SUMMARY

This report reviews briefly State-of-the-Art of certain bioengineering instrumentation useful in craniofacial research and assessment. Brief reviews are included in the areas of Radiography, Electromyography, Intra-oral air flow/pressure, Lingual/palatal pressure, Oral-sensory perception, Visualization techniques, Acoustic processing, and Digital Computers. It should be obvious, even from this limited effort, that the variety and quality of available equipment is expanding rapidly. While it is conceded that there probably have been no abrupt or profound instrumental breakthroughs in any of the areas discussed, the sum total of the advances being made in each of the cited areas, taken collectively, are impressive. It is quite evident that both the clinical and basic researcher now have at their command great quantities of equipment of excellent intrinsic quality that are appropriate for the types of assessment and research being carried out or contemplated. These devices are at a level of sophistication not dreamed of as little as 20 years ago. It is now necessary for the scientist and practitioner to exploit this wealth of facilities and to be prepared to utilize effectively the future instrumental advances that can be expected in this area.

Status Report on Instrumentation Useful for Craniofacial Research*

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This paper will review the current status of instrumentation and procedures[1] that are being utilized in, or would be potentially useful for: 1) research related to orthognathic surgery, 2) assessment of post-operative craniofacial function, and 3) basic research on craniofacial relationships and anomalies. The presentation will be organized into eight sections of differing length and importance. They are: 1) Radiography, 2) Electromyography, 3) Intraoral air flow/pressure, 4) Lingual/palatal pressure, 5) Oral-sensory perception, 6) Visualization techniques, 7) Acoustic processing, and 8) Digital computers. Evaluation of the limitations and robustness of each technique will accompany the descriptions.

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[1] Only instrumentation and approaches of reasonable potential have been included; i.e., descriptions are limited to apparatus that is reasonably available, is in current use, or suggests a potential for appropriate use.

1. Radiography

Radiographic techniques have the advantage of allowing the investigator to obtain internal views of the craniofacial areas. These views rarely are comprehensive enough to permit complete and fully accurate analysis of the area/function desired; however, if used judiciously (and selectively), they permit useful information to be acquired. Unfortunately, radiographic techniques suffer from several general and system-oriented limitations. The five major problems associated with all x-ray approaches include the following: First, there is danger to the subject or patient from radiation exposure. Hence, it is necessary to limit strictly the amount of radiation received. As Bzoch (1970) points out, "Careful calibration, radiation monitoring, filtering and protection, and supervision of data collection should be conducted by qualified radiologists." Second, in virtually all cases, the obtained radiographic image is a collapsed two-dimensional view of three-dimensional structures. This means that all target elements in the x-ray field are shown as though they were equadistant from the film. Moreover, if opaque structures are in line with the area of interest, they sometimes mask it. Third, good soft tissue x-rays are difficult to make. Hence, definition of the targets of interest may not be obtained with sufficient contrast. It is especially difficult to obtain simultaneously good clear views of both soft tissue areas and structures of greater density (such as bone). Fourth, even slight movements on the part of the patient or subject can cause disproportionate differences in the size and/or shape of the target area. In any case, the use of an encephlostat, or head positioner, will minimize—but not eliminate—this problem. Finally, the rays of the x-ray beam spread over distance (and sometimes geometrically). Hence, if measurements are to be made on the viewed structures, corrections must be applied. Moreover, it is unfortunate that no correction formulae have been developed for certain classes of x-ray (notably laminagraphy).

a. *Spot or still x-rays.* Standard x-ray utilizes an emitter in fixed relationship to a cassette holding a film; in many cases this system can be used with image intensification in order to reduce exposure levels. Spot x-rays are most often utilized to obtain a lateral view of craniofacial areas (see Buck, 1954; Graber, 1959; Wildman, 1961) or of the larynx (Hollien, 1960). They are less frequently used for anteroposterior information as the skull, mandible, and spinal column tend to mask soft tissue targets of interest.

   Measurement procedures on spot x-rays require the identification of reference points, primarily easy-to-locate, stable prominences on the skull, maxilla, and/or vertebra. Areas of interest then can be traced onto overlays—or the films can be overlaid, aligned by the skeletal landmarks, and evaluated. Subjective evaluations of x-ray films often are useful in the clinical setting but do not permit objective and permanent records to be made. The major difficulty with spot x-rays is that most structural movements or progressive phenomena are not obtainable by this technique—even when rapid film or cassette changers are utilized.

b. *Cinefluorography.* Image intensification (primarily by electronic means) permitted the development of this radiographic technique and, later, of videofluorography. Here relatively low-level x-ray images are amplified 1000-3000 times and displayed on a fluorescent output screen. The image then can be viewed, photographed, or stored in a video-recorder. By this means, the motion of any target structure can be captured, an especially desirable feature when it is necessary to study movements of the tongue, velum, pharyngeal walls, etc. As with spot x-rays, cinefluorography is most often used to obtain lateral views of the articulatory and other craniofacial structures (see Moll, 1965, and Berry and Hoffman, 1956, 1959, for its use in studying temporal mandibular function).

