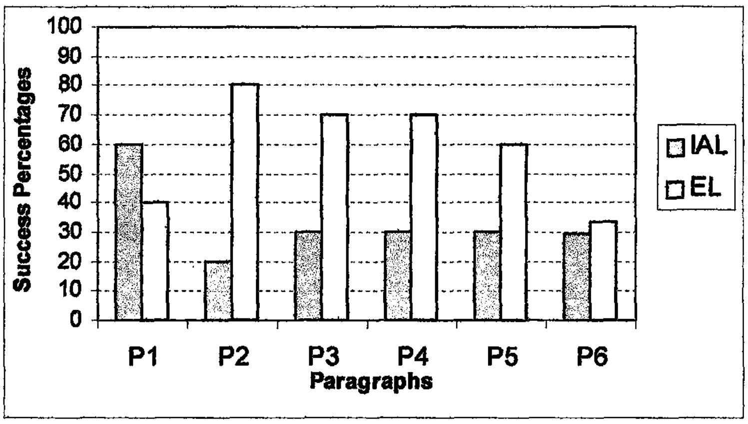


Figure 8. 5. The average success percentages in the Fifth Listening Session (L5) for the first patient (H1)

The average success percentages of both EL and IAL systems for the second patient for each paragraph and for each listening session are tabulated in Table 8. 2 in order to obtain charts to compare the performances of both systems.

Table 8. 2.

The average success percentages of IAL and El for each paragraph of the second patient-2 (H2) for listening sessions L1 through L5,

H2	L1		L2		L3		L4		L5	
	IAL	EL	IAL	EL	IAL	EL	IAL	EL	IAL	EL
P1	22	36	19	48	27	50	38	63	48	49
P2	48	40	51	53	57	37	56	57	63	57
P3	67	37	83	38	80	67	86	69	86	70
P4	40	76	50	81	43	67	53	68	57	61
P5	32	32	40	50	45	50	45	56	45	56
P6	49	40	47	39	45	53	60	40	55	39

According to the chart shown in Figure 8. 6 for the first listening session L1, the success percentage of EL is better than that of IAL in the first paragraph. The performance of IAL is higher with a little difference second paragraph. The performance of IAL is significantly higher than that of EL, in the third paragraph in contrary to fourth paragraph.

In the fifth paragraph the success percentages of both system are equals. In the sixth paragraph, the success percentage of IAL is again higher than that of EL.

In the second listening session illustrated in the chart illustrated in Figure 8. 7., the percentage of EL is still higher than that of IAL for the first and fourth paragraphs. In the second paragraph the performance of both system is almost the same. In the third paragraph, the performance of IAL is better than that of EL like in the first session. The percentage of EL becomes higher with a little difference for the fifth paragraph. For the sixth paragraph, the same situation is continuing as the first listening session.

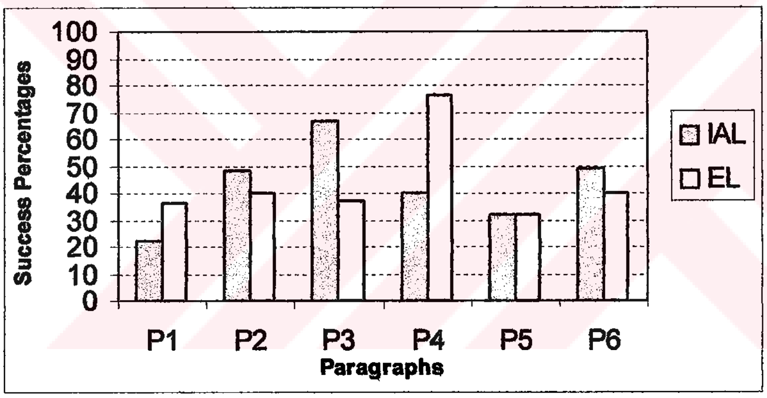


Figure 8. 6. The average success percentages in the First Listening Session (L1) for the second patient (H2)

In the third listening session represented with the chart of Figure 8. 8, EL has better success rates for the first and fourth paragraphs, where as IAL has higher percentages for the second and the third paragraphs. EL has higher percentages for the fifth and sixth paragraphs with little differences.

For the fourth session, EL has higher percentages again for first, and fourth paragraphs. Both systems have virtually the same percentages for the second paragraph while in fifth paragraph EL is more successful. In sixth paragraph, IAL is significantly higher performance. These results are illustrated in Figure 8. 9.

