DIGITALLY CONTROLLED DYNAMIC RADIOGRAPHY

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I. Introduction

Radiography and cineradiography are probably the most generally used techniques both in research and clinics for the observation of the internal organs of the human body. However, acquisition of necessary information by these methods is always at the risk of undesirable effects of radiation on the human body, and development of an optimum system which would make it possible to obtain the required information with a minimum radiation dose has always been a primary concern of the radiologist.1)

In order to overcome this limitation of the present radiographic system in its application to the investigation of the articulatory activities of the human speech organs, a new radiographic technique has been proposed which might be called computer-controlled dynamic radiography.2) It consists of a deflectable x-ray microbeam controlled by on-line computer in combination with a high-sensitivity scintillation counter for its detection. The proposed scheme not only operates on a substantially reduced dosage but also provides a practical and effective way of processing radiographic data. The first prototype system has been actually assembled, and some preliminary experiments have been carried out. This paper reports on some of the results.

Recent progress in speech science has revealed that more knowledge about the physiological mechanisms involved in the articulation and phonation processes is very much in need for further understanding of the complex human speech activities.3) A sufficient accumulation of systematic data about the articulatory movements is seriously desired. The work of Chiba and Kajiyama4) was the first study which accounted successfully for the acoustic phenomena based on the vocal tract shape observed by lateral

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1) Morgan and Roach (1949).

2) Fujimura (1967), Fujimura *et al.* (1968), Fujimura *et al.* (1969).

3) Fujimura (in press).

4) Chiba and Kajiyama (1941).

radiography of the human head. This line of approach was given a more general theoretical framework by Fant,1) whose study, independent of Chiba and Kajiyama, was based on radiographic data of Russian articulations.

Later, interest in the dynamic aspects of speech activities became intense2) and various kinds of x-ray high speed motion picture studies have been conducted by many workers. 3) The works of Houde, 4) and Perkell5), for example, which represent the most recent analyses of articulatory data, have revealed many interesting and important facts about speech activities.

Unfortunately, but inevitably, the data for these excellent studies were severely restricted in quantity. The amount of data that has been analyzed and published actually is about one-minute net in Houde's study and is about half-a-minute net in Perkell's study, both with a single subject. There are practically two limiting factors that restrict the amount of data that can be obtained in x-ray high speed motion picture studies; one is the dose problem, and the other is the difficulty in retrieving and processing necessary information from the motion picture film.

Even with use of the best available image intensifier and the most careful experimental setup, a frame rate of 50-100/sec would give the subject a dose density of about one roentgen per minute over a large volume of the pertinent organs, and thus, a continuous exposure in a data recording session of one minute in total, which usually accompanies some more actual exposures for practical reasons, requires a cautious planning of the experiment in respect to the possible radiation disturbances. It would not be advisable for any subject to complete an utterance list of a moderate size that would be necessary for the systematic comparison of different phonological units.

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1) Fant (1960).

2) Fujimura (1961a), Fujimura (1961b), Lindblom (1963), Öhman (1966), Vieregge (1969).

3) Moll (1960), Truby (1962), Stevens and Öhman (1963), Heinz and Stevens (1964), Hollien (1965), DeClerk et,al. (1965), Lubker and Moll (1965), Öhman (1967), Houde (1967), Subtelny et al. (1968), Perkell (1969), MacNeilage (1969).

4) Houde (1967).

5) Perkell (1969).

It should be noted that speech activity like any other human activity is characterized by some inherent fluctuation as well as idiosyncracy. The evaluation of the effects of these factors and the separation of the linguistically significant factors from others are one of the major points to be studied Such a study cannot be expected from a very limited amount of data.1)

In both works mentioned above, extraction of the necessary data was based upon tracing of the film image and frame by frame measurements of the positions of the specific points of the articulatory organs. The number of frames that has to be examined easily adds up to several thousand for one specific study. A careful frame by frame analysis of such a large number of x-ray images is a very difficult task. A more effective way of data processing is obviously needed.

As for the dose problem, the best possible way to reduce it, in principle, is to limit the x-ray exposure to only the moment and location at which it is effective in obtaining immediately useful data, and to catch and exploit the information carried by the x-ray photons by using a highly sensitive detector. Ordinary x-ray film is very unsatisfactory for the purpose of efficiently detecting the x-ray signal, because only a limited portion of the x-ray photons can interact within such a thin material. It is known that ordinarily only a few per cent of the incident x-ray energy is absorbed by the photographic emulsion.2)

The invention of the image intensifier was epoch-making in this respect3), and its combination with the television-type field scanning technique appears to be the best system available at present.4)

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1) See Perkell's comment in his recent book, for example, [Perkell (1969), p. 42]:

> The apparently premature movement of these structures for /hə´sɛ/ in Figure 3. 33 emphasizes the inadequacies of this study in dealing with only one sample of each utterance and in arbitrarily comparing phonetic segments by aligning the utterances temporally at the time of consonant release.

2) Ter-Pogoisson (1967).

3) ditto.

4) Capp and Spach (1962), Webster and Wipfelder (1962).

This system not only achieves a remarkable improvement in the sensitivity but also allows us to avoid the irradiation due to the scattered x-ray during the radiographic observation. It also enables us to process the data in the form of electric signals in a flexible way and dispense with such time consuming tasks as the developing of the photographic film.

However, there is an inherent technical difficulty in any of conventional methods of cineradiography: when the layer of the fluorescent material is thick enough so that it may interact with all the incident x-ray photons, resolution will become worse due to the diffusion of light within the material. Thus, the fluorescent layer used at the input stage of the present image intensifier is rather thin and the absorption of x-rays is generally not more than 20-30 %. 1)

There are some more problems concerning the clarity of image. The regular generator of x-rays as the source usually does not make a small enough point source, and this can cause some blurring of the image when fine details are studied. There is also some limitations concerning the dynamic range of blackness in the photographic emulsion.

Reprocessing of photographic film by logetronography provides an apparently better image for visual inspection than the original film. 2) The result is an increase in local contrast and a decrease in overall gross contrast, and the obtained image has an improved delineation of the fine structures. Of course, information not contained in the original photographic film cannot be recovered.

This kind of operation, which seems very helpful in practical data aquisition, can be carried out more effectively and flexibly by using a digital computer. Appropriate logical processes that consider both temporal and spatial contexts for reducing noise or any random factors are presumably very effective in obtaining useful information from generally rather unclear radiographic images. This capability of computer processing appears to be very valuable particularly because the quantum noise constitutes an

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1) Ter-Pogoisson (1967).

2) St. John and Craig (1957), See also Perkell (1969).

unavoidable theoretical limiting factor for the quality of the radiographic image, when, as in this proposed system, the detector is sufficiently sensitive and thus the exposure is reduced to the theoretical minimum. 1)

Restriction of the x-ray exposure only to necessary portions of the subject is desirable not only to reduce the dose but also to decrease the scattered radiation which causes significant degradation of the image quality as well as the environmental hazard. Use of the field limiting diaphragm is the only possible method so far. An automatic device which maintains the area of x-ray radiation equal to the film size has been developed, and this has been shown to be very useful in practical applications. 2)

Similar efforts have been made for saving dose in the time domain. In cineradiography, an on-off control of the x-ray generator by synchronising pulses derived from the cine camera has been employed by some workers. 3) Apart from this, again, no essential improvement in this aspect has been made so far.

Application of computers to cineradiography has been restricted so far only to the reprocessing or facilitating visual measurements of the original film image. 4) No attempt has been done to reduce the dose with the application of computer techniques. It is apparent now, however, that the whole radiographing process should more closely contain the computer system in it.