Measurement techniques utilized for film obtained by cinefluorographic procedures are very similar to those described for spot x-rays. However, one of the problems here is that frame-to-frame measurements usually have to be made and this constitutes a very laborious task. A number of authors including Sloan *et. al.,* (1964) and Perkell (1969) have provided information about measurement techniques. In any case, if this method is used, a substantial amount of tracing is necessary even for the simplest investigations. Thus, large comprehensive studies become difficult as does clinical evaluation of a patient within a short time-frame.[2]

Another problem facing the investigator who uses cinefluorography results from both structure movement and film movement; it is that sharp, clear images are somewhat difficult to obtain by this procedure. This factor, coupled with the lack of the third dimension on the film often makes it difficult to track moving structures reliably. In this regard, Moll and his associates (see in particular, Moll, 1965a; Carney and Moll, 1971; and Kent and Moll, 1972) are among those investigators who have successfully used barium sulphate and other radiopaque markers to mitigate this problem.

Laminagraphy. This particular radiographic technique permits internal cross-sectional planes to be viewed. The process is accomplished by the coordinated rotation of the x-ray emitter and the cassette (the relationship must be constant) around the target area. Only a small plane at the fulcrum of the x-ray beam will appear in focus on the film. Structures in any direction from this plane either do not appear on the x-ray plate or are blurred. This technique is especially useful in obtaining coronal cross-sections of the larynx (Hollien, 1962) and antero-posterior views of the head. It permits the investigator to obtain views of internal soft tissue areas because surrounding bone is blurred out. Laminagraphy has been utilized effectively to study the vocal tract (see for example, Wendahl, 1957; Subtelny and Subtelny, (1959). By utilization of multiple film packs, several simultaneous planes through a structure can be obtained at one time. For example, this film-pack technique permits 5–10 different saggital

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[2] A number of investigators currently are attempting to develop computer assisted measurement techniques that would be useful for such measurements; among them are A. Paige (at the Institute for Advanced Study of the Communication Processes, University of Florida, Gainesville) and W. J. Gould (at the Vocal Dynamics Laboratory, Lenox Hill Hospital, New York City).

sections of the velum to be made with a single exposure—a useful feature for certain types of research.

There are, of course, a number of limitations to laminagraphy. For one thing, since all structures are blurred out except the relatively small area at the target, stable reference points are difficult to identify. Hence, certain types of measurements are virtually impossible to make on laminagrams. Further, a) there are no known corrections for enlargement so most measurements must be of a relative nature, and b) the useful area on the films is much smaller than for other types of x-ray. Moreover, laminagraphy exhibits some of the same limitations that exist with spot x-ray, viz., movement cannot be visualized. Finally, it takes 1–2 sec. to make a laminagram so certain structural movements within the craniofacial and laryngeal areas appear as blurs rather than as clear-cut images.

d. *Comments.* Fletcher *et. al.,* (1960) suggest that the three types of radiography described above can be used to supplement each other in the analysis of a given activity. Indeed, there is no question but that these authors are correct, and information can be enhanced by multiple x-ray techniques. Unfortunately, however, since such an approach increases the radiation danger to the subject or patient, an intelligent and conservative balance must be struck.

Finally, Hollien *et. al.,* (1968) have described a new type of laminagraphy—that of stroboscopic laminagraphy. While this technique was designed to provide serial stop-action pictures of the vocal folds in coronal cross-section, it has two features that would be useful in any type of research or assessment involving structures related to the craniofacial area. First, this system makes serial laminagrams automatically and in rapid succession. However, most other radiographic systems could be modified to do so also. Moreover, the x-rays emitted by this unit are pulsed; that is, they are emitted in the form of very high energy, very short bursts. By this means, comparable x-ray images can be obtained with the subjects receiving only a small fraction of the x-ray they would from standard electronically intensified fluorography. Modification of the x-ray source in other units (to operate in this mode) would permit a great deal more radiography to be accomplished with much less radiation to the patient.

2. Electromyography

Basmajian and his associates (1961, 1962, 1967) have pioneered electromyography (EMG), and Cooper (1965) has provided an excellent description of EMG techniques. These materials constitute a useful supplement to this brief review. Basically, EMG provides information concerning the electrical activity resultant from contraction of muscles or, more properly, from a motor unit. The motor unit can be identified as the motor neuron, its motor end-plate (i.e., the interface between the neuron and the muscle fibers), and the group of muscle fibers that are operated by this neural mechanism. When excitation occurs, the fibers contract, are depolarized, and a corresponding—but very small and localized—flow of electrical current results. This current can be measured by placing terminals along the set of muscle fibers; i.e., action potentials can be recorded graphically or stored for later processing. Electromyographic data are useful in craniofacial research since they can provide information about muscle activity, especially as it relates to structural movement. Specifically, EMG will permit the investigator to determine 1) if a muscle is operating, 2) at what point in time a muscle starts to contract and ceases to contract, 3) if paired muscles are firing in synchrony, and 4) to what extent the muscle is contracting (force of contraction and amount of electrical activity are positively correlated).

