# ROENTGENOGRAPHIC TECHNIQUES AND PHONETIC RESEARCH

JOANNE D. SUBTELNY and J. DANIEL SUBTELNY

## INTRODUCTION

The X preceding the word ray was originally used to indicate an unknown factor. To this day, many facts pertaining to the "X" remain unknown and mysterious to some people. To a degree, this is understandable. After all, X-rays are invisible to the human eye, and yet, these same invisible rays can penetrate the deeper structures of the living human and make it possible to visualize hidden structures on specially prepared film. For this very reason, X-ray technology found its greatest and most immediate application in diagnostic procedures, especially in the medical areas. During the earlier years of radiography, there appeared to be limited research interest in the X-ray film. However, this technique has emerged from a somewhat restricted clinical use, until now its use involves a separate specialization in medicine, and as a research technique it has developed in varied forms with potential applications extending far beyond the specific uses to which it was originally applied.

If radiography is to be applied as a research technique, investigators must be thoroughly familiar with its limitations. Each X-ray film reflects these limitations and because of this, X-ray films are subject to abuse as well as to use by investigators. The degree of confidence that can be placed in any X-ray film interpretation depends upon a knowledge of these limitations and methods of dealing with them. Technical limitations are present and possibly a few should be mentioned. The X-ray film is a flat image and represents a composite of many curved surfaces. Because of this many of the desired anatomic structures are poorly defined. Enlargement and distortion of certain structures must always be present in any flat X-ray image. To a great extent, these difficulties can be overcome by the intelligent use of X-ray films and strict adherence to scientific principles in securing and analyzing films.

In addition to understanding the limitations of X-ray technology the judicious application of radiography to phonetic research requires cooperative effort on the part of: individuals capable of obtaining, reading and measuring standardized radiographs as well as individuals versed in the anatomy and physiology of the speaking mechanism. Without this cooperative approach, much useful information may be overlooked. The interpretation of X-ray films is a "science" in itself, which is based on information attained through the study of many X-ray films of a specific area.

It would seem that this skill, in cooperation with the other specialized skills, would provide minimal expenditure of time and the most reliable results.

## X-RAY PROCEDURES

At the present time, three basic radiographic techniques have been developed which can provide the investigator with adequate research tools to visualize and study the speaking mechanism. They are: 1. Cephalometric roentgenography, 2. Cephalometric laminagraphy and 3. Cephalometric cineradiography. Each of these three X-ray techniques is prefacd by the word "cephalometric", which means head measurment. The utilization of the word implies a careful control of the technique employed in obtaining X-ray reproductions of the head and neck (1.) The very same structures are visible in radiographs obtained by conventional X-ray techniques. However, the introduction of cephalometric principles to conventional radiography imposes rigorous standardization in technique and thereby create the possibility of accurate measurements. This has particular value if films are to be quantitatively analyzed in phonetic research. If X-ray films are to be compared and measured, the aforementioned standardized cephalometric procedures must be applied. This requires the placement of the subject in a precise and reproduceable position with a careful control of head and neck posture. A head positioning device is frequently used for this purpose. Usually the head is stabilized within a headholder by means of a rest which engages the bridge of the nose and by ear rods inserted into the ear canals (Fig. 1) The ear rods may be undesirable in phonetic studies, if they affect the speaker's ability to hear and monitor his own speech. For this reason, other devices which do not involve partial blocking of the auditory canal may be applied to prevent postural changes of the head.

It is also imperative that the X-ray film and X-ray source be in fixed positions relative to the head positioner so that, radiographic enlargement and distortion can be controlled. The X-ray source is usually positioned at a fixed five foot distance from the midplane of the head positioning device (1.). The film can be brought adjacent to the lateral aspect of the head which minimizes distortion, or it can be kept at a fixed distance from the midplane of the head holder. The fixed distance allows increased distortion but the degree of magnification, is standardized. If the film is brought as close as possible to the subject, a leaded aluminum scale can be placed at the midplane of the head. An image of the scale appears on the X-ray film and the degree of enlargement can be measured. Some degree of enlargement and distortion is inevitable, but the methods described, control such factors. Standardization in procedure also makes it possible to reposition the subject, in the same fixed relationship of the subject ot the X-ray source, and the X-ray film. This permits one film to be compared to another despite lapses in time intervals.

Each of the three X-ray techniques, previously mentioned, has certain advantages

Fig. 1. Subject stabilized within a headholder controlling head and neck posture.