The deflectable x-ray microbeam system can be combined with on-line computer control, and it appeals to us as a very promising system for coping with all of the problems mentioned above. A type of scanning x-ray microbeam system was actually proposed and tested in a very early work by Moon. 5) Unfortunately, he could not exploit the full advantages of the new principle because the necessary techniques and devices did not exist at that time. In particular a high speed digital computer was simply not available

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1) Sturm and Morgan (1949), Burger (1949).

2) Walche *et al.* (1967).

3) Bloom (1964).

4) Becker et al. (1964), Winsburg et al. (1967), Toriwaki et al. (1968).

5) Moon (1948), Moon (1949), Moon (1950).

for an on-line control of experimental systems. No substantial progress seems to have appeared since his pioneer work.

One salient feature of the scanning x-ray method is the conversion of spatial information into temporal information. This permits us to use a thick dense material for the detector because we do not need any spatial resolution of the image. At the time of Moon's experiment, a highly sensitive scintillation counter was apparently not available, either. Recent experimental techniques mainly developed in the field of nuclear physics enable us to use a large piece of scintillation crystal that can detect practically all the incident x-ray photons and is comparatively transparent to light.1) In a well-designed detector system by use of the scintillation crystal, the noise in the detector system is predominantly due to the quantum effect of x-ray photons and the natural radiation (cosmic rays), when the signal level is low, as is true in typical cases of our experiment. The resolving power of the system is thus essentially determined by the effective power of the x-ray source. We need a fair amount of x-ray energy produced at the target, because the portion of the x-rays taken out of the pin-hole lens is very small, and the rest of the x-rays are wasted. In this respect, we can obtain a very fine electron beam with sufficient power, thanks to the advance in electron optics and the development of various kinds of the electron probe devices including electron bombardment machining devices.2) Since all the electron-beam energy has to be concentrated on a very small area (such as 10-50 microns in diameter) on the target, the limiting factor that determines the maximum power density of the electron beam on the x-ray generating target seems at present to be the amount of locally concentrated heat that is tolerable for the metal. The fast and random-access type deflection of the electron beam makes this problem solvable, too.

II. Overall Experimental Scheme and its Characteristics

The block diagram in Fig. 1 explains the experimental method. Details of the particular apparatus we used for our pilot study are given in the next

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1) Birks (1964).

2) Grivet (1965).

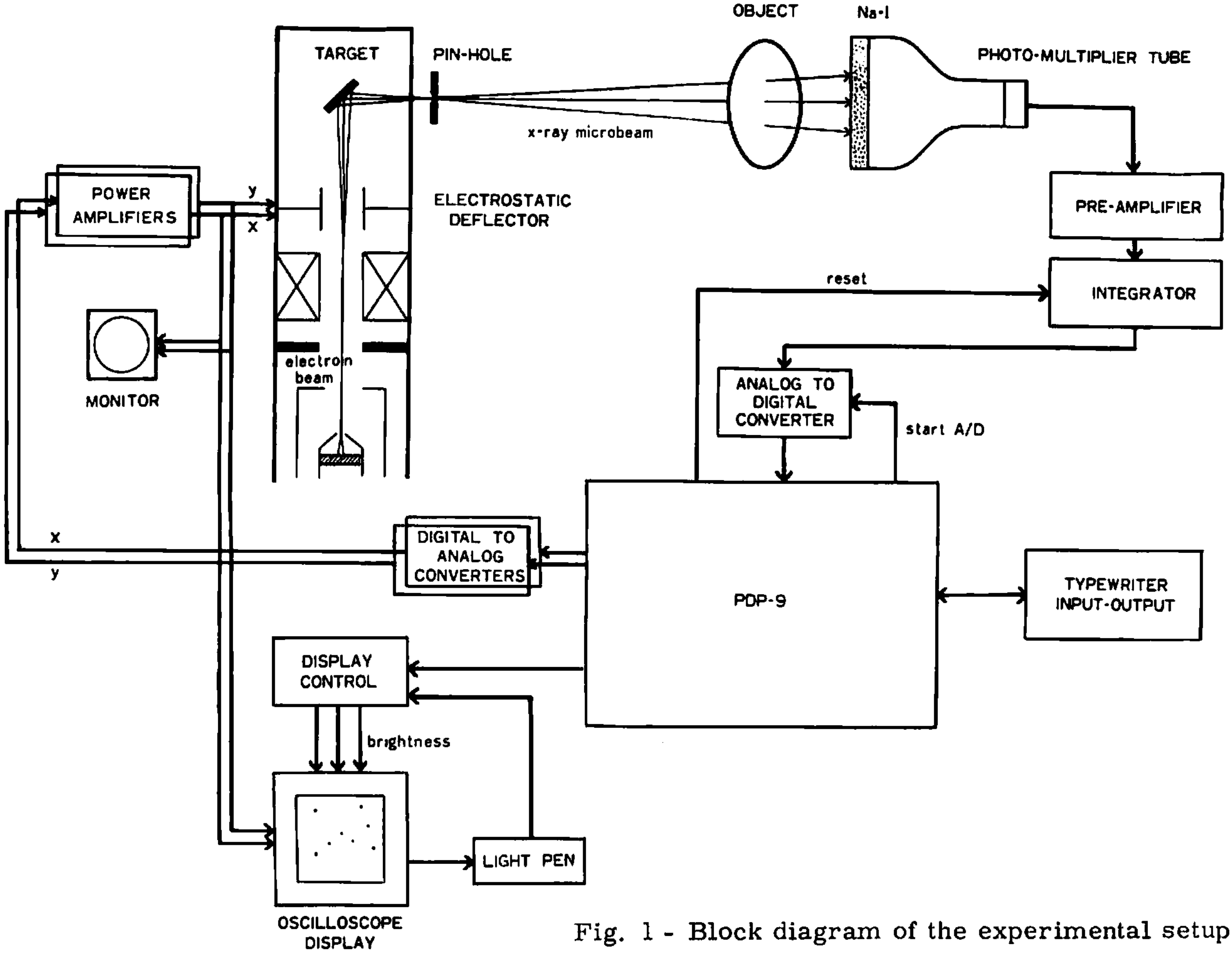

Fig. 1 - Block diagram of the experimental setup.

section. An electron beam emitted from an electron gun is focused by an electron-beam focusing lens onto a tungsten target. A small portion of the x-rays radiated from the target runs out through a pin-hole lens and forms an x-ray microbeam. Electrostatic deflection plates are placed between the focusing lens and the target. The deflection voltages that are applied to the deflection plates determine the destination of the electron beam on the x-ray generating target and consequently control the direction of the x-ray microbeam. A human subject, who utters the speech samples to be studied, sits in between the pin-hole lens and the x-ray detector, his head serving as the object for the x-ray beam. The intensity of the x-ray beam that has run through the object is measured by the detector which consists of a large piece of Na-I scintillation crystal and a photo-multiplier tube.

The point on the object to be hit by the x-ray beam is determined by the computer for each selected time moment by specifying the deflection voltages that are generated through two digital-to-analog converters and amplifiers. At the same time, the output signal of the photo-multiplier tube is integrated over a time interval. For executing the integration, the central processor delivers a clear-and-start pulse to initiate integrating the analog signal. After a time interval which is specified by the program, the integrated signal is sampled and held and then analog-to-digital converted. The digitized value is then stored in the core memory as the intensity value of the x-ray beam that has passed through the specific point of the object at the specific time moment. It is also used as the brightness control signal for a monitor oscilloscope, the deflection terminals of which are connected to the deflecting electrodes of the microbeam generator through appropriate attenuators. If the deflection voltages are given to scan over a field of the object, its x-ray image is thus observed on the cathode-ray oscilloscope surface. The deflection of the x-ray beam, however, can be given in a random-access fashion. Thus any manner of sampling selected points on the object in the time series is possible.