Of course, there are problems and limitations with EMG when it is utilized as a research tool in craniofacial research. Some of these problems are general in nature. Others are related to the type, size, and placement of the electrodes, and some are related to the interpretation of data. Indeed, EMG actually should be thought of as a group of techniques that can provide several related types of data. For example, sometimes the issue relates to whether or not a whole muscle (or even a group of muscles) is operational under certain conditions; at other times the primary interest might be in the fine detail of how a particular muscle is operating or if a fiber is firing in synchrony with some other event. In the first case, surface electrodes might be used, in the second, some type of needle, or wire, electrodes. Usually, however, decisions concerning electrode selection are not simple. For example, depending on a number of factors, action potentials can be detected from only a few millimeters to several centimeters from the target muscle. Thus, if large muscle activity is desired but the muscles are deep within the body and/or are surrounded by other muscles, the experimenter faces the dilemma of how to obtain the desired information. Even if multiple needle electrodes are used, there is the problem of subject comfort and the accurate placement of the electrodes. In short, some of the problems to be faced in EMG research are:

1. Identification of the exact location of the muscle under study.
2. Selection of the EMG technique that will provide the desired information.
3. Proper placement of the electrodes so that field effects are minimized and only the desired action potentials are obtained—or at least, placement should permit these signals to be differentiated from competing ones (i.e., action potentials from other muscle fibers and system noise).
4. Proper selection of events to be compared with EMG results.
5. Problems related to interpretation of recorded EMG signals.

Both surface and needle/wire electrodes exhibit advantages and disadvantages in their use. Surface electrodes are easy to place, do not cause the subject discomfort, and permit a large area to be sampled. However, their high-frequency response is limited; the data they produce often lacks precision, and they are particularly subject to field effects (Shipp, et al, 1968).

a. *Surface Electrodes.* Several types of surface electrodes are available (disc, cup, suction, etc.). All operate in roughly the same manner. Essentially, surface electrodes can be used when: 1) the response of the whole muscle is the primary issue of interest; 2) the muscle is near the body surface; and 3) the muscle is reasonably easy to identify. Only gross data on major movements can be expected from EMG studies that utilize surface electrodes. For example, it is difficult to separate the effects produced by several adjacent muscles.

The simplest types of surface electrodes are small discs placed on the skin area over the muscle. Abrasion of the surface epidermis is necessary, and some type of adhesive is used to hold them in place. If they are not used in pairs, a ground lead can be placed at any convenient location (clipped to an ear lobe, for example). When a) rapid movements of a structure are present, b) the electrode is to be placed on mucous membrane[3], or c) there is difficulty of any type in adhering the electrode to the skin, a suction electrode can be used. Good descriptions of such electrodes are provided by Cooper (1965), Harris and her associates (1964, 1966), and Rothman (1971). Basically, suction electrodes are small silver jewelry beads cut in half; they are coupled to the amplifiers and graphic recording equipment by steel wires. The suction is provided the electrode via small diameter tubing connected to a manifold. It is possible to design these units to operate in either the monopolar or bipolar (pairs) mode. System output may be displayed visually on monitors, permanently recorded (pen writers, graphic recorders), stored for later processing (FM tape recorder), or fed into a digital computer.

Signals generated by surface EMG generally tend to be somewhat gross in nature, portraying AP's associated with many motor units, so that they do not show spike potentials related to single units. However, these data are particularly amenable to signal integration. That is, in addition to the on-off strength of the AP pattern, it is also possible to obtain a summated mean AP amplitude. In this manner, the strength of muscle contraction can be compared to the particular physiological event that elicited it. However, because of the problems previously stated—and because the hooked wire electrode technique has proven effective, the use of surface electrodes is falling into relative disuse.

b. *Needle Electrodes.* Actually "needle" electrodes are of two classes: ordinary needle electrodes and hooked-wire electrodes. The standard electrode consists of a hypodermic needle containing one or two insulated wires in the cannula exposed at the needle tip. The electrical potentials generated in the muscle are detected across the wire(s) and the needle shaft (ground). Needle electrodes exhibit a number of advantages and disadvantages. On the positive side, they permit the body to be penetrated and the pickup unit inserted directly into the muscle with the following results, when compared to surface electrodes: 1) reduction of field effects, 2) increase in sensitivity of the system, and 3) constant positive-ground distance. On the negative side: 1) the presence of the mass of the needle itself may generate AP's; 2) subjects may suffer considerable discomfort; and 3) movements may dislodge the units.