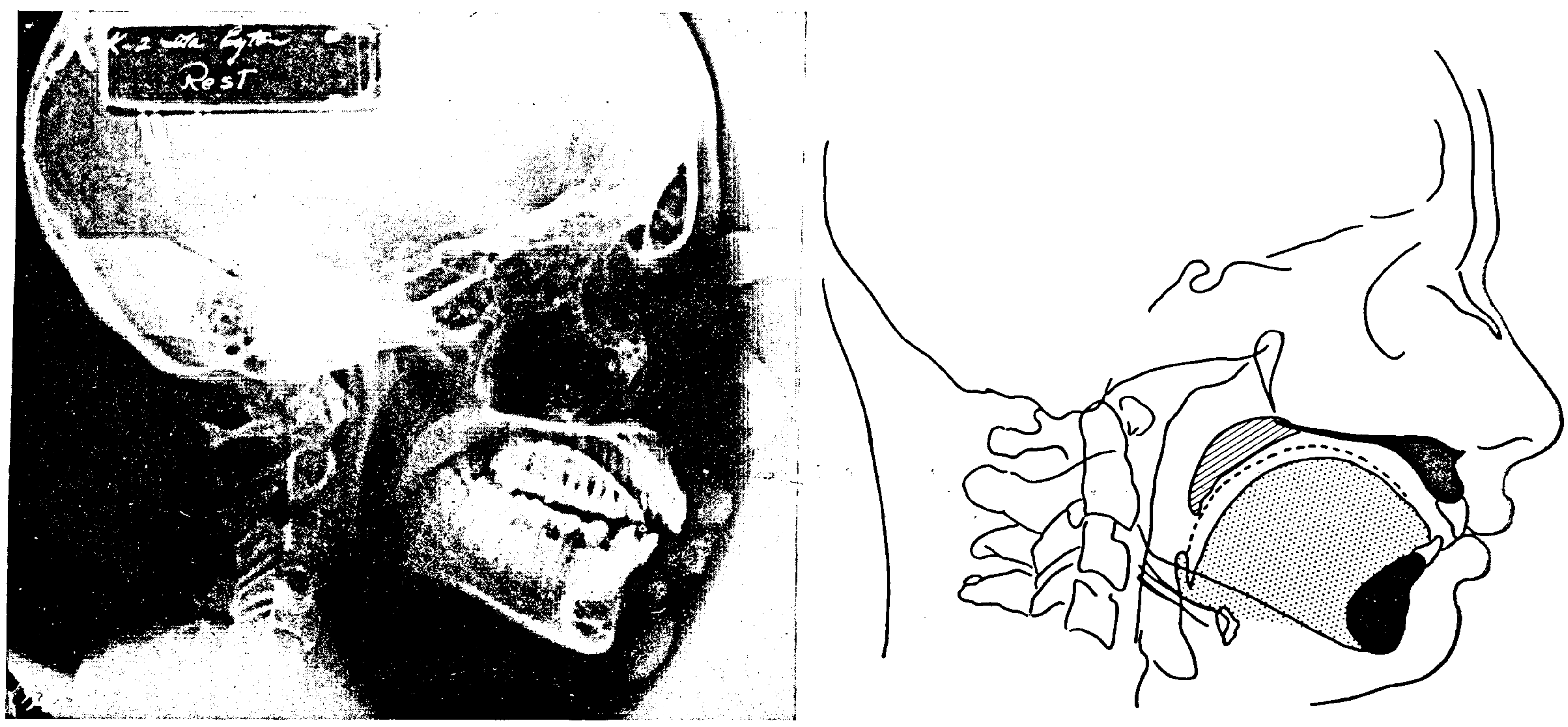

Fig. 2. A cephalometric X-ray obtained with the patient at rest. The line drawing represents a tracing of the X-ray film.

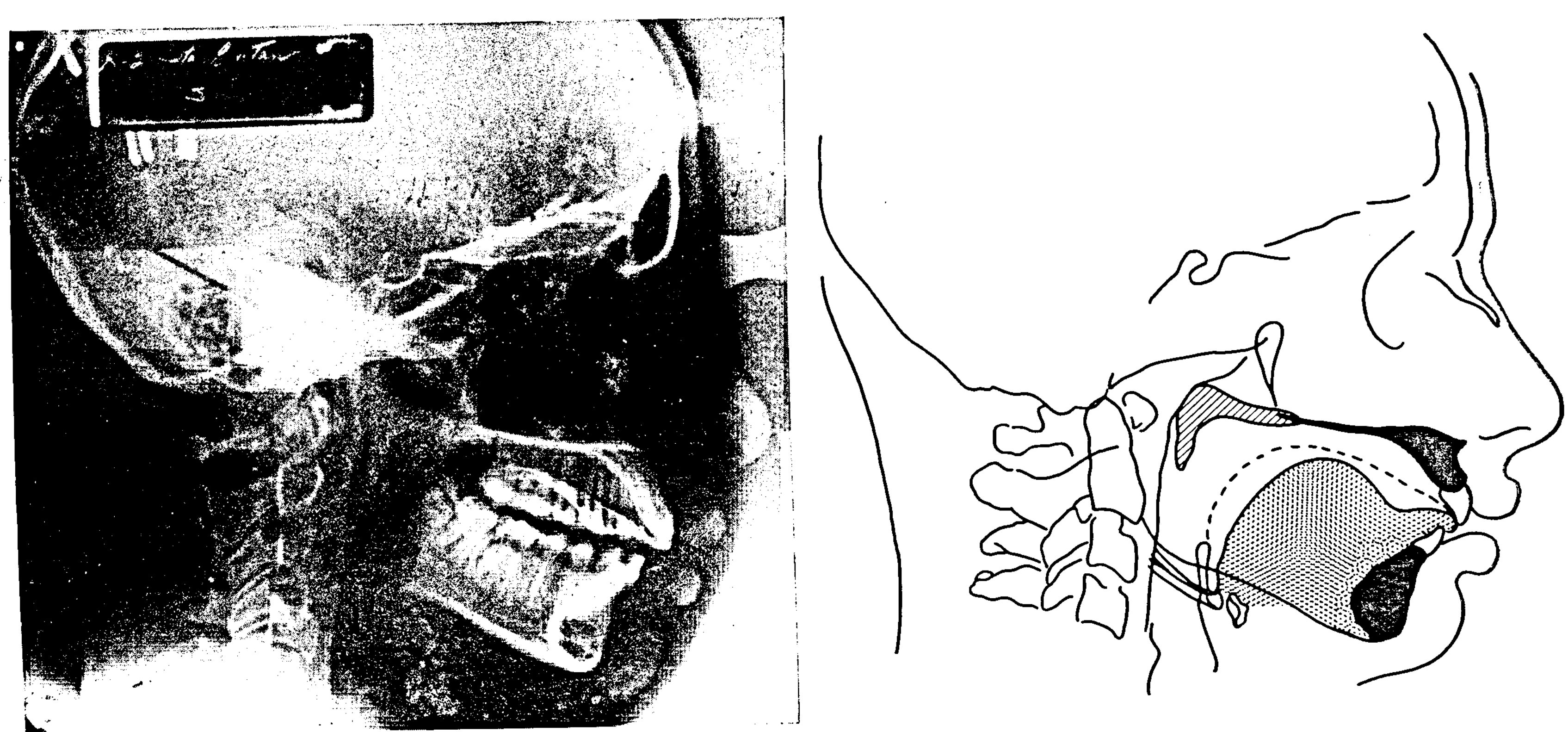

Fig. 3. A cephalometric X-ray and tracing, obtained during the sustained production of [s].