The data of the current observation and the results of the analysis can be monitored by a display oscilloscope unit of the computer. This makes it possible for the experimenter to check in real time if the present experiment is being run as desired. If not, parameters for the measurement can be readjusted through either a light-pen or a keyboard serving as the input to the computer. The data thus obtained can be stored in digital form on magnetic tape, for example, and drawn for further processing whenever necessary.

One of the most significant features of the system described above is the flexibility in the control provided by the on-line computer. All conceivable sorts of information can be exploited to reduce the radiation dose, and this necessitates only a slight increase in sophistication of the computer programing. Combined with the very high sensitivity of the detector (see § III 2), the attainable reduction in dose is very significant. Since it varies, however, depending on the specific purpose and the programing technique, it is impossible to make a general estimation of the extent of the reduction. For collection of certain kinds of articulatory data, the dosage to be spent may well be reduced by a factor of $10^3 \sim 10^5$ compared to the collection of the same information by conventional cineradiography. Our specific application of this system is in observation and measurement of articulatory and phonatory movements, in particular, tracking of movements of metal pellets which are placed on specific points of the articulatory organs such as the tongue. In this case, the following kinds of contextual information are now in consideration for reducing the net exposure.

(1) The position of a pellet can be predicted to a considerable extent by considering its current position and the state of movement. Therefore, it is possible to restrict the scanning area of the x-ray beam to a small field around the predicted position (cf. infra).

(2) In the case of simultaneous tracking of several pellets, there will be correlation between the positions of different pellets, because the possible shapes of the tongue surface are highly restricted for physical and physiological reasons. Therefore, knowledge about the position of one pellet can be used to facilitate the detection of others.

(3) The rate of sampling and also the duration of exposure for one time-space sample can be adaptively varied according to the speed of the movement of the pellet at the time, and also depending on the detected x-ray intensity

and consistency of the observed pellet location with the prediction by context (in time and space).

(4) When preliminary knowledge concerning the articulatory movements under investigation is available, it can be taken into consideration in devising computer program with better pellet-search strategies. In particular, a successful model of the articulatory system that describes the articulatory movements in terms of a small number of time variables will make it possible to predict the range of the pellets' next positions, thus making it easier and more accurate to locate them in noisy circumstances.

The result of the measurement in turn can be described in terms of the parameter values of the model. Thus we have an immediately responsive loop for the specialization and improvement of the model and observation of the experimental fact. The participation of the experimenter in an interactive experimental system with use of an on-line computer control has been demonstrated to be extremely effective in investigation of complex phenomena in many fields of application, particularly, in speech science. 1)

III. Apparatus for the Pilot Study

1. The Deflectable X-Ray Microbeam Generator

In order to carry out the proposed scheme, it is essential to produce an x-ray microbeam with a high enough intensity so that a sufficient number of outcoming quanta can be measured within the time interval alloted for each scanning point (i. e. , for each time-space sample). The high voltage for accelerating the electron beam in the x-ray generator must be supplied from a well stabilized D-C power supply because we need constant intensity of the generated x-ray beam during the measurements. This good stability is also mandatory for constant focusing of the electron beam.

Thus, for the preliminary stage of our experimental study which was designed as an exploration of the new radiographic method, we use the Micro

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1) See, for example, Schroeder (1968), Denes (1968), and the papers compiled in The Human Use of Computing Machines (Proceedings of a Symposium Concerned with Diverse Ways of Enhancing Perception and Intuition), Bell Telephone Laboratories, Murray Hill, New Jersey, June 20-21, 1966.

Focus X-Ray Unit manufactured by the Japan Electron Optics Laboratory Co., Ltd.,[1] modified to incorporate an electrostatic electron beam deflecting system that was specially designed for fast response.

An electron beam produced by a tetrode telefocus electron gun is focused by an electromagnetic lens onto a water-cooled tungsten target. The acceleration voltage of the electron beam available with this system is 50 kV. The size of the electron beam on the x-ray generating target surface is about 30 microns in diameter. A small portion of the generated x-ray passes through an x-ray outlet pin-hole, which is 30 microns in diameter, made of platinum, and located at a distance of 35 mm from the target.

The position of the object plane is set at a distance of 35 cm from the pin-hole. The effective size of the x-ray beam is approximately 0.6 mm in diameter on the object plane when the target current (the electron beam current which actually arrives at the target) is 250 microampere. The useful area for deflection of the x-ray microbeam free from deformation or defocusing of the beam spot is, on the object plane, 5 x 10 cm^2. Fig. 2 illustrates the deflected spots of the beam that were observed by photographic film placed at the object plane.

For the present purpose, the deflector amplifiers must provide deflection voltages with good frequency response within the range from D-C to about 1 MHz. Considerably large deflection voltages are required because of the high speed of electrons. Two D-C amplifiers with transmitter triode tubes were constructed to supply push-pull deflection voltages of ± 5 cm deflections of the x-ray beam in the x and y directions on the object plane. Output signal for a step input is characterized by a certain transient response. In the present circuit conditions, for example, the transient time which is required for the x-ray beam to travel into a prespecified point within ± 0.5 mm in the object plane is approximately 6 microsec for passage across a distance of 3 cm. A special negative feedback is employed in the deflection amplifiers in order to reduce degradation of the electron-beam focusing due to a slight imbalance of the push-pull electrode potentials.

2. X-Ray Detector

The present x-ray detector consists of a large piece of Na-I

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1) Kanaya et al. (1968)

scintillation crystal, 3 cm in thickness, 10 cm in diameter and covered with an Al sheet of 0. 7 mm in thickness, and a photomultiplier tube with an effective sensitive surface of a matching size. It is known that the linear absorption coefficient of the Na-I crystal is greater than 20/cm for the photons with energy less than 50 keV.[1)] This means that 100% of the incident x-ray photons interact with the scintillator. The quantum yield of light photons by an x-ray incident photon is also sufficient for detection by a photomultiplier tube.[2)] Thus the sensitivity of the detector itself is significantly higher than that of the image intensifier (cf. § I).

The output signal of the photomultiplier tube is fed to a D-C amplifier, which has a good response up to 2 MHz. In the output signal of the D-C amplifier, individual x-ray photons are actually countable as separate pulses for the x-ray beam intensity typically encountered in our measurements. An example is shown in Fig. 3. The amplitudes of the single pulses range up to about 900 mV at our amplifier output, and the mean amplitude of noise is approximately 30 mV at the same output. Assuming that the regularly occurring pulses with the largest amplitude represent the 50 keV photons, and that the relation between the pulse amplitude and the x-ray photon energy is linear within the pertinent range, a 10 keV photon will give rise to a pulse with an amplitude of 180 mV. Thus, all the photons of the useful energy range are securely detected against the noise in the electronic circuits. The mean number of photons that are essentially discretely counted by the present detector is in maximum about 2. 5 x 10^5/sec.

Before integration, the output signal of the D-C amplifier is first sliced at a level of about 100 mV to eliminate the effect of low frequency fluctuation, and then amplitude-limited to reduce the effect of the occasional large background pulses. The background pulses, whose amplitudes are larger than normal x-ray pulses, are presumably due to the cosmic rays and are observed at an average rate of 10^2/sec approximately.

The input and output signals of the integrator are compared in Fig. 4. Each step observed in the integrated signal reveals the arrival of an individual x-ray photon. After integration (without rectification), the effect of

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1), 2) Birks (1964).