The newer class of "needle" electrodes are those made of wire. Specifically, a pair of wires (together or individually) are introduced to the muscle site via a hypodermic needle, which is then removed. According to Shipp (1968), hooked-wire electrodes display most of the advantages—but not many of the

[3] For use on the tongue, see MacNeilage and Sholes (1964).

limitations—of needle electrodes. Specifically, a wire improves subject comfort, is more difficult to dislodge, and tends to produce fewer artifacts. Moreover, Shipp notes that this type of unit permits selection of inter-electrode distance, a condition, which maximizes AP pickup from target muscle and reduces field effects. Conversely, however, hooked wire electrodes cannot be replaced with precision and the exact interelectrode distance usually cannot be specified. Placement of both needle and wire electrodes is accomplished via reference to anatomical landmarks and by palpitation, x-ray, visual observation, or similar techniques. They are verified by having the subject or patient perform some maneuver associated with the target muscle and observing the resultant electrical activity (for example, see Fritzell, 1963, 1969).

As with surface electrodes, the transducers, cited are coupled to visual display units (CRT's, etc.), graphic recorders, storage recorders, or digital computers (both Cooper, 1965, and Shipp, et al, 1968, provide excellent descriptions of such equipment). Indwelling electrodes provide relatively detailed information about the firing of the target motor unit. Indeed individual spikes ("firings") usually are discernable within a given burst of activity. Such records can be analyzed with respect to amplitude, form, pattern, etc., or, as with surface electrodes, summated to provide a mean integrated trace. These data can be transformed into digital form for computer analysis.

In summary, EMG techniques constitute important and powerful investigational tools within the scientist's' or practitioner's' repertoire. They are particularly useful when combined with other research methods. Virtually any muscle or muscle system within the craniofacial area is amenable to this technique. It can be used in basic research, to investigate muscle inadequacies, and to compare physiological function before and after surgery.

3. Oral-Nasal Air Pressure and Flow

The problem of cleft palate/lip and related congenital or induced abnormalities would appear to be of particular importance to individuals studying craniofacial function. Within the cleft palate area, one of the most devastating effects of this anomaly on human speech results from palato-pharyngeal incompetence. In turn, the study of oral-nasal air pressures and flow have proved to be an effective means of assessment of velar function, especially with respect to such issues as diagnosis and management of the disorder, pre- and post-operative assessment, and so on. Moreover, investigational techniques of this type may be used in a variety of ways to study craniofacial function and anomalies. Specifically, they can be used a) to study air pressure alone, air flow alone, or air pressure and flow together; b) to assess only intraoral air pressures/flow or oral-nasal relationships; or c) to investigate speech physiology relationships with respect to oral cavity size or clinical problems. In short, air pressure/flow apparatus can aid the investigator in the study of a constellation of questions ranging from those relating to baseline data in normal subjects to very specific problems with respect to the management of a disorder in a single individual. The nature of the apparatus utilized also can vary from very simple spirometers and manometers (see Chase, 1960) to extremely complex systems capable of the simultaneous assessment of virtually any question involving oral-nasal air pressure/flow (see Warren and Dubois, 1964, for example). Rather substantial amounts of research have been carried out in all of the areas cited above. Modern bioengineering instrumentation is permitting even more sophisticated and complex questions of this type to be asked and researched.

a. *Air Flow Apparatus.* A number of instrumental approaches for intraoral and oral-nasal air flow projects are available; three publications that provide good illustrative material about such systems are Warren (1964), Lubker and Moll (1965) and Brown and McGlone (1974). If intraoral air flow is to be studied, the nasal ports simply are closed or plugged; if nasal-oral flow is to be investigated simultaneously, the use of special calibrated masks that separate the oral and nasal chambers is necessary or some system must be utilized to sample directly (and separately) from the mouth and nose. Pneumotachographs are the most popular flow metering devices currently in use. Commercial models are efficient and convenient to operate. Basically, a fine wire mesh in the pneumotachograph causes a small pressure drop to occur when air passes over it. This pressure drop is linearly related to flow. In any case, pressure transducers convert this variation to electrical signals which drive a graphic recorder of an appropriate type. These signals can also be stored for later analysis or can be adapted for input to a digital computer. They provide information about air flow rates related to production of phonemes, oral-nasal relationships related to velopharyngeal valving, and so on.

b. *Pressure Apparatus.*[4] Basically, the apparatus used in obtaining pressure measurements includes a polyethylene sensing tube placed in the oral cavity. This tube is coupled to a manometer or pressure transducer and amplifier array which feeds the monitoring device (graphic, storage, computational). As with air flow, pressure data can be processed digitally or, as currently is more common, converted to some visual representation whereby the variation in the output trace can be related to a variety of physiological and/or speech events (that is, after time-alignment is accomplished). It should be noted that proper placement of the sensing tube is considered to be of some importance. However, currently there is some disagreement among investigators about just what constitutes "proper" placement (see for example, Warren, 1964; Arkebauer *et al.*, 1967, and Brown and McGlone, 1969). As would be expected, intraoral/oral-nasal air pressure is related to air flow. However, this second measurement technique is particularly useful in estimating such things as pressure behind a constriction, cavity size, and so forth. It is perhaps not as effective a measure of velopharyngeal closure as is air flow.