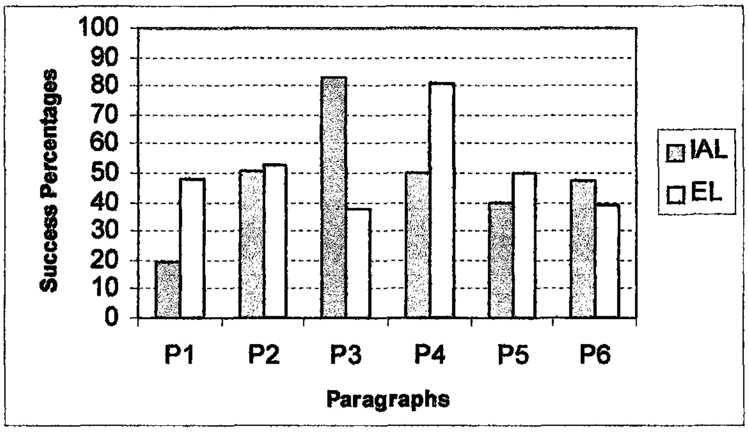


Figure 8. 7. The average success percentages in the second Listening Session (L2) for the second patient (H2)

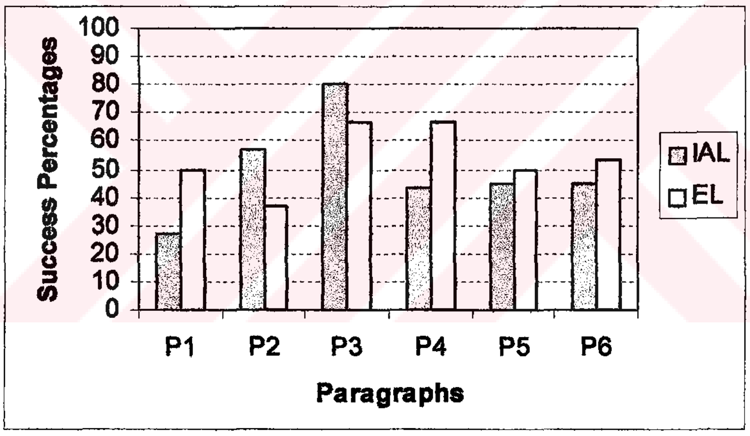


Figure 8. 8. The average success percentages in the third Listening Session (L3) for the second patient (H2)

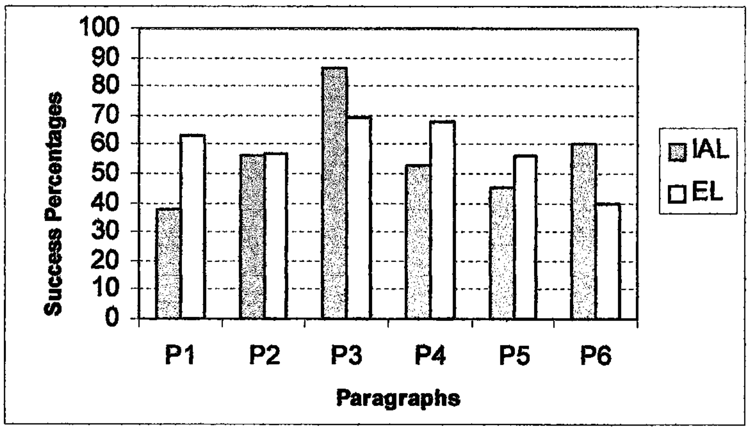


Figure 8. 9. The average success percentages in the fourth Listening Session (L4) for the second patient (H2)

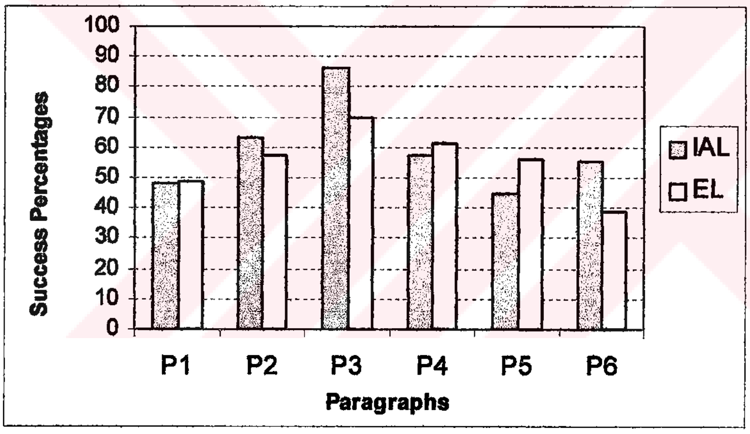


Figure 8. 10. The average success percentages the fifth Listening Session (L5) for the second patient (H2)

In the fifth listening session represented by the chart in Figure 8. 10, both systems have almost the same performance for the first paragraph. For the second paragraph, IAL has a better success rate with a little difference. IAL has still higher success percentages in the third paragraph. EL is more successful in the fourth and fifth paragraph with a little. For the sixth paragraph IAL has again significantly higher performance.