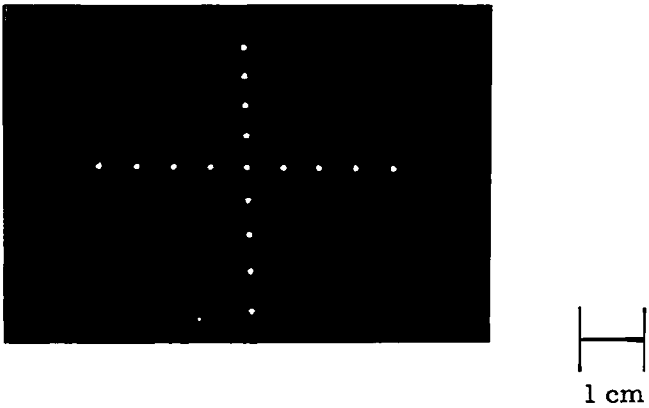
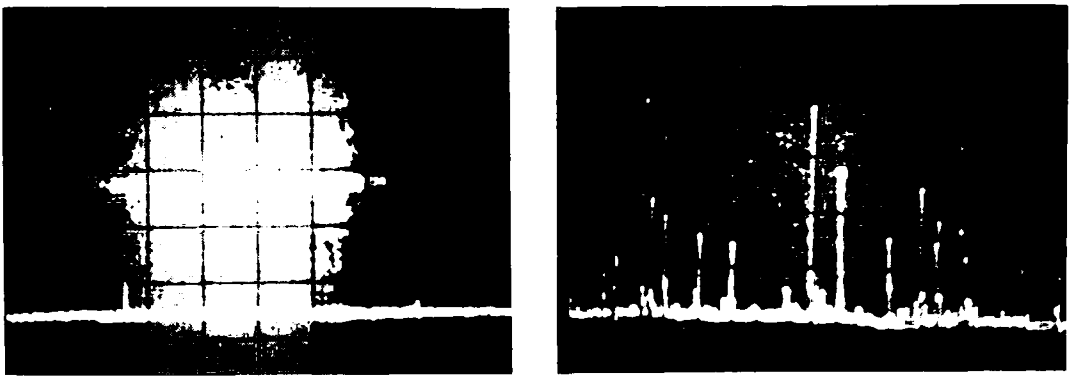


Fig. 2 - The deflected x-ray beam spots on the object plane, photographed by using a high speed x-ray emulsion (FUJI SOFTEX FILM HS) with an exposure time of 15 seconds for each point



(a)

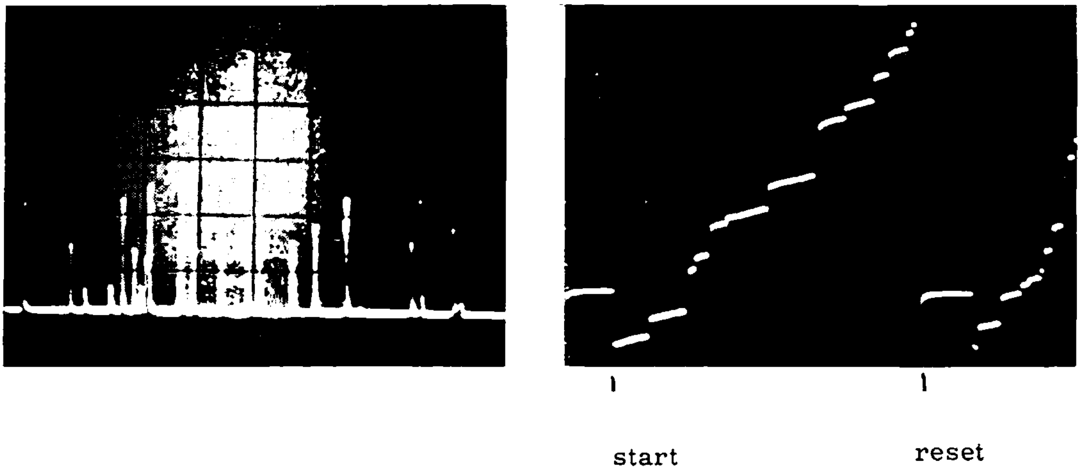
(b)

Fig. 3 - The x-ray detector output observed at the output of the D-C amplifier.

(a) Without x-ray.

(b) With x-ray (no object).

Abscissa : 10 microseconds/div. , ordinate : 200mV/div.



(a)

(b)

Fig. 4

(a) The input signal to the integrator. The output signal of the D-C amplifier is center-clipped and saturated. Abscissa: 10 microsec/div., ordinate: 200mV/div.

(b) The output signal of the integrator. The time interval between the integration start and reset (i. e. integration duration) is 100 microseconds.

the high-frequency noise becomes substantially reduced. When the integration time is increased, both the quantum noise and the random circuit noise increase, the average values being roughly inversely proportional to the square root of the integration duration, but the former always predominates. When the pulse duty ratio is low, however, fluctuation in the integrated signal is mainly determined by the fluctuation of the slicing level. This fluctuation is estimated to be less than 0. 2 mV in the present circuit. Thus, an extremely weak x-ray beam with photons arriving at an average frequency of less than one per 100 microseconds will not be detected by the present circuit. The integrating circuit, rather than a pulse counting circuit, is adopted for the detector system mainly because we are planning to use an x-ray generator system with a higher acceleration voltage by which a greater rate of x-ray photons will be observed (see infra). In that case, the pulse counting technique will be inaccurate in estimating intensity because of the occasional overlaps of the detector output pulses.

The integrator is reset to zero for a preset time interval when a trigger pulse is delivered from the computer, and then restarts integration automatically. Approximately 7 microsec is required to reset the integrator from the maximum output level to the zero level.

3. Resolution and Capacity of the Present X-Ray Generator

In the present x-ray system, the resolution of the details in the image is primarily determined by the x-ray beam size in the object plane. Fluctuation in the deflector amplifiers also causes some blur in the image. The smaller the pin-hole in diameter, the finer the x-ray beam we can obtain. However, we need a certain value of the x-ray beam energy for each time-space sample in order to obtain a clear image against the quantum fluctuation.

Fig. 5 shows some results obtained by scanning the x-ray beam around the edge of a copper coin (23 mm in diameter and 1 mm in thickness). The output intensity signal from the detector is digitized into 10 levels in a linear scale after normalization and the digitized value for each scanned point is printed out by the computer. The step in the scanning is 0. 25 mm and the exposure times for one scanning point are 100, 50 and 10 microsec for the three cases (a), (b) and (c), respectively.

It can be seen that the boundary becomes irregular and less definite as the exposure time decreases because of the larger fluctuation in intensity. Thus, the exposure time of several tens of microseconds is necessary for clearly outlining a large enough object with a high enough absorption of x-ray, against the quantum fluctuation. The determination of the position of the object by its outline can be made by the present system to a small fraction of a millimeter (in the regular object plane, where a field of 5 x 10 cm^2 can be used effectively).

Fig. 6 shows some results of scanning across a 0. 5 mm-wide slit between sheets of lead (1 mm in thickness) for three different exposure times. The step of scanning is 0. 25 mm, again. The signal to noise ratio of the intensity value at the center of the slit is also shown in Fig. 6(d) as a function of the exposure time.

A more practical measure of resolution (or accuracy in locating a pellet) will be given in the following section.

The mean number of photons for each time-space sample is, e. g., in the case Fig. 5(b), approximately 13. The dose rate (per cm^3) measured on the object plane by removing the pin-hole is 3 R/min. Taking into account the fact that the beam size is 0. 6 mm in diameter, and assuming that the entire area of 5 x 10 cm^2 is scanned by this beam uniformly, the average dose rate would be estimated at approximately 10 mR/hr.