[4]The concept of air pressure level in a cavity is not to be confused with sound pressure level (SPL) which is a different (albeit somewhat related) measure. For example, fluid pressure can exist without the presence of acoustic energy. On the other hand, while SPL is not treated in any detail here, it is conceded that it can be a useful measure and has been widely used. Indeed, research of this type varies from the study of stress in sentence productions (Brown and McGlone, 1974) to relationships between SPL and velopharyngeal closure (Shelton, *et. al.*, 1969). The apparatus used in their research includes a calibrated condenser microphone coupled via amplifiers to the processing/storage equipment.

In summary, intraoral/oral-nasal air pressure/flow data are useful in defining the aerodynamic operation of the craniofacial system in the production of speech. Further, data obtained from apparatus of this type can be particularly useful in assessing palatopharyngeal functioning and the effects on this area of certain surgical procedures. As is usually the case, relatively simple instruments of this type are usually employed in the clinic. However, with modern advances in electroaerodynamic devices, more sophisticated units should soon be in common use.

4. Lingual/Palatal Pressure Instrumentation

As Proffit *et al.*, (1966) pointed out, "Tongue and lip pressures against oral structures during swallowing, phonation, and other oral activities have aroused considerable recent interest in dental research." While, admittedly, the kinds of questions asked and the types of research carried out in this area relate more to the normal physiological functioning of certain craniofacial systems (see, for example, Brown, McGlone, and Proffit, 1973), instrumentation of the type described below could be adapted for certain types of clinical studies. For example, by these techniques, compensatory tongue or lip movements in cleft lip or palate could be studied as a function of the quality of speech produced. Indeed, if mandibular movement apparatus is added to this group, a rather substantial corpus of pressure/movement research becomes feasible. In any case, equipment that will support research relative to lip and tongue pressure, palatal pressures/seals, and mandibular displacement will be described briefly below.

a. *Tongue/lip pressure apparatus.* The basic problem faced by investigators who wish to conduct research of this type involves development of sensor units to be used between the lips or inside the mouth. In this regard, Proffit and his associates (1965, 1966) have described cantilever-beam strain gauge transducers which can be secured at various points on the hard palate via an acrylic pseudopalate. These units, which are water-proofed, are connected across a Wheatstone bridge; in turn, the circuit output is amplified and fed to graphic recording equipment or to a digital computer (after proper interface) for processing. A modification of this system has been described by Appl and Leeper (1973). Malecot (1966) has developed a system which is similar but one that utilizes pneumatic pressure pads instead of the cantilever-beam strain gauge sensors. No matter what type of sensor is used, some problems are encountered with research of this type. First, control of transducer placement is difficult. Probably the best way to circumvent this problem is to place the sensors in (or on) some type of acrylic plate, custom made for each subject or patient. In this manner, the sensors may be accurately positioned and/or returned to the same place for subsequent research/evaluations. Second, the sensors, and any device used to position them, have bulk and can interface with, and/or distort, physiological or speech events. In order to avoid serious problems in this case, all such structures should be made as small and thin as possible. Finally, most sensors are temperature-sensitive. This condition must be monitored and controlled in order to keep artifactual data from contaminating the research. Indeed, Malecot utilized a face mask to control temperature levels at the sensors. In any case, the instrumental state-of-the-art in this area has now progressed to a point where significant and valid research can be carried out with relative ease.

b. *Palatograms*. Devices that permit investigators to continuously monitor tongue-palate relationships during physiological events (particularly during connected speech) have been evolving slowly. Even today, however, it is still difficult to track tongue movements except where they touch some structure such as the teeth or palate. In the past, the palate and teeth have been coated with dye or powder (Bloomer, 1953) and the transfer of these substances to the tongue photographed after a single speech gesture. This approach is crude, slow, and hard to quantify, and it does not permit more than one palatogram to be obtained at a time. While a viable capacitance based micro-miniature device has yet to be invented, some progress recently has been made in this area. For example, Kozhevnikov *et al.*, (1963) describe the development of a "dynamic palatograph". Their system includes a number of small electrodes inserted in a thin custom-fitted plastic dental prosthesis which is adhered to the subject's hard palate. A small current is placed on these conductors so that, when they are touched by the tongue, a signal is fed to the output equipment. A more sophisticated, but somewhat similar, system has been described by Miyawaki *et al.,* (1974); associated computer techniques by Tatsumi (1972). This unit utilizes a far greater number of sensors than does the Russian device, and the obtained data are much more easily quantified and processed. Neither approach provides information concerning the magnitude of tongue pressure—only its presence or absence.

c. *Mandibular displacement*. Equipment of this type has been used to investigate jaw and lip movement (Abbs *et al.*, 1971); it should be useful in the study of anomalies of the tempero-mandibular joint. Basically, the subject is positioned in relationship to the equipment by means of positioners usually fixed to the maxillary teeth. The subject moves the lips or jaw against a resistance, and associated strain gauge equipment feeds the resulting information to the analysis or monitoring equipment (visual, graphic, storage or computational).