8. 9. Discussion:

For the first patient, the success percentages of EL are higher than those of IAL with little differences or they are almost equal for the sixth paragraph. For that paragraph consisting of twenty-five independent words, instead of long sentences, the patient had an occasion to rest between each word. In addition, to establish exaggerated articulations was easier for each word of that paragraph in contrary to a continuous speech.

For the first patient, the success percentages of EL are significantly higher than that of IAL for all paragraphs except the first paragraph. The success rates of IAL are increased and become higher than those of EL for the first paragraph. These probably result in short sentences of that paragraph easier to utter in a continuous speech.

The success rates of IAL are increased and become higher than that of EL for the first paragraph in the three last sessions. That situation may be explained with the increased perceptions of the testers in the preceding listening sessions. Due to the fact that the testers may not be focused to the testing materials in the first sessions, their lower comprehensions are probably reflected to the success rates. So, each sentence of each paragraph is repeated five times in order to provide the occasion of understanding contexts of the paragraphs in the following listening sessions.

The lower success rates of IAL in paragraphs having long sentences may be related to the salivation stimulated by the silver contacts of the pause switch of IAL system. THA patient was establishing a grounding path between these contacts to stop between each word of these sentences by using the tip of his tongue. So, the current passing through his tongue was exciting the salivation especially at the end of the long sentences. Therefore, to perform a continuous speech became difficult for that patient in those paragraphs.

The thickness of the prosthesis is another factor to be considered. Due to the morphological structure of his palate, the prosthesis of the first patient was thickened to gain sufficient place to install the circuit board, the battery pack and the speaker by covering acrylic after the fixation of these three parts of the system. As a result, the movements of tongue of that patient are restricted for an efficient continuous speech.

For the second patient, the performance of IAL is higher for the sixth paragraph. That may be the result of either the structure of dental prosthesis that do not restrict the movements of the tongue due to its suitable morphological structure or the individual skill of that patient in performing exaggerated articulation.

EL is more successful in the first paragraph for second patient except the fifth listening session. The success percentages of IAL for the second and third paragraphs are higher than that of EL or they are almost equal. However the performance of EL is higher in the fourth and fifth paragraphs. But the differences of both systems are decreased in the third, fourth and fifth sessions for these paragraphs. Although the success of EL in these paragraphs may be related to length of sentences of those paragraphs, the success rates of IAL for the second patient are higher in general, than those for the first patient. That may be explained by the suitable morphological structure of the palate of that patient being wide and shallow that permits to install circuit boards and the other complementary units without increasing the thickness of the dental prosthesis. In addition, there was sufficient place for this purpose due to the removed teeth of that patient. Therefore, the movements of his tongue are less restricted for an efficient articulation. And also, since the constraint of place was less than that of first patient, there was a possibility of installing a push-button switch which he might control by pressing with his tooth, and which does not disturb the patient as the silver contacts of the first patient provoking the salivation.

9. CONCLUSION

Even though IAL has success rates similar to f EL or higher than EL in some cases, EL has higher performance than IAL in general. Since the output amplitude of EL is higher than that of IAL, it provides more intelligible and comprehensive speech. This may be related to the difference between the power supplies of both systems. Since there is no constraint of place for the battery pack in EL, it is possible to use powerful and rechargeable batteries that allow to generating vibrations of greater amplitude. For IAL, the batteries should be as small as possible to be placed in a dental prosthesis. The lithium batteries of watches, which are not powerful as well as those of EL, are used for this study. More powerful and rechargeable batteries appropriate in size for IAL may be specially designed and produced by the battery manufacturers in the future.

The circuit board and the complementary units could not be minimized due to the insufficient technical possibilities. So the increased thickness of dental prosthesis due to the dimension of the circuitry has been restricted the movements of the tongue. If the circuitry as small as possible in size can be designed and manufactured by using hybrid technologies, the dental prosthesis may be covered by acrylic in convenient thickness. As a result, standard IAL systems that are not specific to divers morphological structures of different patients may be established.