At present, no filter for the radiating x-ray beam is present except a very thin Al foil, which is placed inside the pin-hole to secure vacuum in the x-ray generator. The scintillator is covered by a 0. 7 mm thick Al sheet. For practical exposures of a human subject, a similar Al sheet would be placed in between the subject and the pin-hole to filter out the low energy photons, replacing the one attached to the counter by a thinner foil. Then the dose would decrease by one order of magnitude, without substantially affecting the exposure duration in most cases.

The mean count of photons effectively detected by the present scintillator is 2. 5 x 10^5/sec when there is no object, and therefore the average photon density would be 2 x $10^7/\mathrm{cm}^2\cdot$hr if we used the beam for uniform

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557676634........1......
735659652......11.......
579955923..1.......1....
78774565................
577275221...........1...
456565641...............
65655553................
98966452................
7774532211..........1...
76476752................
68556742................
67565523......1.........
95566521....1...........
46765552.1..............
49775652....1.1.........
655763511...............
59443772..........2.....
66759653.1.............1
6775773211..........1...
355947332...............
765465532..1............
347658622...............
6557777322.11...........
755694732...............
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(a) 100 microseconds

```
6779977635741...2.......
566856533731..1.........
677769797612.2..........
776577755731.2.1........
9967477943..11..........
7495766422.1............
5993962742..1...........
3233937742......1.....1.
67654947621..1..........
779939923..1...1........
75737757322......1....1.
9657556341..............
497677952.1.............
73359695211..11.........
778789753...............
469636332...............
357996932.......1.......
996565732........1......
63567934................
577894621............1..
677776753..1..11...1....
577567552...............
775398751...............
6679754232.1.1..........
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(b) 50 microseconds.

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57959539551.121123...11.
55599875814.1...1.......
89731555211....1...11...
5595899931322.....2.11..
158591917531.1.1..1...1.
85599594195111...1.....1
59897395751...1..1....13
595999852515.2.1....1...
91899995.1....1.13.....1
9899958313.121.1.1.2....
35899339....2..1..2...1.
999958993....2..........
9959914154.12.1..1......
558429995211....1.....1.
5551894911.......1...3.1
941958573...1.11.....1..
9958999131...11..1.....1
81981858211.1.....1..213
32998598111..12.....1...
81895991............1...
8939954251.....11.......
954958985.1..1..4.......
195352535..2.....1...1.1
8155991511.11.1..11...1.
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(c) 10 microseconds

Fig. 5 - Computer print-out of the x-ray shadow of the edge of a copper coin obtained with 3 different exposures, with the numbers representing the digitised intensity values for each scanning point. The dot represents the lowest level of the detector output. Distance between the neighbouring scanning points is 0.25 mm.

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.....1...1352...........
..........353...........
.........1341...........
..........131...........
.........1331...........
..........331...........
..........231.1.........
.........1142...........
..........231...........
..........151...........
1.........2331..........
..........431...........
..........132...........
..........241...........
.........1241...........
..........131...........
..........231...........
..........331...........
..........211...........
..........132...........
.........1331...........
```

(a) 200 microseconds

```
..........552.....1.....
........123413..........
........11312...........
........1133..1.........
.........1451.......1...
.........3522...........
..........531...........
..........224...........
.........2221...........
........1.13............
........1.34...1........
.........133............
.........243............
.1.......1122.1.........
..........131..........1
.........1521...........
..........221....1......
..........531...........
.......1.342............
.........1351...........
..........233...........
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(b) 50 microseconds

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.2.......3..............
..........6544..........
.........14.1...........
..........14............
...........62...........
.........19.2...........
..........52.2..........
........................
........1.44............
..........94............
...........43...........
..........3.1.3.......2.
..........31............
.........1.52...........
...........22...........
.........2642...........
....1....1..............
..........44..1.........
...........33..........2
.........4256.......2...
..........2.............
```
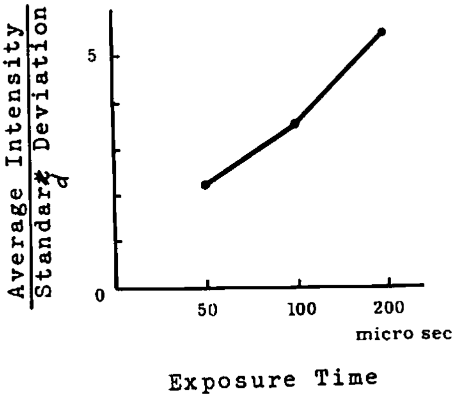

(c) 10 microseconds



(d)

Fig. 6- (a), (b) and (c) Computer print out of the x-ray image of a 0.5mm slit between lead sheets of 1mm in thickness, obtained with three different exposure times. The step of scan is 0.25mm. (d) The value of signal to noise ratio of the x-ray intensity at the center of the slit is plotted with regards to the exposure time.

scanning of the entire field. The mean energy of the detected x-ray photons may be estimated at 20-30 keV and the photon density for 1-R x-ray radiation is approximately $10^{10}/cm^2$ for this energy range. Thus, the dose rate with filtering by the 0.7 mm-thick Al may be estimated at 2 mR/hr maximally, i.e., for a continuous stretch of exposure. However, this photon density from the present generator of rather long wavelength x-rays is not appropriate for practical data acquisition that relies on detection of pellets surrounded by the boney structures of the human articulatory system (see § IV).

IV. Preliminary Tests of the Computerized Techniques

1. Pellet Tracking Program

One of the major factors that contributed to materialization of this method is the recent development of small high-speed computers for laboratory use. The present system employs a PDP-9 computer manufactured by the Digital Equipment Corporation. Some simple computer programs have been written for the automatic tracking of the pellet, and limitations of the experimental method due to the computer capability in its application to articulatory measurements have been evaluated in comparison with those due to other factors. A basic strategy for the pellet tracking is shown in Fig. 7. In order to find the present position of the pellet, a complete scanning of either a 5 x 5 or 7 x 7 mesh of points is tried centering around the previously detected pellet position. Digitized values of the x-ray intensity signal for all twenty-five (forty-nine) points are stored into the core memory. The point of the minimum intensity is determined and its coordinates are stored as the current position of the pellet, which together with other data is displayed on the oscilloscope.1) At the next sampling time for the same pellet, scanning will be made around this up-dated pellet position. This process is repeated with an appropriate time interval, and

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1) In the present setup where we do not use separate D/A converters for the deflection voltages, we actually take out the x- and y- voltages of the oscilloscope display as the inputs to the deflection amplifiers of the microbeam generator.

the track of the pellet is displayed on the oscilloscope.

Assuming that each output sample is digitized into one of 6 bit levels (in 9 microseconds), and that the tracking is to be done as fast as possible, a program can be written for the data inputting during the beam scan in the x-direction in such a way that it takes 24 microseconds to read in a sampled level for one time-space sample. An integration time of 17 microseconds is allowed within this cycle. A timing diagram for the execution of this program is shown in Fig. 8.[1)]

It can be shown similarly that the minimum time required to scan a complete 5 x 5 field of points is about 720 microseconds (1.4 msec in the case of 7 x 7). If we track 10 pellets with a frame rate of 100 frames/sec, about 280 microseconds are available for locating each pellet position (determining where in the 5 x 5 mesh the pellet is). The actual time required to locate a pellet depends heavily on the kind of tracking strategy we use. In any case, a frame rate of 100 per second for a real-time movie-like display is possible by tracking ten pellets in parallel if we consider only the PDP-9 computation speed, assuming an appropriate x-ray generator.

The speed of this local scan process could be raised significantly by constructing simple hardware stepping circuits for the x- and y-coordinates, where a complete cycle of the mesh scanning would be triggered by computer control. The present system for the pilot study is limited by the capacity of the x-ray generator rather than by the computer speed, as discussed in § III-3.