Excepting for the multiple measurement system described by Fletcher (1975), the approaches described above have not been developed to levels as sophisticated as have those listed in most other sections of this report. However, some reasonably useful devices are available, and it is suggested that they could be profitably adapted to provide more extensive clinical and basic information than is currently available.

5. Approaches to Oral-Sensory Perception[5]

Not a great deal is known, currently, about the tactile-sensory feedback mechanisms that accompany many of the physiological events related to speech in particular and to the craniofacial area in general. As Ringel and Ewanoski (1965) have pointed out, most available information about these issues is

[5] For an excellent and detailed review of the research in this area, see Bosma (1967, 1970).

inferential in nature or has resulted from a) studies of (oral) tactile deprivation or b) observations of the performance of individuals with neuro-sensory diseases. Some research is currently being carried out, but the level of the instrumentation in this area is still relatively primitive. Hence, a brief review of two approaches should suffice to illustrate the types of apparatus that currently are available. Virtually all of these devices are mechanical in nature.

Ringel and Ewanoski (1965) have described an oral esthesiometer for use in two-point discrimination experiments in the area of oral (tongue, palate, etc.) perception research. It can be used in relatively inaccessable areas. Basically, this unit permits the calibration and control of distance (0–10 mm between its two probes when they come in contact with the skin or mucosa. Moreover, the mechanism permits the experimenter to control rather exactly the pressure exerted by the probe points (a range of 1–3 grams). Specifically, a pair of monitor lights allow the experimenter to monitor and control the amount of force exerted on the skin surface by the stimulus probe. The authors have utilized this device to study two-point sensory perception of the lips, tongue, alveolar ridge, and velum.

Another approach to oral sensory perception has been described by LaPointe, Williams, and their associates (1971, 1973, 1974, 1975). These researchers have developed a set of geometric shapes that permit oral sensory research to be carried out with respect to 1) weight discrimination, 2) thickness discrimination, 3) two-point discrimination, and 4) intra-oral shape recognition. In most of their research, they have utilized these devices to study perception in the lingual area. They also have utilized a commercially available electrogustometer to supplement their studies with data on taste perception.

6. Visualization Techniques

With the exception of the radiological procedures, most of the instrumentation discussed above provides indices or analogs of function rather than visualization of the mechanism involved. Nevertheless, in some cases it is desirable to study such issues by means of some visualization system that will provide permanent records of the area or function under study. Ideally, quantitative measures of function, change, etc. could then be derived from processing these records. The four types of instrumentation that will be discussed here include photography, video-recording, fibreoptics, and ultrasonics. All would appear to relate to each other in some fundamental way. Moreover, these techniques can be utilized to provide information about certain functions that cannot be obtained by any other means.

a. *Photography*. By-and-large, photography suffers from a limitation that transcends any form of visual observation of craniofacial areas; viz., that visualization is confined primarily to the outside of the head and neck. However, some useful research is possible using this method. For example, Fujimura (1961) has utilized motion pictures to study lip movements related to bilabial consonants. Moreover, permanent photographic records of patients with cleft lip are common at most clinics. Most photographic procedures utilize oridinary 35 mm through-the-lens, reflex cameras or similar types of

16 mm motion-picture units as well as associated mounts, lenses, and lighting systems.

Intra-oral photography also has been utilized to study speech movements and craniofacial mechanisms. In this case, subjects are instructed to open their mouths as widely as possible, and the oral cavity is illuminated. Cheek retractors and tongue depressors often are utilized so that the posterior portion of the oropharynx and at least part of the pharyngeal area can be visualized. The subject is instructed to produce a low vowel (such as /a/), and either single-frame or motion pictures are made. By such intra-oral photographic procedures, observations can be made of movements of the soft palate, the faucial pillars, or the posterior and lateral pharyngeal walls (in a relatively distorted state, however). It should be stressed that estimates of the degree of palato-pharyngeal closure cannot be reliably obtained from intraoral photography as the place of contact between the velum and the pharyngeal walls is superior to the field of view. It also is possible to observe the velopharyngeal mechanism via photographs made through a surgical opening in the face (Bloomer, 1953; Calnan, 1953). Of course, the view obtained depends on the size and location of the opening. Finally, many investigators have described photographic procedures which are used with other research techniques (such as radiographic ones) in order to provide a permanent record and permit measurements to be made on the obtained research materials. Procedures that permit measurements to be made (i.e., quantification of the observed events) have been described for situations where photography at standard or high shutter speeds is utilized either as the primary research tool or the process by means of which the records are made. (See Fletcher, 1958, and Fujimura, 1961). In short, photographic procedures constitute a reasonable methodology for the study of certain normal or abnormal functions.