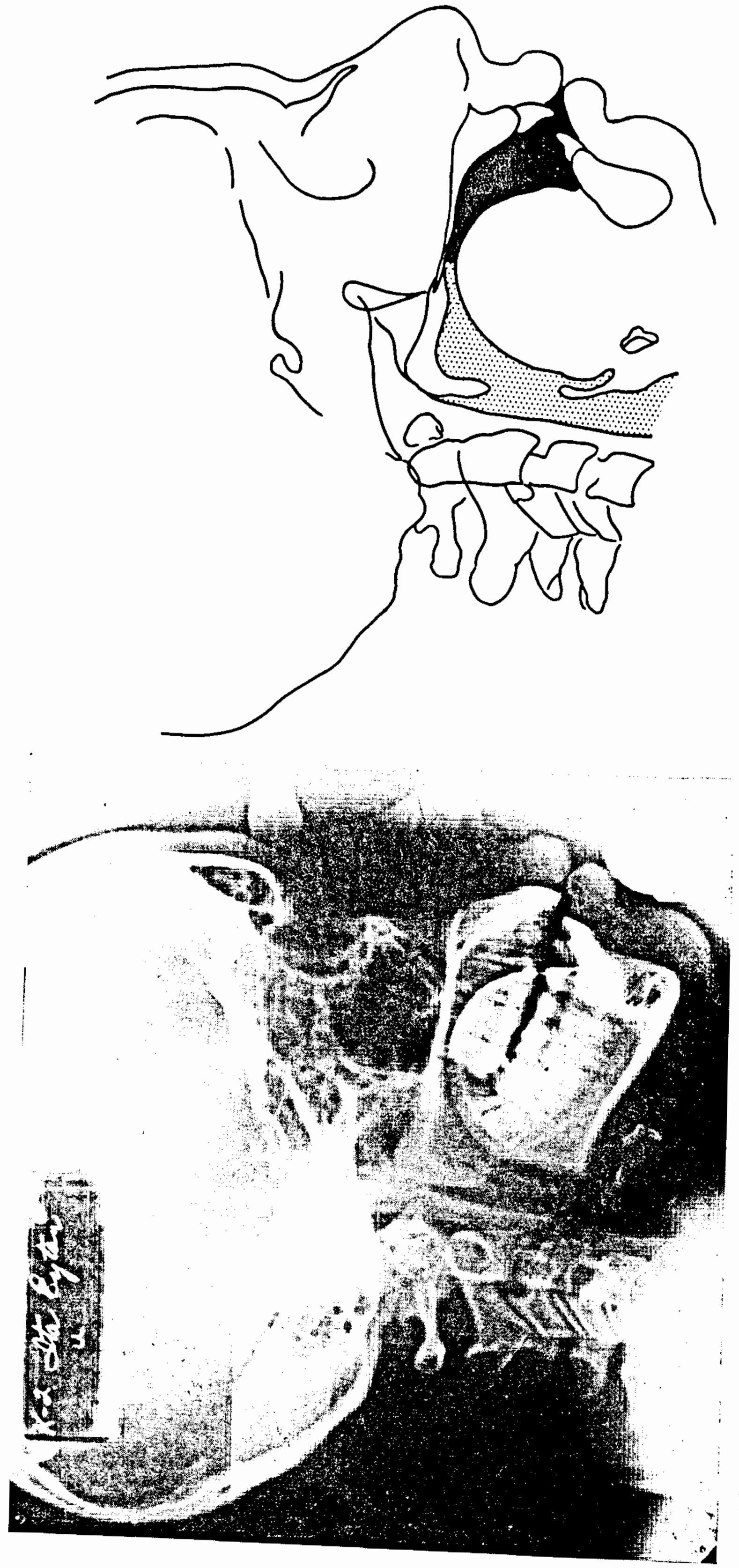

Fig. 4. A cephalometric X-ray and tracing, obtained during the sustained phonation of [u]. An anterior and posterior resonance cavity are depicted by black and stippled areas, respectively.



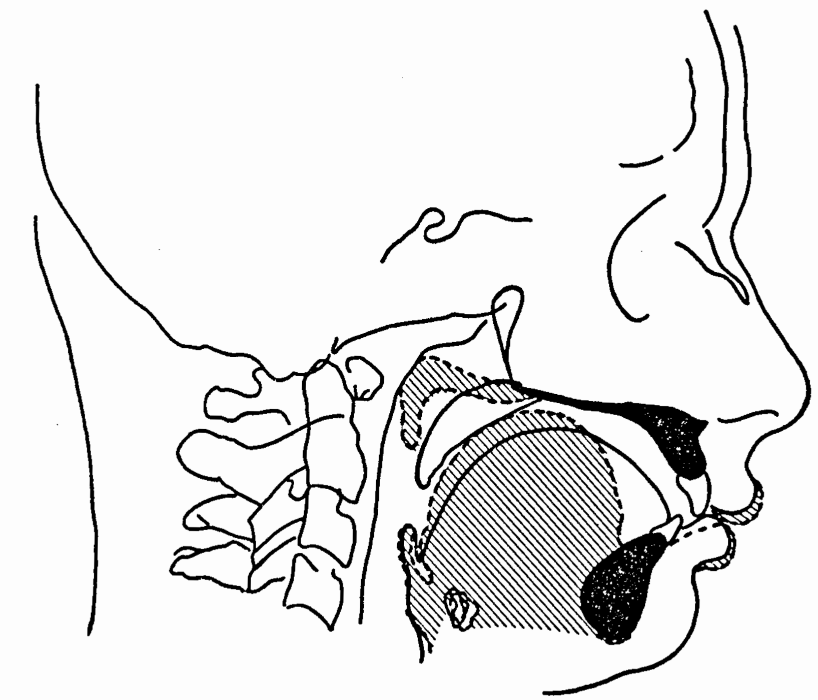

Fig. 5. Superimposition of one tracing (sustained sound production) on another tracing (rest) to illustrate functional changes.