2. Determination of the Pellet Position

For our purpose, it is essential that the exposure time required to determine the position of the pellet with a given accuracy should be sufficiently small so that fast movements of many such pellets can be tracked in a time-shared fashion. The accuracy is lower when the exposure time is shorter for the quantum fluctuation becomes statistically more appreciable. It will also depend on the logical process that is adopted to derive the position of the pellet from the obtained intensity pattern. If the logic is

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1) See for details of the program Fujimura et al. (1969).

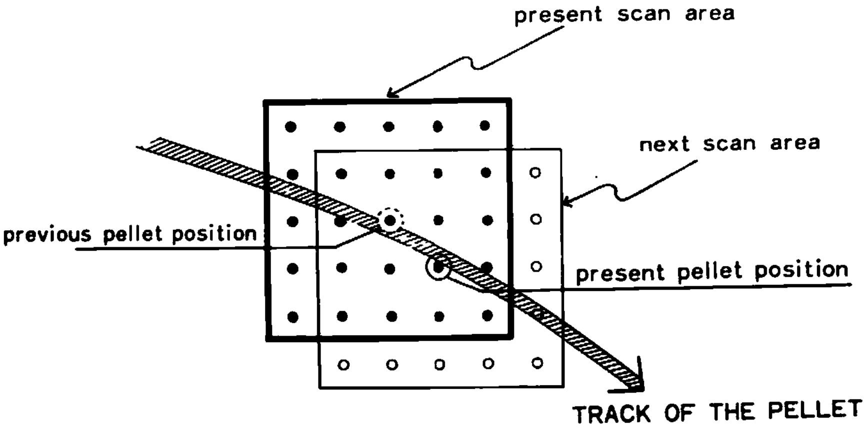


Fig. 7 - A simple strategy for pellet tracking.

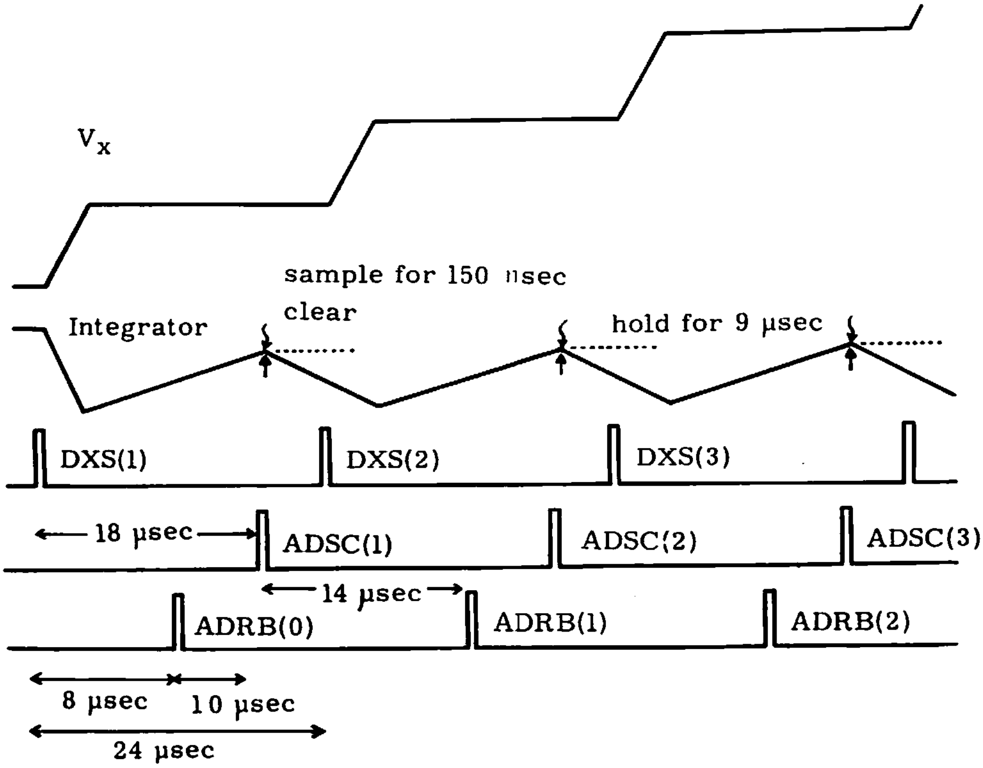
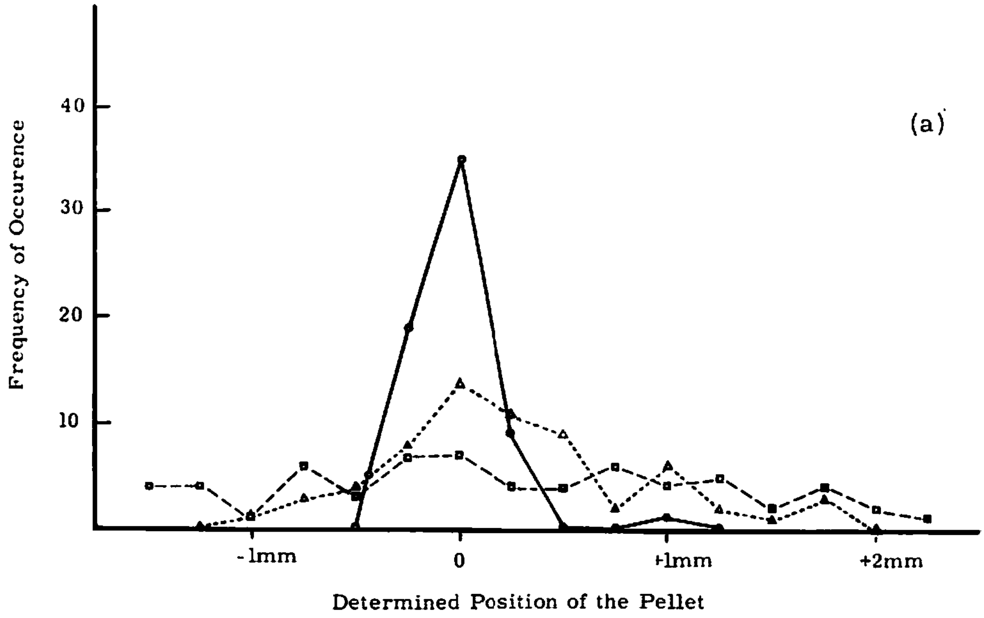


Fig. 8 - Timing diagram for the computer commands, in relation to the time change of the deflection voltage Vx for the electron beam. Computer commands are written by PDP-9 Basic Assembler.