b. *Video systems.* Closed circuit television systems have not been exploited in this area as fully as their potential appears to warrant. Briefly, the type of materials that video techniques can provide the investigator are virtually the same as those obtained by photography. However, most video-recorders have the advantage of instant replay, unused tape does not deteriorate with age (as does film) and the recording tape can be erased and reused as appropriate. Video systems are readily available commercially. Indeed, firms marketing these devices can meet virtually any set of specifications. Once the initial cost of such a system is met, video recording is an extremely inexpensive research tool.

c. *Fibreoptics.* The use of fibreoptics as an adjunct to research photography of craniofacial mechanisms will permit visualization of some areas not readily accessable by other means. Although a number of researchers have developed fibreoptics as a research tool, Sawashima and his associates (1969, 1972) have described particularly good procedures of this type for visualizing both the larynx and movements of the velum. Fibreoptics are simply flexible bundles of glass fibers that are organized either as light transducers or with an integrity that permits images to be transmitted. In research, it is usual to employ two or more bundles, one to visualize the target area and the rest to transmit light for its illumination. In discussing their unit for use in viewing velar movements, Ushijuma and Sawashima (1972) describe a "wide angle model" which they insert through the subject's nose. By means of this device (and associated lenses), which they coupled to a 16 mm motion picture camera, they were able to photograph the superior surface of the velum and correlate its movements with certain speech acts. Quite obviously, there are many potential uses for fibreoptic systems in the support of research relative to clinical issues—especially in the area of velopharyngeal function. By such means, improved diagnosis and assessment of the effects of treatment should be possible without radiating the patient.

d. *Ultrasonics.* The use of ultrasonics as a research methodology in dental research and in investigations of craniofacial function has been extremely limited. Some studies have been carried out related to the use of ultrasonics to visualize vocal fold movement (Hertz, *et. al.*, 1970) or pharyngeal wall movement (Kelsey, *et. al.*, 1969; Minifie, *et. al.*, 1970). There are several types of ultrasonic systems, but basically they operate as follows: A transducer produces a frequency in the ultrasonic range; this beam is focused on a target area. The sound waves are reflected by target structures whereupon the echo is picked up by a sensor, is amplified, and displayed via some means (usually a CRT). Permanent records of the structure can be made by photographing the face of the CRT or by other (often direct) means. By this method, a particular internal area can be outlined and studied. To date, ultrasonic techniques have not been very popular. It is possible, however, that such approaches could be adapted to provide information not currently available about a number of fixed—or very slowly moving—target structures within the craniofacial area. If appropriate techniques could be developed, they would, at the very least, provide the clinician with data that is presently obtainable only via radiation of the patient.

7. Acoustic Processing of the Output Signal

There is such a great variety of electroacoustical systems and devices currently available to the investigator that, if a full review were attempted, this section would exceed all of the others combined. Accordingly, only two illustrative classes of equipment will be discussed here; i.e., 1) a device for use in assessing cleft palate speech (Voice Systems Nasality Meter) and 2) Spectrographs, primarily of the time-frequency-amplitude class. It should be stressed also that modern electronics is providing experimenters with processing hardware of greater and greater sophistication. The exotic dimensions of this thrust are accelerating at such a rate that they are outstripping the current expertise of many scientists. Indeed, new hardware coupled with computers is advancing so rapidly that the primary limiting factor now appears to be the sophication and imagination of the scholars themselves.

a. *The Voice Systems Nasality Meter.* Substantial research has been carried out on the acoustic correlates of nasality. However, it must be stressed that there still is some controversy concerning the acoustic parameters that correlate with perceptual identifications of the various forms of nasality.

Nevertheless, a number of investigators have attempted to develop hardware which would be useful in the laboratory and clinic in objectively identifying and quantifying the nasality component in the speech signal. One unit of this type is the Nasality Meter described by Weatherly-White *et al.*, (1964, 1966). Apparently, it was derived from a speech recognition device which, as part of the logic for the transcription of spoken words, made use of the nasality of vowels. The authors judged that the process could be reversed to permit the assessment of nasality. Furthermore, as nasality has described as one of the principal stigmata of cleft palate speech, it was hoped that the instrument would be of use in the classification of the speech performance of post-operative cleft palate patients. In any case, the speech signal is introduced into the instrument either live or on tape. The pressure wave is then integrated and subjected to phase-shift, producing an asymmetric wave-form. The result may be observed by means of a meter, which is part of the instrument, or may be recorded permanently by graphic recorders. No frequency filters are used in the system. Rather, the time relationships or phase of the frequencies in the speech are analyzed. Weatherley-White suggests that a distinct and consistent response to changes in nasal resonance can be obtained by utilization of this device with the wave-form showing positive polarity when nasal resonance is achieved by means of the open velopharyngeal port. He suggests that such measures of nasal resonance are useful when acoustic studies of cleft palate speech are attempted.