and disadvantages. However, if one technique is used to supplement the others, in totality the disadvantages may be minimized. Of the three radiograph techniques, cephalometric X-ray films offer the clearest definition of skeletal and soft tissue structures (F. 2). Because of this, pencil tracings can be made on transparent paper which is placed over the X-ray film. From the tracing various linear and angular measurements can be made. Wherever possible, proportional measurements are suggested to eliminate the variable of head size when comparing one subject with another.

Cephalometric X-rays have been attained during sustained vowel production as well as during the production of sustained consonants (Fig. 3). Analysis of films obtained during sustained sound production can reveal changes in resonance cavities of the mouth, pharynx and nose (Fig. 4). With high kilovoltage, it is now possible to attain a lateral cephalometric headplate with an exposure time as little as 1/3 to 1/2 of a second. By securing simultaneous tape recordings of the sustained sound and by analyzing the phonetic accuracy of the sustained sound, some disadvantage in the use of sustained sound production can be overcome. If these methods are used to assure phonetic accuracy and stability during sustained sound production, the validity and reliability of the radiographs is greatly improved. A series of X-ray films can be attained with the subject at rest and during the sustained production of different

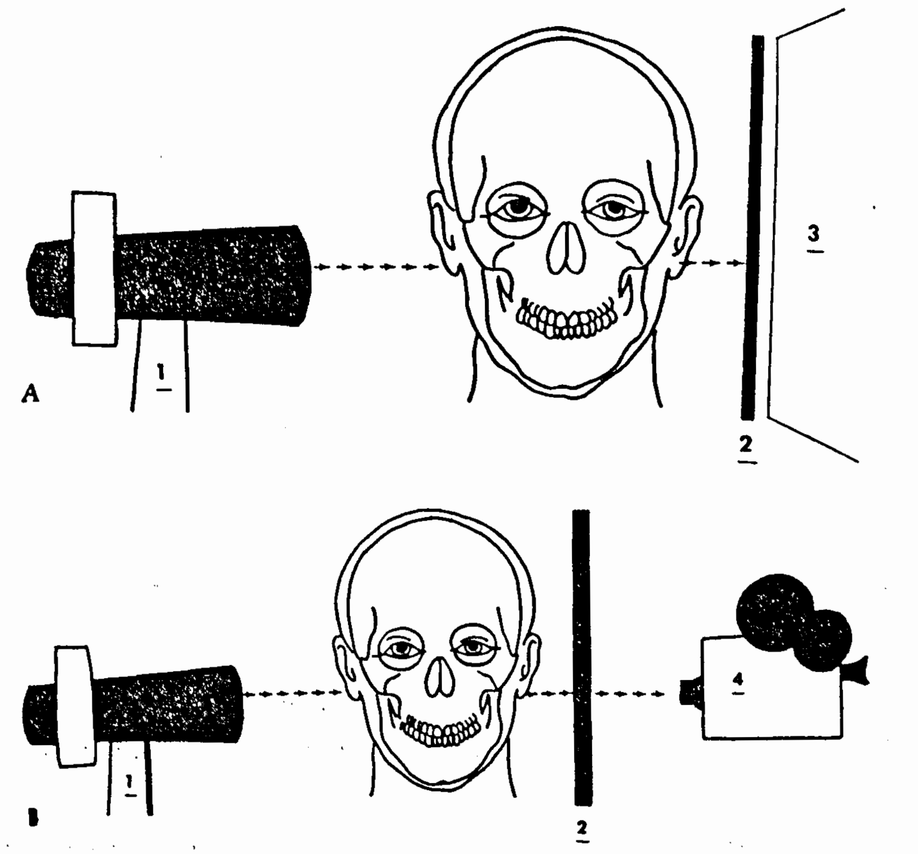


Fig. 6. (A) Direct Cineradiography; (B) Indirect Cineradiography. 1: Source of X-rays; 2: Fluorescent screen; 3: X-ray film; 4: Cine Camera.

sounds. By superimposing one tracing upon another, it is possible to evaluate changes in the position and configuration of the lips, tongue, soft palate, jaws and pharyngeal structures, and to relate such changes to diffences in the sound produced (Fig. 5).

Intelligent interpretation of cephalometric radiographs requires that certain limitations be recognized. Placement of the head within a rigid head holder may create some abnormality in posture and speech production. Then again, it is possible to study only sustained speech sounds and in this sense a static appraisal is applied to functional changes. The assumption that these same relationships will be observed during continuous speech may be questioned. To properly analyze speech physiology X-ray films which record the actual movements of the speech organs and the configuration of the spaces created by these organs would be needed. These can be obtained by applying another X-ray technique – Cephalometric X-ray Cinematography.

Dynamic function of the vocal mechanism can be studied by either "direct" or "indirect" cineradiography (2) (Fig. 6A and B). In the direct approach, X-ray films are exposed. This requires rapid change of the film casettes which severely limits the number of exposed films obtained per second; usually about twelve films per second.