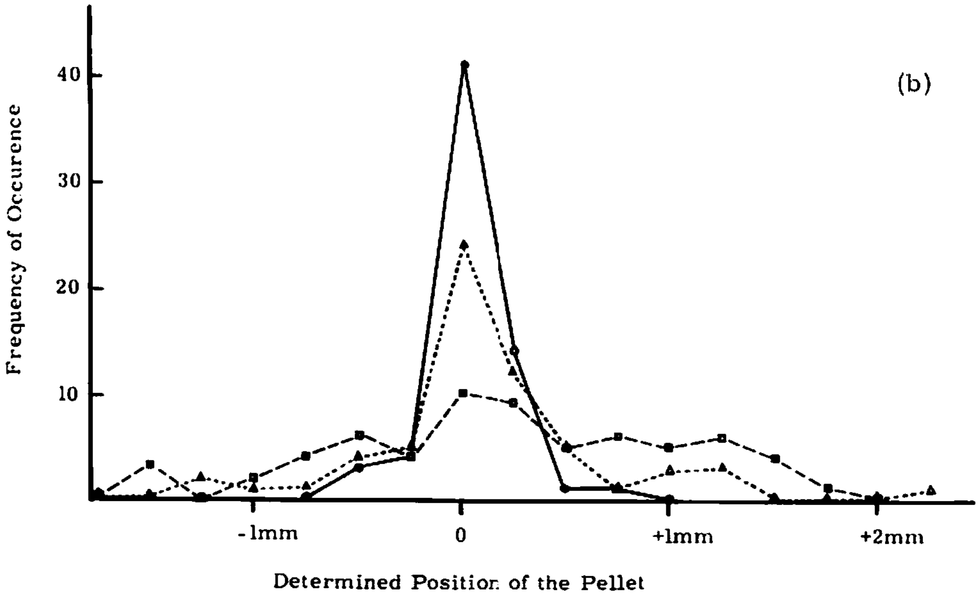


Fig. 9 - Fluctuations observed in the position of a stationary pellet as determined, (a) by simply detecting point of minimum intensity, and (b) by comparing a local intensity pattern (a 9 x 9 mesh of points) with that of an ideal intensity pattern obtained as the shadow of the pellet with a long exposure. Exposure times in microsec: 100 (circle), 50 (triangle), 25 (square).

sophisticated and exploits all redundancy involved in the measurement, or if the process is adaptive so the exposures may be repeated whenever the estimation is judged inconclusive, the accuracy can be higher with use of a given dosage.

As a means of practical evaluation of the accuracy in spatial measurements, fluctuation in the estimated position of an actually fixed pellet has been examined as a function of exposure time. The result is shown in Fig. 9.

A lead pellet, approximately 1 mm^3, was placed at about the center of the swept area and a fixed area around this position was scanned. In the case of Fig. 9(a) the point of minimum intensity was determined and this was defined as the position of the pellet. In the case of Fig. 9 (b) a pattern matching technique was used for determining the pellet position. A 9 x 9 mesh was set as the frame for matching, and the center of this frame was taken as the pellet position. The pattern of intensity values of the 9 x 9-mesh points for a tentative position of the mesh was obtained, and it was compared with a reference intensity pattern that was predetermined as the shadow of the pellet using the same method but with a very long exposure time. The mesh position which gave the minimum overall difference between the observed and reference patterns (in terms of the sum of absolute values of the intensity differences at each mesh point) was defined as the position of the pellet.

In the case of a long enough exposure, fluctuation in the determined position is not caused by the quantum effect of the photons, and the accuracy will be determined by the fluctuation and drift in the electron beam deflecting system. This has been estimated as being less than 0. 25 mm (see the curve for the longer exposure in Fig. 9). It can be seen that the position is well defined for the exposure time of 50 microsec. For this exposure time, the pattern matching method clearly gives a better result than that of local minimum detection.

An approximate estimation of the net exposure required for tracking of the pellet can be made as follows. Let us assume that we must determine the position of the pellet with an accuracy of ±0. 25 mm. Then, by the 5 x 5-points mesh scan with a 0. 5 mm step at an average frame rate of

100/sec, a pellet movement with a maximum speed of 100 mm/sec will be followed successfully by this method of continuous tracking with a fixed fine step. Assuming that 50 microseconds are necessary for each time-space sample, the total exposure time for tracking of the movement of the pellet during a period of 1 minute of a continuous pellet tracking is 7.5 sec. In reality, this amount of exposure will never be given because none of the pellets will be moving constantly at high speed. For a very fast movement of some particular speech organs such as lips and the tongue tip, on the other hand, the maximum speed exceeds the above value by a large factor.1) For these cases, we will need to speed up the process by the hardware stepping signal generators (see <u>supra</u>) for local scans, and also by a more sophisticated tracking strategy that considers the velocity of the object in predicting its next position. However, at present the most significant contribution to speed up the pellet tracking is by an increase in the x-ray intensity at the detector, so that we can shorten the exposure time. For this we need a higher acceleration voltage for the x-ray generator (cf. § V).

3. Pellet Tracking

The most remarkable advantage of adopting an on-line computer in the system is that we can form a dynamic feedback loop for the control of the radiographic process. Information obtained from the current exposure can thus be most effectively used in determining when and where the next exposure should be given for optimal efficiency.

A pellet tracking program based on the principle described in the preceding section has been tested in some simple model cases. For example, a lead pellet of 1 mm in diameter pasted on a small circular piece of plastic film (3 mm in diameter) was dropped from air into water and its movement was tracked in the water tank (2 cm thick in the horizontal dimension through which the x-ray beam travels). Initially, a narrow field just below the surface of water is constantly scanned horizontally until the pellet is found. Then the program is switched to a track mode. A field of 5 x 5 mesh points are examined by the local scan program and the point of

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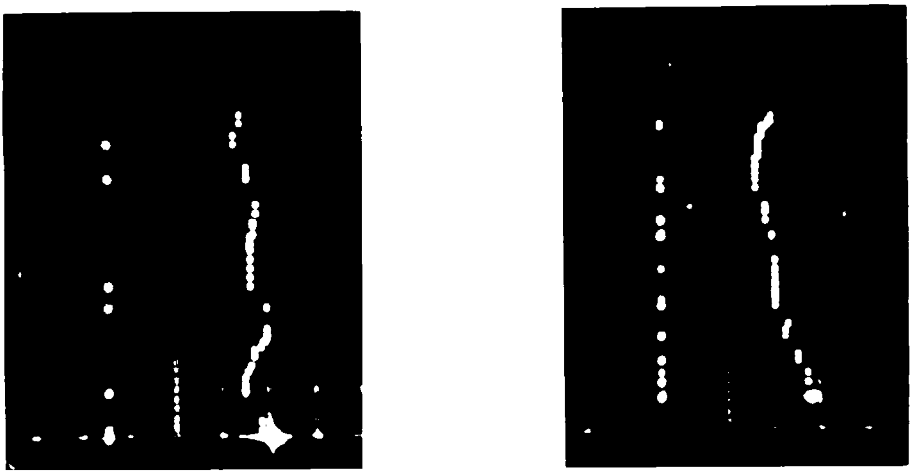
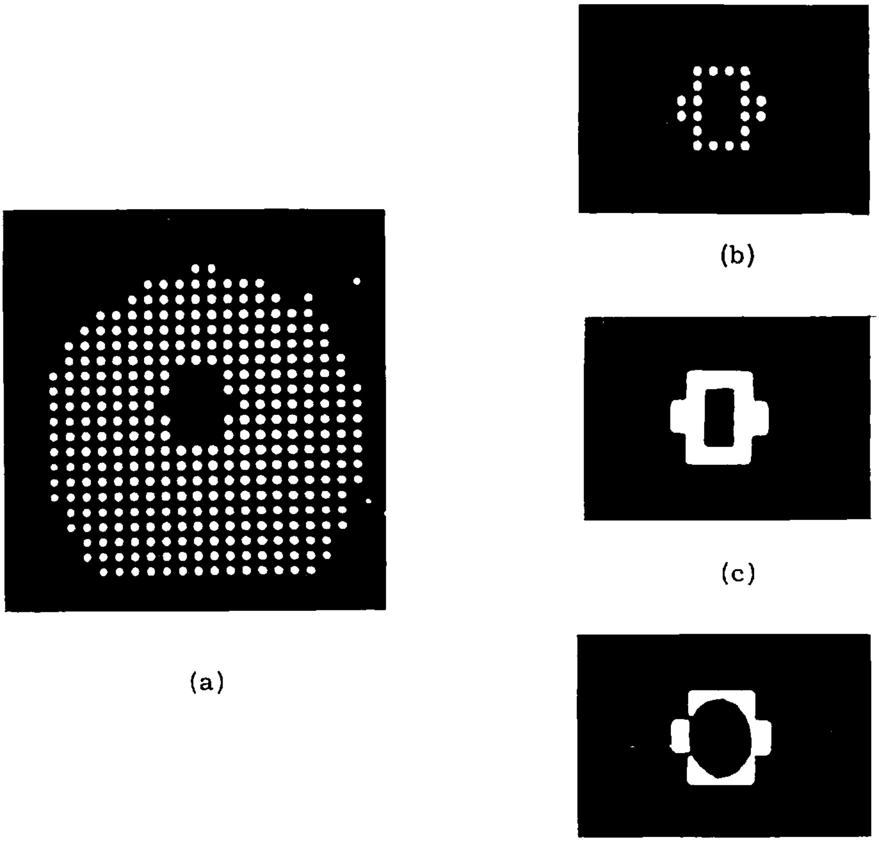
1) Fujimura (1961b), Perkell (1969).