The metal contacts of switches have been provoked the salivation of the patients due to the current passing through the tip of their tongue when they have been establishing a grounding path between these adjacent contacts. This is also restricting the patients to perform an efficient continuous speech. New switches made of rubber and that can be pressed either by the tongue or the teeth of patients may be designed and applied to this IAL system.

The EL systems can use the whole acoustic transfer function of the vocal tract whether it is placed to the correct location on the neck. This situation gives EL to produce almost correct formants that is necessary to perform more intelligible speech. In the IAL system, the speaker must be placed at a location that does not provoke the gag reflex of the patients in the dental prosthesis. Therefore, the source of phonation is located in the palate being upper part of the vocal tract. As a result, the IAL system does not profit the whole acoustic transfer function of the vocal tract. The oscillators generating vibrations of frequencies similar to the formants F_1 and F_2 beside the oscillator generating vibrations of f_0 may included to the circuit in the new designs of IAL systems in order to compensate the acoustic transfer function of vocal tract.

The training of patients may be useful in motivating the patients not only in using the system efficiently but also in encouraging them to try to again to communicate with other people. An efficient and short-term training program, which will enhance the articulations of such patients, may be developed and applied by a speech therapist.

APPENDIX: TESTER EVALUATION FORM

The testers were requested to fill a form while they were listening audio records. They were wanted to write on these forms what they understood in each listening session. The abbreviations are representing the following variables;

H1: Patient-1 (First Patient) H2: Patient-2 (Second Patient)

P1: First paragraph of patient-1 p1: First paragraph of patient-2
P2: Second paragraph of patient-1 p2: Second paragraph of patient-2
P3: Third paragraph of patient-1 p3: Third paragraph of patient-2
P4: Fourth paragraph of patient-1 p4: Fourth paragraph of patient-2
P5: Fifth paragraph of patient-1 p5: Fifth paragraph of patient-2
P6: Sixth paragraph of patient-1 p6: Sixth paragraph of patient-2

C1: First sentence of a paragraph for patient-1
C2: Second sentence of a paragraph for patient -1
C3: Third sentence of a paragraph for patient-1
C4: Fourth sentence of a paragraph for patient-1

c1: First sentence of a paragraph for patient-2
c2: Second sentence of a paragraph for patient -2
c3: Third sentence of a paragraph for patient-2
c4: Fourth sentence of a paragraph for patient-2

K1...K25: Words of sixth paragraph for patient-1
k1...k25 : Words of sixth paragraph for patient-2

i: intraoral Artificial larynx e: electrolarynx

L1..L5: First Listening Session through Fifth Listening Session

In order to prevent the testers to be biased during the testing process, each paragraph of each category is distributed successively according to the system as follows;

For category-1;
H1iP1, H1eP2, H1iP3, H1eP4, H1iP5, H1eP6
H2ep1, H2ip2, H2ep3, H2ip4, H2ep5, H2ip6

For category-2;
H1eP1, H1iP2, H1eP3, H1iP4, H1eP5, H1iP6
H2ip1, H2ep2, H2ip3, H2ep4, H2ip5, H2ep6

As an example to illustrate the tester evaluation form, only the parts of this form prepared for the first second and sixth paragraphs of both patients for the category-1 and category-2 successively are represented on the following pages instead of representing whole tester evaluation form.

The notations used in the following examples illustrated in this form are as below;
For category-1;

- H1iP1: First paragraph read by the first patient using IAL
- H1eP2: Second paragraph read by the first patient using EL
- H1eP6: Sixth paragraph read by the first patient using EL
- H2ep1: First paragraph read by the second patient using EL
- H2ip2: Second paragraph read by the second patient using IAL
- H2ip6: Sixth paragraph read by the second patient using IAL

For category-2;

- H1eP1: First paragraph read by the first patient using EL
- H1iP2: Second paragraph read by the first patient using IAL
- H1iP6: Sixth paragraph read by the first patient using IAL
- H2ip1: First paragraph read by the second patient using IAL
- H2ep2: Second paragraph read by the second patient using EL
- H2ep6: Sixth paragraph read by the second patient using EL

Category-1 Tester No (Name): Date:

H1iP1 C1)

L1)

L2)

L3)

L4)

L5)

H1iP1 C2)

L1)

L2)

L3)

L4)

L5)

H1iP1 C3)

L1)

L2)

L3)

L4)

L5)