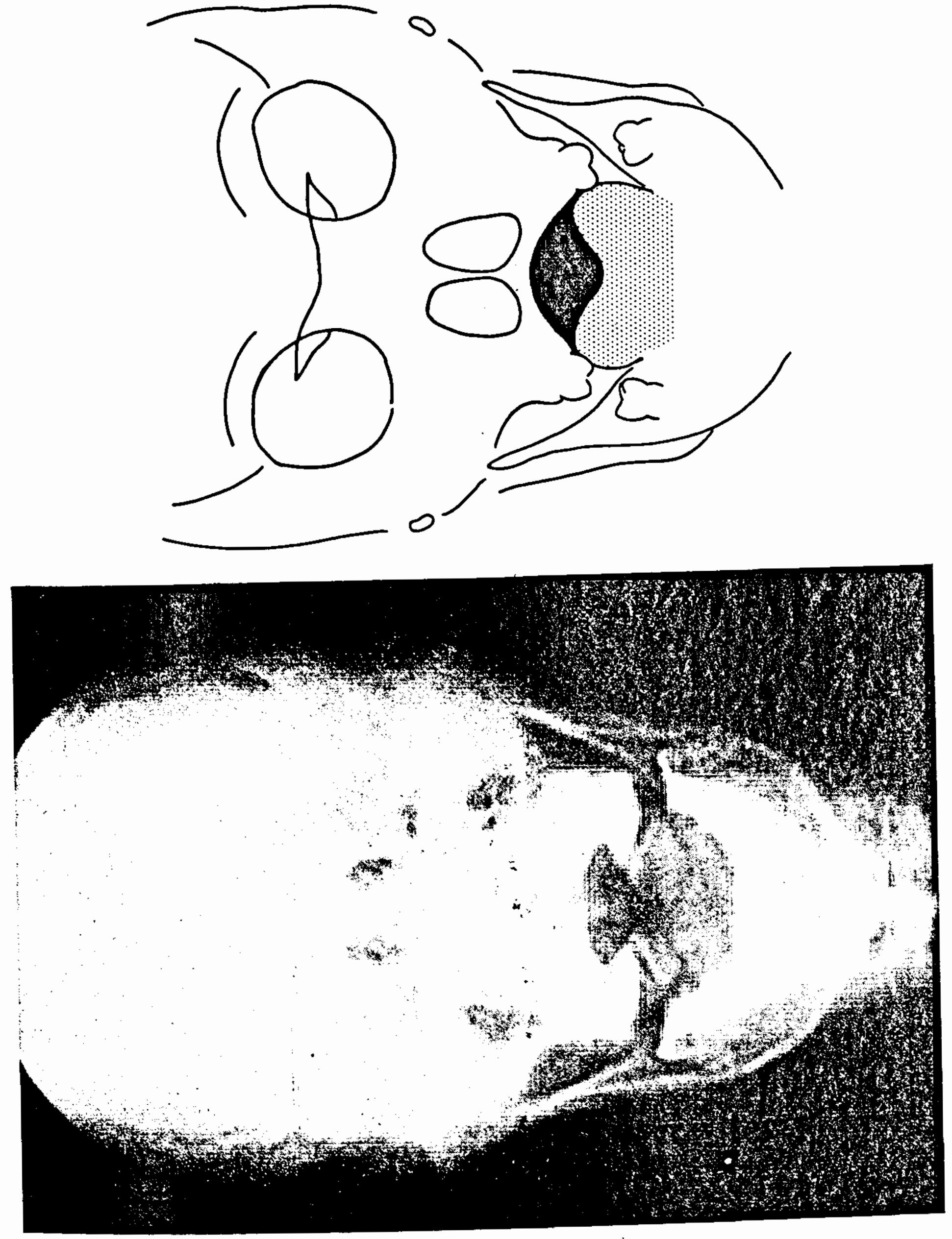

Fig. 7. Frontal laminagraph, and tracing of the laminagraph, attained during the sustained phonation of [a]. In this case, the tongue seems to function symmetrically. The black area represents the resonance cavity and the stippled area represents the tongue.