(a) 100 frames/sec

(b) 200 frames/sec

Fig. 10 - Tracks of a falling pellet. A lead pellet with a small plastic collar was dropped into water and its movement was tracked. Exposure time for each scanning point was 400 and 200 microseconds for (a) and (b), respectively.



(b)

(c)

(a)

(d)

Fig. 11 - Local scan around the boundary of a copper coin.

(a) Image obtained by the initial coarse scan. The step of scan is 8mm.

(b) Boundary of the shadow determined automatically from the image shown in (a).

(c) The field for further scanning for detection of details. The field is limited to the vicinity of the coarse boundary points shown in (b).

(d) Image obtained by the second scan with a finer step of 0. 5 mm.

minimum intensity is determined. When the value of the minimum intensity is smaller than a certain threshold value, that point is taken as the present pellet position. Otherwise, it is judged that the pellet is located outside the mesh field and the mesh scan is repeated for an expanded field by moving the center of the mesh around the previous pellet position in a spiral form.

When the pellet is found, the program comes back to the track mode. Finally, the track of the pellet is displayed on the oscilloscope. Fig. 10 illustrates examples of such resultant displays. Several breaks observed in the track show that sometimes the pellet either went out of the mesh scanning field or was obscured by quantum or other noise and was recaptured successfully a few time units later. The spots on the extreme right of the field indicate the moments where the computer lost the pellet, one spot corresponding to one determination of the pellet position.

The position of the pellet was determined approximately every 5 msec and 10 msec, respectively, for the two cases in Fig. 8. The step of scan was set at 0.5 mm. The exposure time for each space-time sample was 200 and 400 microsec respectively, in the two cases. The logical operations were carried out during the exposure as much as possible and therefore essentially no extra time had to be spent for them. If we adopted more complex strategies for determining the pellet position, the exposure time could be shorter. There will be an optimal balance between the time required for the program execution and that for x-ray exposure.

4. Detection of Known Objects

There are many cases when we desire to track the movements of some anatomical structures having a fixed shape, e.g. the mandible, without using pellets. For some portion of the object, detailed examination may not be necessary. In such cases, we can decrease the sampling rate in certain portions in the field, reducing total dose without any loss of information. In particular, when our aim is to define the boundary of a structure such as the mandible, we should concentrate the exposure around the boundary of the bone and give no exposure within it. Automatic tracking of the object makes this possible. Furthermore, when the smoothness of the boundary could be assumed, we may scan with a larger step in a direction along the boundary being detected than in a direction perpendicular to it. Even a more substantial reduction of dose can be achieved when it is known that the shape of the boundary does not change or undergoes only limited kinds of geometrical transformation, and we require only determination of the position and perhaps some transformational parameters such as the angles of rotation.

The required exposure may vary from point to point according to the transparency and the contrast of the object, and it would be better to control the exposure time by considering the position or perhaps more preferably the estimated intensity at the detector. These procedures can be carried out by the present system by writing appropriate computer programs. Another important strategy is an adaptive control of the scanning process, in particular the stepping parameters.

Fig. 11 shows an elementary example of boundary scanning by use of a metal sheet (a copper coin). Initial scanning was carried out with a larger step of 8 mm covering the entire field (Fig. 11a), and the boundary was determined automatically from the intensity pattern by selecting those points where a transition from white to black(defined by a certain two-dimensional criterion) takes place (Fig. 11b). The surrounding belt-like area of a certain width around these "transition spots" were scanned with a finer step of 0.5 mm (Fig. 11c). The resultant shadow of the coin in this search area is shown in Fig. 11d.$^{1)}$ In the case of more complex images, completely automatic processing may be difficult, and intervention by the human observer, by use of a light-pen, etc., would be effective.

V. Concluding Remarks

In view of the results we have obtained so far by using our preliminary experimental setup, it is clear that the method of on-line control of a

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1) There is some distortion of the image due to the non-perpendicular incident angle of the electron beam onto the x-ray generating target. No corrections of this distortion is given in the data presented here, although it is technically feasible to do this by calculation or table look-up in the computer.

deflectable x-ray microbeam for observation and automatic tracking of dynamically moving objects works effectively for many purposes. In particular, the tracking of small metal pellets that are placed on the speech organs seems quite feasible, even though we have not as yet tried any observation of human articulatory activity.

There are three major components of the experimental system, the performance characteristics of each of which is crucial to the successful application of this method to actual speech data acquisition. One is the computer for the on-line control. It has been shown that a standard high speed computer, with core memory of 8,000 18-bit words and some peripheral equipment, essentially serves the role required for this system, even though it is clear that for efficient data acquisition we will need some expansion of the system now in use, particularly in respect to external memory devices which we lack now. In fact, we can speed up the control process by the addition of some minor hardware devices, and this will facilitate more complex strategies than those that have been employed in our preliminary experiments.

The second major component is the high sensitivity detector of x-rays. As discussed in § I, the scintillation counter using NaI crystal and a photomultiplier tube, combined with some appropriate circuitry, seems to be quite satisfactory for our purpose.

The third major component of the system is the x-ray beam generator. We used a rather inexpensive microbeam generator which was on the market as a device for local x-ray crystallography, but added some special modifications to the deflection system. However, it has been concluded that this system is insufficient in its power for general use in articulatory observation; particularly, the acceleration voltage of 50 keV is too low for penetrating the thick bony structure of the human articulatory organs. For the purpose of tracking several pellets placed as markers on crucial points of the tongue, a similar but more powerful x-ray microbeam generator with a 150 kV acceleration and a 1 mA beam current at the x-ray generating target is desirable.[1] According to the preliminary data we have obtained

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[1] In our present system, the beam current at the target (to next page)

by use of the present system, we assume that this new x-ray apparatus now under design, with a beam diameter at the target surface of 30 microns, will meet all our requirements for the proposed real time articulatory observation using up to about 10 pellets.

The present system as it is, however, can be quite useful for actual articulatory observations in some cases. Tracking of certain structures, e. g., the hyoid bone, in articulation does not require very short wavelengths of x-rays. In these cases, pellets are not necessarily required, and some comparatively complex programming techniques will demonstrate the inchallengeable capability of this kind of computer controlled system.

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(continued from footnote, p. 29)

is 250 microamp. When we increase the acceleration voltage, the current that can be taken out of a telefocus electron gun is also increased due to reduction of the space charge effect. The efficiency of the x-ray photon emission at the target, even in terms of the number of photons per electron, is also significantly higher when the electron energy is higher. In addition, of course, the absorption by the anatomical structures is significantly less, giving much less dose even for the same x-ray intensity, and very much higher counts in detection. The design of such powerful generators is apparently not technically difficult (see also discussions in § I).

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