b. *Spectrographs*. The time-frequency-amplitude units such as those of the Kay Electric Co. (Sonagraph) or Voiceprints, Inc. are simply one form of spectrometer. They are based on a design originally developed at the Bell Telephone Laboratories. This type of spectrography is, in some senses, a rather crude one. However, it constitutes a technique that has many uses in a laboratory and modern clinic. The basic feature of this approach is that it provides a pictorial representation of the acoustic signal in roughly three dimensions. The uses of such material in speech research and clinical assessment are obvious. As one example, a great deal of baseline or normative information about the acoustic patterns that can be expected in normal phoneme production by men, women, and children is presently available. Thus, assessment of clinical progress in certain types of cases can be carried out not only by means of subjective perceptions by the therapist but also with the aid of a Sonagraph. In this case, the speech patterns thus portrayed can be compared to those produced by normals, and the patient's ability to approach the desired target is objective evidence of progress. It also provides insight into the mechanisms that are operating. Finally, other types of spectrometers are available to the clinical and basic researcher. However, it is not possible to review these other devices and their uses here.

In summary, there are great constellations of electroacoustical devices potentially capable of assisting the investigator or clinician in the analysis of the extra-oral signal produced by individuals with craniofacial disabilities of all types. In general some of these instruments are more useful than others. However, since it is not possible to review a significant number of these devices each investigator must individually match these specialized systems to the specific needs of the research being undertaken.

8. Computer Support

The modern digital computer is advancing in sophistication at a pace that sometimes is difficult to comprehend. Moreover, on-line and hybrid units are becoming so plentiful, and so easy to acquire that it is often easier and cheaper to interface a computer to existing hardware than it is to develop or purchase additional systems demanded by a particular research or assessment program. Indeed, the CPU for the average minicomputer currently is so inexpensive that its purchase usually is based on the need for associated IO (input-output) and other "hang-on" components. Two relationships must be kept in mind however.

First, a digital computer is simply a tool, albeit a fairly sophisticated one. Accordingly, research and assessment considerations should not be adjusted to fit the computer. Rather, the computer facility—and its associated software—should be developed to serve the needs of the research and/or evaluations specified by the design protocols. Since many scientists and clinicians do not personally operate their computers, this perspective should be kept in mind when planning research.

Additionally, it should be remembered that control computers have as yet only a limited usefulness for most types of research associated with craniofacial mechanisms and function. For example, it is relatively easy for investigators in Psychoacoustics to design research in which the computer controls the experiment. In some cases, it can be programmed to virtually conduct the study; and then automatically processes the data. In the case of many of the research designs and instrumental techniques described in this report, however, such an approach usually is not possible. Indeed, much of the work in our area consists of exploratory ventures or the assessment of relationships that are not directly under our control rather than the study of behavior as a response to the application of particular stimuli.

The above cautions should not be construed to suggest that computers are not revolutionary "weapons" in the repertoire of the clinical or basic scientist interested in issues relating to craniofacial function. The evidence is quite to the contrary. A number of examples of the imaginative and sound use of computers in dental research have been cited above. Also, the computer approaches of Gibbs and his associates (1971, 1972) in the study of complex mandibular movements are excellent illustrations of this trend. Moreover, the modern digital computer allows us to store and process data efficiently and effectively—often on-line—and to be privy to the results of the research/assessment procedures within a very short period, sometimes even within the experimental period itself. Even more exciting is the possibility that on-line digital computers can effectively close the gap between basic research and the diagnostic/therapeutic informational needs of the practicing Physician, Dentist, or Speech Pathologist. Indeed, the practitioner no longer will have to wait for laborious and lengthy data reduction to be carried out in order to obtain the information needed. Finally, computers are now permitting us, mathematically and theoretically, to study behaviors that are not approachable *in situ* and to construct for study theoretical models of extremely complex mechanisms and systems. An excellent example of such an approach and of an innovative use of computer resources can be seen in the work of Walker (1969, 1972) and Walker and Kowalski (1972). They generated mathematical models of the craniofacial morphology of the skull based on large-scale cephalographic measures. They stored these values as a string of coordinate points which mirrored anatomical structure. The data were then used to study such factors as normal or abnormal growth patterns or to compare the craniofacial structure of a particular patient to the norm for his or her age and sex. In summary, the use of computers has had a profound effect on medical technology. It is now having the same effect on dental and speech research, and these effects should accelerate over time.

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