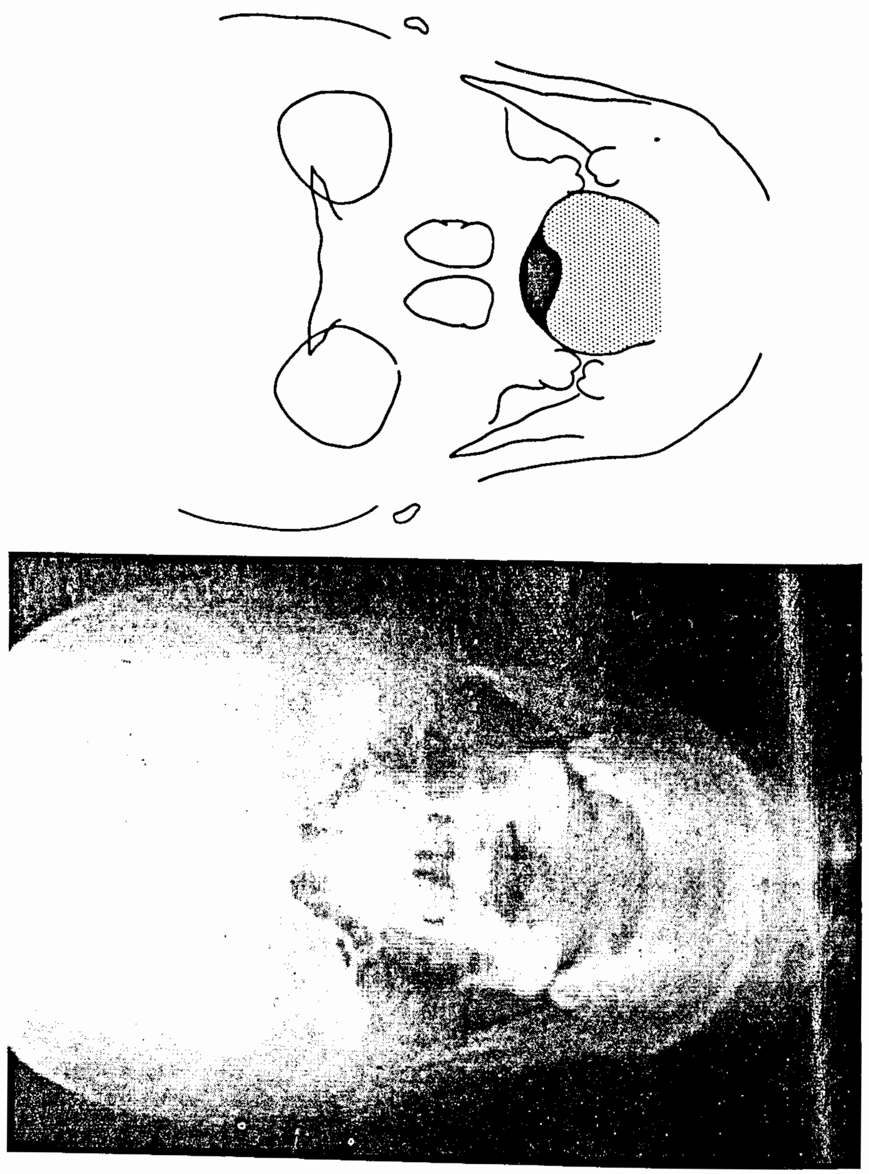

Fig. 8. Frontal laminagraph and tracing obtained during the sustained phonation of [a]. Note that in this case the tongue does not function symmetrically so that an asymmetrical resonance cavity is created.



However, the X-ray image can equal the size of the structures being studied and the sharpness of anatomic detail is almost equal to that of standard X-ray films. For research purposes this may offer the most ideal approach because of the clarity of the exposed film. The indirect method involves the use of a cine camera to photograph the X-ray images which appear on a fluorescent screen. This procedure has disadvantages, in that the sharpness of the image on the photograph is not as good as that attained on the X-ray film. The photographed image also does not equal the actual size of the structures being studied and must subsequently be enlarged for comparative purposes. With enlargement some detail is lost.

Today, image intensifiers are employed in cinefluorographic procedures (2). By the use of image intensifiers it is possible to increase the brightness of the fluoroscopic image for photographic purposes and thus to reduce the radiation exposure of the subject. Originally the intensifier tube permitted a field size of only 5 inches. Presently large intensifier tubes are available permitting field sizes of 8, 9, and 11 inches. Unfortunately the increase in field size is accomplished only with some loss in detail.

The 9 inch intensifier seems to offer the best compromise. With this size field it should be possible to visualize the whole vocal tract superior to the larynx. It would seem important to visualize the whole tract since each X-ray frame records what happens in one area in conjunction with what is happening in another area. Synchonous activity must be occuring within the different areas of the vocal tract. Cineradiography offers an excellent method of determining how all of the parts of the speaking mechanism work together within the reference of time. This technique can reveal the timing or duration of different functional movements, as well as changes in cavity spaces.

Cinefluorography itself is not a panacea for speech research, it too has its limitations. For one thing, when the indirect technique is used, the detail of structures is not as clear as would be desirable in individual frames. Once again, many curved surfaces are represented on a flat image, making it difficult to ascertain mid-line structures. The difficulties in cinceradiographic film analysis may be reduced by the combined use of cephalometric radiographs and cephalomeric cineradiography for research purposes. Cephalometric radiographs which offer excellent definition of fixed structures such as the skull base, the hard palate etc., could be easily traced to serve as reliable references. Selected frames of the cineradiographs could be magnified to the same degree as the cephalometric X-rays, and then traced. The tracing of the cephalometric radiograph might then serve as a basis for orientation of the fixed skeletal structures in the cineradiographic tracings. In other words, selected cineradiographic frames could be superimposed on the static cephalometric radiographics to insure proper skeletal orientation, thus facilitating the study of dynamic soft tissue changes. This combined procedure should help minimize the effect of distortion and reduced clarity in cirneradiographs and thereby permit more accurate measurement.

Another limitation of the cineradiograph relates to the number of frames achieved per second which still do not approximate the speed of some dynamic changes within the vocal mechanism during speech production. Limitations of the cineradiograph do not preclude the use of this or any other radiographic technique for speech research. However, a complete understanding of limitations is requisite to the research application of roentgenographic procedures.

Perhaps the most serious limitation of both cephalometric radiographs and cephalometric cineradiographs relates to the fact that they permit a radiographic visualization of only 2 planes of space. The speech mechanism is a three dimensional structure and it can be studied adequately only if all three dimensions are visualized. Frontal exposures obtained by the aforementioned techniques are usually unsatisfactory, because the superimposition of many bony structures make it almost impossible to visualize soft tissue structures and cavity spaces. For visualization of the third dimension, another radiographic technique, cephalometric laminagraphy may be applied.

Laminagraphy is a body sectioning radiographic technique to which the principles of cephalometric roentgenography have been applied (3). It permits a radiographic visualization of structures in selected planes within the human body. Some of the deeper structures that would ordinarily be obscured by the superimposition of other structures may be visualized. During a laminagraphic exposure the subject is stabilized, but the film and X-ray source move. As a result of this motion only structures in the selected plane are clearly visible; structures above or below this plane are blurred or displaced off the film. Blurring related to structures close to the selected plane cast a radiographic haze over the laminagraphic X-ray and gives the impression of loss of detail, however, only the *clearly defined* structures are traced and studied.