H1iP1 C4)

L1)

L2)

L3)

L4)

L5)

Category-1 Tester No (Name): Date:

H1eP2 C1)

L1)

L2)

L3)

L4)

L5)

H1eP2 C2)

L1)

L2)

L3)

L4)

L5)

H1eP2 C3)

L1)

L2)

L3)

L4)

L5)

Category-1 Tester No (Name): Date:

H1eP6

K1:	**K2:**	**K3 :**	**K4 :**	**K5:**
L1)	L1)	L1)	L1)	L1)
L2)	L2)	L2)	L2)	L2)
L3)	L3)	L3)	L3)	L3)
L4)	L4)	L4)	L4)	L4)
L5)	L5)	L5)	L5)	L5)
K6:	**K7:**	**K8:**	**K9 :**	**K10:**
L1)	L1)	L1)	L1)	L1)
L2)	L2)	L2)	L2)	L2)
L3)	L3)	L3)	L3)	L3)
L4)	L4)	L4)	L4)	L4)
L5)	L5)	L5)	L5)	L5)
K11:	**K12:**	**K13 :**	**K14 :**	**K15:**
L1)	L1)	L1)	L1)	L1)
L2)	L2)	L2)	L2)	L2)
L3)	L3)	L3)	L3)	L3)
L4)	L4)	L4)	L4)	L4)
L5)	L5)	L5)	L5)	L5)
K16:	**K17:**	**K18 :**	**K19 :**	**K20:**
L1)	L1)	L1)	L1)	L1)
L2)	L2)	L2)	L2)	L2)
L3)	L3)	L3)	L3)	L3)
L4)	L4)	L4)	L4)	L4)
L5)	L5)	L5)	L5)	L5)
K21:	**K22:**	**K23:**	**K24 :**	**K25:**
L1)	L1)	L1)	L1)	L1)
L2)	L2)	L2)	L2)	L2)
L3)	L3)	L3)	L3)	L3)
L4)	L4)	L4)	L4)	L4)
L5)	L5)	L5)	L5)	L5)

Category-1 Tester No (Name): Date:

H2ep1 c1)

L1)

L2)

L3)

L4)

L5)

H2ep1 c2)

L1)

L2)

L3)

L4)

L5)

H2ep1 c3)

L1)

L2)

L3)

L4)

L5)

H2ep1 c4)

L1)

L2)

L3)

L4)

L5)

Category-1 Tester No (Name): Date:

H2ip2 c1)

L1)

L2)

L3)

L4)

L5)

H2ip2 c2)

L1)

L2)

L3)

L4)

L5)

H2ip2 c3)

L1)

L2)

L3)

L4)

L5)

Category-1 Tester No (Name): Date:

H2ip6

k1:	**k2:**	**k3 :**	**k4 :**	**k5:**
L1)	L1)	L1)	L1)	L1)
L2)	L2)	L2)	L2)	L2)
L3)	L3)	L3)	L3)	L3)
L4)	L4)	L4)	L4)	L4)
L5)	L5)	L5)	L5)	L5)
k6:	**k7:**	**k8 :**	**k9 :**	**k10:**
L1)	L1)	L1)	L1)	L1)
L2)	L2)	L2)	L2)	L2)
L3)	L3)	L3)	L3)	L3)
L4)	L4)	L4)	L4)	L4)
L5)	L5)	L5)	L5)	L5)
k11:	**k12:**	**k13 :**	**k14 :**	**k15:**
L1)	L1)	L1)	L1)	L1)
L2)	L2)	L2)	L2)	L2)
L3)	L3)	L3)	L3)	L3)
L4)	L4)	L4)	L4)	L4)
L5)	L5)	L5)	L5)	L5)
k16:	**k17:**	**k18 :**	**k19 :**	**k20:**
L1)	L1)	L1)	L1)	L1)
L2)	L2)	L2)	L2)	L2)
L3)	L3)	L3)	L3)	L3)
L4)	L4)	L4)	L4)	L4)
L5)	L5)	L5)	L5)	L5)
k21:	**k22:**	**k23:**	**k24 :**	**k25:**
L1)	L1)	L1)	L1)	L1)
L2)	L2)	L2)	L2)	L2)
L3)	L3)	L3)	L3)	L3)
L4)	L4)	L4)	L4)	L4)
L5)	L5)	L5)	L5)	L5)

Category-2 Tester No (Name): Date:

H1eP1 C1)

L1)

L2)

L3)

L4)

L5)

H1eP1 C2)