Because body sectioning can clearly delineate changes in density, contrast due to cavity spaces within the oral and pharyngeal areas, can be readily visualized. For this reason and others laminagraphy can be effectively applied to study the vocal mechanism (Fig. 7). However, it should be noted that a thorough knowledge of the anatomy of the speaking mechanism is required so that selected planes will reveal the desired structures. A leaded aluminum scale placed at each level or lamina radiographed will provide means to determine the degree of magnification for each laminagraphic film. Without this, measurements would be inaccurate and unacceptable for scientific investigation.

At the present time multiple casette explosures are in use which make it possible to view as many as seven different layers during one exposure. Each plane may be approximately one centimeter apart so that a considerable area of the vocal tract could be covered. Radiation dosage is higher in multiple exposures of this type. However, one multiple exposure offers a good opportunity to view different areas during the sustained production of one sound. This overcomes the necessity of repeated phonations and exposures. Since speech scientists now realize that sustained sounds may be phonetically inaccurate and unstable in repeated productions, this feature of the multiple exposure seems to have additional value in phonetic research.



Use of the laminagraphic technique has some disadvantages for phonetic research. Exposure time and roentgen dosage usually are greater than those required in the more common X-ray techniques. These factors are related to the extent of tube travel and the density of structures surrounding the selected plane or planes of study. Unlike cineradiography, laminagraphy is not adaptable to study of speech as a dynamic process, it is limited to a static type of appraisal. A sustained sound production, of approximately 3 seconds is usually necessary.

Despite these disadvantages, laminagraphy has its application in speech research since cavities and constriction areas should be studied in the frontal as well as the lateral planes. Organs such as the tongue do not necessarily function symmetrically (Fig. 8). Thus for information relative to the third dimension of space, laminagraphic exposures might supplement the other radiographic techniques in speech studies.

To return to the original premise, it would seem that a combination of the 3 radiographic techniques would be desirable in speech research. Cephalometric cineradiography can reveal motion of structures and dynamic changes of spaces and constrictions within the speech system. Cephalometric radiographs can be used for greater detail of structures and to help minimize magnification and distortion Tracings of the cephalometric X-rays can then be used to facilitate analysis of the cineradiographic films. Cephalometric laminagraphs can be used in combination with the others to permit a visualization of the third dimension – a view that is inadequately attained through the other radiographic procedures.

## PHYSIO-ACOUSTIC RESEARCH

Investigations, utilizing synthesized speech and analogues of the vocal tract, have been encouraged by: the tremendous complexity of the acoustic spectra, incomplete information concerning the physiology of the vocal tract, and by the ultimate need to understand the relationship between the physiologic, acoustic and perceptual parameters of speech. The type of information derived through these experimental studies, probably could not have been obtained by other procedures, and represents a major contribution to speech science. However, synthesized speech and analogue experimentation involve simplifications of the actual speech spectra and the vocal tract. This basic fact, combined with recent technological developments and a wealth of information already accumulated through speech synthesis indicate that the time is right to concentrate research upon a cineradiographic study of dynamic speech behavior and the continuously changing acoustic pattern, spectrographically studied.

The need for study of dynamic speech behavior has been emphasized by increasing evidence which reaffirms the syllable as an irreducible unit of speech, both acoustically and physiologically (4). At the present time, perceptual identity of a sound seems to be dependent upon acoustic structure plus modifications of that structure which are determined by continguous phonetic elements and the physiologic factors associated with the production of sound in sequence.

The modifications in acoustic structure which occur at junctions between sounds, are called transitions. The importance of the transition to perception is well established. Studies (5–11) have progressed further to define transition dimentsions in terms of their respective direction, degree and duration. Research in these areas has led to the concept that acoustical or physiological specifications of isolated sounds are essentially incomplete, because the production of isolated sounds does not involve physiologic factors responsible for the modification in acoustic structure. Interest in studying the physiologic aspect of transitions has increased with a better understanding of their acoustical characteristics and their essential value to perception.

Experimental studies (12–13) have helped to direct investigators studying speech movements by providing information pertaining to questions such as these: In the analysis of X-ray films, what are the most significant factors to define as a function of time? Which are the most appropriate acoustical parameters to select for measurement and correlation with the physiological measures? Which of the acoustical parameters are most important to perception?

Selection of physiologic and acoustic parameters, and the particular method employed in the analysis of films and spectrograms seems to be dictated by the investigator's basic purpose. The abundance of information accessible from cineradiographic films and spectrographs suggests that many methods of analysis can be profitably employed. The particular method of analysis described in the following paragraphs is one which seems reasonable for a research project designed to correlate resonance function of the vocal tract with acoustical aspects of the speech produced.

In this pursuit, sounds should be selected to reduce the number of physiological variables. Relative consistency in laryngeal activity is suggested to control possible changes in pharyngeal dimensions associated with the presence or absence of vocal fold vibration. It would also exclude sound sources, olther than the larynx, which would complicate the spectrographic analysis. Consistency in palatopharyngeal valving would exclude the complicating factor of the nasal cavity and its effect upon the acoustic spectrum.

To take maximum advantage of the cineradiographic method, syllables should be constructed to secure physiologic and acoustic data which record movements and transitions in their simplest form. In addition to careful phonetic structuring, a broad area of radiographic visualization including the entire supra-laryngeal tract, synchronization of sound and film recording and broad spectrum analysis will be necessary. The following premises have suggested the projected method of analysis.

Vowels are products of resonances of different configurations of the vocal tract.



The frequency region of maximal intensity in the spectrogram is termed the formant and its frequency position is related to the frequency response of a resonator. However, physiologically and acoustically the vocal tract functions as a system of coupled resonators in complex response to an activating force. Advording to Fant (14), "In general, everypart of the vocal tract contributes somewhat to the tuning of all formants." As a corollary, it has been stated (15), "No single acoustical parameter, such as a particular formant frequency, is dependent upon any single physiological parameter." These and other statements (16) indicate that an analysis of the physiologic apparatus and the acoustic spectrum must be broad and that it may be unwise to attempt correlation of specific formants with particular cavities.

Generally, the physical properties of the vocal tract should be considered as a system of modifiable spaces which vary continuously as a function of time. With this concept, physiologic analysis should attempt to define factors which influence the physical character of the vocal tract as a sound transmitting apparatus. Thus, a quantitative analysis of cavity and constriction dimensions and the manner in which such dimensions are altered as a function of time is indicated. Physiologic data of this type seems most appropriate for correlation with a spectrographic analysis of formant structure and changes in formant structure during syllable articulation.

Movements by themselves do not determine the acoustic output. Movements of specific structures should be evaluated as factors which contribute to, but do not completely determine, properties of the vocal tract as a sound transmitting system. The movements or adjustments of mobile articulators in relation to adjacent structures seem to be the more important factors to define if correlation with acoustic output is desired.

Movements of specific structures do not occur within an otherwise static physiologic environment. Activity during speech production is wide spread: it is not only sequential but synchronous in nature. By neuromuscular structure the behaviour of individual structures within the vocal system is tied in with the behavior of other structures. In a physiologic system such as the vocal tract, it is known that the behavior of one structure is not determined by its own properties, but it is controlled and directed by the system as a whole (17). Dynamic speech production also is said to show specificity in neuromuscular activity. The pattern of movement expressed by one structure is not necessarily the same as the pattern of movement observed in contiguous structures (18).

In the final analysis, measures of the spatial dimensions represent a composite of all the movements of all the structures within the entire vocal tract at any one unit of time. Thus, synchronous physiologic adjustments or coarticulations are recorded. The function of the tongue as a modifier of space is also recorded. Complex muscular structures, such as the tongue and velum, can change in shape or position or both. Such changes, which require many measurements to describe ,may or may not effect a concomitant change in cavity and aperture relationships. This strongly suggests that space is a more inclusive and significant measurement than movement.

Movements during speech production differ in temporal characteristics. If transitions are the acoustic correlate of movement, it follows that the longer the duration of the transition the slower would be the associated movement, or movements responsible for the changing resonance response of the vocal cavity system. It has been explained (19) that as resonance is changing in frequency the problem of measuring this frequency is complicated by increases in the formant band width. It is further stated that the increase in band width associated with change in resonance is dependent upon rate of change. On the basis of these statements, sound combinations which provide well defined formant structures and transitions of long duration seem to offer certain advantages in acoustial analysis. At the same time the slower rate of movement could be recorded with greater accuracy by the cineradiographic film.

Voiced resonant consonants [w], [r], [j], [l], have been found to have the acoustical features desired [20]. Their study, in combination with various vowels, would offer variety in movements which might be relatively simple and measureable for preliminary investigation.

The rationale for the spectrographic analysis of formant frequencies, formant levels and band widths is summarized as follows : The formants are the major physical determinants of vowel quality. Formant structure, as portrayed by the spectrograph, is perhaps its most obvious and measureable feature. Methods of formant analysis furthermore have been clearly described (14, 21) and normative data pertaining to formant structure is available (22).

Formant analysis is also indicated because modifications in resonance resulting from physiologic movements are expressed as shifts in formant positions. Because such shifts, or transitions, may be reflected at Formant 1, 2, or 3, depending upon phonetic context, analysis of all formants and formant changes as a function of time would be required.

Several technical limitations should be mentioned which seem to emphasize the need for a controlled physio-acoustic study of resonance.

1. From the acoustical viewpoint, the sound spectrograph is not well adapted to study sound intervals of extremely short duration (14). It also has been observed that weak sounds are portrayed rather incompletely by the spectrograph. Vowels combined with resonant consonants seem to overcome these limitations of the spectrograph.

2. From the cineradiographic viewpoint, reports indicate that film speed, at the present time, is not fast enough to record consistently articulatory features of sounds of short duration. Lingua-alveolar stops have been specifically mentioned in this regard (23). Some speech sounds are articulated at a faster rate than that of the cineradiographic camera. In order to remain within present technical limitations of the cineradiograph, temporal characteristics of sound production should be considered.

3. A third limitation in cineradiographic-spectrographic study relates to recording conditions which may be considered unsatisfactory for the recording of *weak* sound



Noise introduced by the cineradiographic technique has been found to constitute a real problem, particularly when spectral analysis is desired.

The study suggested to investigate resonance function of the vocal tract and the associated acoustic output was designed to: (a.) reduce the number of physiologic variables, (b) define movements in their simplest physiologic and acoustic form and (c.) remain within technological limitations. *If speech study is not confined to areas which can be investigated adequately by the prescribed combined techniques, the data obtained can manifest the cumulative limitations of the several techniques employed.* Limitations of cineradiographic films are considerable and inevitable. These limitations, as well as those of the spectrograph and sound recording equipment, must be fully recognized in the selection of the problem posed for study and in the design of the experimental procedure.

Whereas the techniques employed may be the same, the phonetic material, the area of the vocal tract studied, the methods employed in physiologic and acoustic analysis depend largely upon the purpose of study, which in turn is influenced by the professional orientation of the investigator (24–26). The study of resonance projected in this writing reflects the professional orientation of the speech physiologist and pathologist who ultimately would like to make confident and specific physiologic interpretation from the sound spectrogram. Unfortunately, a great deal of physio-acoustic research seems necessary before specific physiological interpretations from the spectrograms can be made.

In conclusion, systematic study of fundamental relationships between speech physiology and the associated acoustical pattern is needed to increase understanding of normal as well as abnormal speech. Cineradiography and spectrography offer the speech scholar remarkable opportunities for serious study. However, before complete understanding is achieved it may well be that these techniques will require further refinements or additional techniques will be needed to supplement information derived from the cineradiograph and spectrograph.

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