L1)

L2)

L3)

L4)

L5)

H1eP1 C3)

L1)

L2)

L3)

L4)

L5)

H1eP1 C4)

L1)

L2)

L3)

L4)

L5)

Category-2 Tester No (Name): Date:

H1iP2 C1)

L1)

L2)

L3)

L4)

L5)

H1iP2 C2)

L1)

L2)

L3)

L4)

L5)

H1iP2 C3)

L1)

L2)

L3)

L4)

L5)

Category-2 Tester No (Name): Date:

H1iP6

K1:	**K2:**	**K3 :**	**K4 :**	**K5:**
L1)	L1)	L1)	L1)	L1)
L2)	L2)	L2)	L2)	L2)
L3)	L3)	L3)	L3)	L3)
L4)	L4)	L4)	L4)	L4)
L5)	L5)	L5)	L5)	L5)
K6:	**K7:**	**K8:**	**K9 :**	**K10:**
L1)	L1)	L1)	L1)	L1)
L2)	L2)	L2)	L2)	L2)
L3)	L3)	L3)	L3)	L3)
L4)	L4)	L4)	L4)	L4)
L5)	L5)	L5)	L5)	L5)
K11:	**K12:**	**K13 :**	**K14 :**	**K15:**
L1)	L1)	L1)	L1)	L1)
L2)	L2)	L2)	L2)	L2)
L3)	L3)	L3)	L3)	L3)
L4)	L4)	L4)	L4)	L4)
L5)	L5)	L5)	L5)	L5)
K16:	**K17:**	**K18 :**	**K19 :**	**K20:**
L1)	L1)	L1)	L1)	L1)
L2)	L2)	L2)	L2)	L2)
L3)	L3)	L3)	L3)	L3)
L4)	L4)	L4)	L4)	L4)
L5)	L5)	L5)	L5)	L5)
K21:	**K22:**	**K23:**	**K24 :**	**K25:**
L1)	L1)	L1)	L1)	L1)
L2)	L2)	L2)	L2)	L2)
L3)	L3)	L3)	L3)	L3)
L4)	L4)	L4)	L4)	L4)
L5)	L5)	L5)	L5)	L5)

Category-2 Tester No (Name): Date:

H2ip1 c1)

L1)

L2)

L3)

L4)

L5)

H2ip1 c2)

L1)

L2)

L3)

L4)

L5)

H2ip1 c3)

L1)

L2)

L3)

L4)

L5)

H2ip1 c4)

L1)

L2)

L3)

L4)

L5)

Category-2 Tester No (Name): Date:

H2ep2 c1)

L1)

L2)

L3)

L4)

L5)

H2ep2 c2)

L1)

L2)

L3)

L4)

L5)

H2ep2 c3)

L1)

L2)

L3)

L4)

L5)

Category-2 Tester No (Name): Date:

H2ep6

k1:	**k2:**	**k3 :**	**k4 :**	**k5:**
L1)	L1)	L1)	L1)	L1)
L2)	L2)	L2)	L2)	L2)
L3)	L3)	L3)	L3)	L3)
L4)	L4)	L4)	L4)	L4)
L5)	L5)	L5)	L5)	L5)

k6:	**k7:**	**k8 :**	**k9 :**	**k10:**
L1)	L1)	L1)	L1)	L1)
L2)	L2)	L2)	L2)	L2)
L3)	L3)	L3)	L3)	L3)
L4)	L4)	L4)	L4)	L4)
L5)	L5)	L5)	L5)	L5)

k11:	**k12:**	**k13 :**	**k14 :**	**k15:**
L1)	L1)	L1)	L1)	L1)
L2)	L2)	L2)	L2)	L2)
L3)	L3)	L3)	L3)	L3)
L4)	L4)	L4)	L4)	L4)
L5)	L5)	L5)	L5)	L5)

k16:	**k17:**	**k18 :**	**k19 :**	**k20:**
L1)	L1)	L1)	L1)	L1)
L2)	L2)	L2)	L2)	L2)
L3)	L3)	L3)	L3)	L3)
L4)	L4)	L4)	L4)	L4)
L5)	L5)	L5)	L5)	L5)

k21:	**k22:**	**k23:**	**k24 :**	**k25:**
L1)	L1)	L1)	L1)	L1)
L2)	L2)	L2)	L2)	L2)
L3)	L3)	L3)	L3)	L3)
L4)	L4)	L4)	L4)	L4)
L5)	L5)	L5)	L5)	L5)

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