PROBLEMS IN THE USE OF THE PHOTO-ELECTRIC GLOTTOGRAPH[1]

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Abstract: This preliminary study originates in some of the recurrent problems encountered at this institute in the course of several years of working with the photo-electric glottograph. The relationship between the amplitude of the glottogram and the glottis aperture is studied by means of synchronous glottographic and fiberoptic recordings of the glottis during the articulation of long, unvoiced consonants in syllables with emphatic stress. According to this study, one does not very often find a linear relation between the glottis aperture and the amplitude of the glottogram. It is pointed out that the non-linearity may be caused by one or several factors affecting the amplitude of the glottogram. This non-linearity is crucial for the interpretation of the amplitude of the glottographic curve.

1. Introduction

Photo-electric glottography,[2] like most other methods of registration, entails some important sources of uncertainty, which must be taken into account in the application of the method.

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1) Part of the thesis for the cand.mag. degree, completed in May, 1975. I am most grateful to Jørgen Rischel, Svend E. Lystlund, Mogens Møller, and Hajime Hirose for many valuable suggestions and an inspiring guidance.

2) The reader is referred to Sonesson 1960, Malécot and Peebles 1965, Ohala 1966, and Frøkjær-Jensen 1967 for a general introduction to the method of photo-electric glottography.

The present paper summarizes a preliminary study of problems in the interpretation of glottograms. The experiments to be reported originate in some of the recurrent problems encountered at the institute of phonetics in the course of several years of working with the photo-electric glottograph.

2. A view of the relationship between amplitude of the glottogram and glottis aperture

One of the problems associated with the photo-electric glottograph is the relationship between glottis aperture and the amplitude of the glottogram: Is there a linear relation between these two variables, i.e., does a change in the amplitude of the glottogram correspond to a proportional change in glottis aperture?

I know of only one methodological study - in a narrower sense - of that problem. R.F. Coleman and R.W. Wendahl (1968) made synchronous high-speed film and glottographic recordings of the vocal fold vibrations in order to compare the variation of the glottis area and the variation of the glottogram during a vocal fold vibration. The authors (1968, p. 1734) conclude: "... that while photocell monitors, under controlled conditions, may provide an indication of laryngeal periodicity, relating waveforms thus derived to glottal area is not only hazardous but invalid in many cases." The authors may be right, but the glottograms shown in the article look so strange that it is tempting to conclude that there was something wrong with the glottographic set-up.

In contrast to the results just cited R.J. Harden (1975) concludes - likewise on the basis of synchronous high-speed film and glottographic recordings of the vocal fold vibration - that "Although the correspondence between the curves is not exact in modal and vocal fry register phonations the photoelectric cell does appear to be capable of generating reasonably approximate information." (p. 734).

In the following subsections some of our general experiences about sources of error in the use of the photo-electric glottograph are presented, serving as an introduction to the experiments to be reported later in this paper.

2.1 Factors influencing the amplitude of the glottogram[1]

First of all, it is important to know whether the glottographic set-up itself has a non-linear performance in some part of its registration range, since the input-output characteristics of the set-up are decisive for the relationship between glottis aperture and the amplitude of the glottogram. But even if the voltages occurring during the glottographic recording are within a linear range, many other factors may influence the amplitude of the glottogram.

These other factors are partly associated with the light source and its position in relation to the larynx, and partly with the phototransducer and its position.[2]

2.1.1 The light source

The position of the light source in relation to the glottis, as well as the diameter and direction of the light beam, influence the glottogram to a considerable degree. If, for instance, it is the hindmost part of the glottis that is illuminated, the light will be strongly modulated by small movements of the carti-

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1) The factors influencing the zero line level and the temporal variation of the glottogram will not be treated in this paper. For a brief survey of sources of error, see Frøkjær-Jensen, Ludvigsen, and Rischel 1971.

2) This study is based on the set-up employed at our institute, in which the light source is placed in a subglottal position and the transducer in a supraglottal position. If the two are placed in the reverse positions, the problems should, in principle, be the same.

laginous glottis. If it is the front part of the glottis that is illuminated, the light will be strongly modulated by small movements of the vocal folds. Therefore, with the first mentioned position of the light source, the glottogram will show a great difference between the maximum amplitudes of the two functions of the glottis, viz. the vibratory pattern and the gross movements; with the second position, on the other hand, the glottogram will show a smaller difference. This means that it cannot be taken for granted that there is a linear relationship between glottis aperture and the amplitude of the glottogram with <u>different</u> functions of the glottis, and certainly not if a light source is used that illuminates only a part of the glottis.

If the larynx, and thus the glottis, is moved relatively to the light source the relationship between glottal configuration and light entering the pharynx via the glottis slit may be altered. This will affect the amplitude and thus the relationship between glottis aperture and the amplitude of the glottogram. Care must therefore be taken to ensure that, during a recording in which amplitudes are to be compared, the subject does not move. If such movements do occur a comparison between successive data is rather doubtful, even within the <u>same</u> function of the glottis. It is very difficult, as will be demonstrated later, for the subject to remain in exactly the same position in relation to the light source for any long period of time. It is, of course, not possible to prevent the larynx from altering its position in normal speech.

Light reflected from the structures above the glottis may also influence the amplitude of the glottogram. This reflected light may vary both as a function of variations in the position of the larynx and as a function of changes in the structures above the glottis.

2.1.2 The phototransducer

The factors mentioned above, which may influence the amplitude of the glottogram, should be seen in relation to variations in amplitude which are due to the phototransducer and its position in the pharynx.

It may be of great importance that the phototransducer does not alter its position during a recording, especially if the transducer is rather directional, i.e. picks up light only within a rather small angle. Furthermore, the transducer is hardly equally sensitive in all directions within the angle in which it picks up light, which aggravates the problem. The position of the phototransducer may be altered both by movements of the subject's head and neck and by the transducer tube being pushed about by the velum, the back of the tongue, or the pharyngeal wall.

The first problem can be solved by fixing the subject's head. The second problem can be solved to some extent by fixing the polyethylene tube containing the transducer in the oesophagus (Malécot and Peebles 1965, Ohala 1966). Furthermore, sounds with a pharyngeal articulation should probably be avoided. The optimal position of the transducer and whether it is to be fixed or not depends on the light source (its position and the diameter of the light beam), and on the directional selectivity of the transducer.

Structures above the glottis (as, for instance, the root of the tongue and the epiglottis) may with certain articulations and types of phonation enter the light field in the pharynx and reduce the quantity of light picked up by the transducer. This may greatly affect the amplitude of the glottogram.

A potential source of uncertainty is the fact that the phototransducer is sensitive to temperature variations. Malécot and Peebles have eliminated this source of uncertainty "by providing the subject with an air supply heated to body temperature from an electric heater and blower connected to a Bennett face mask." (Malécot and Peebles 1965). But, unfortunately, the authors do not explain how important temperature sensitivity is to the glottographic output.

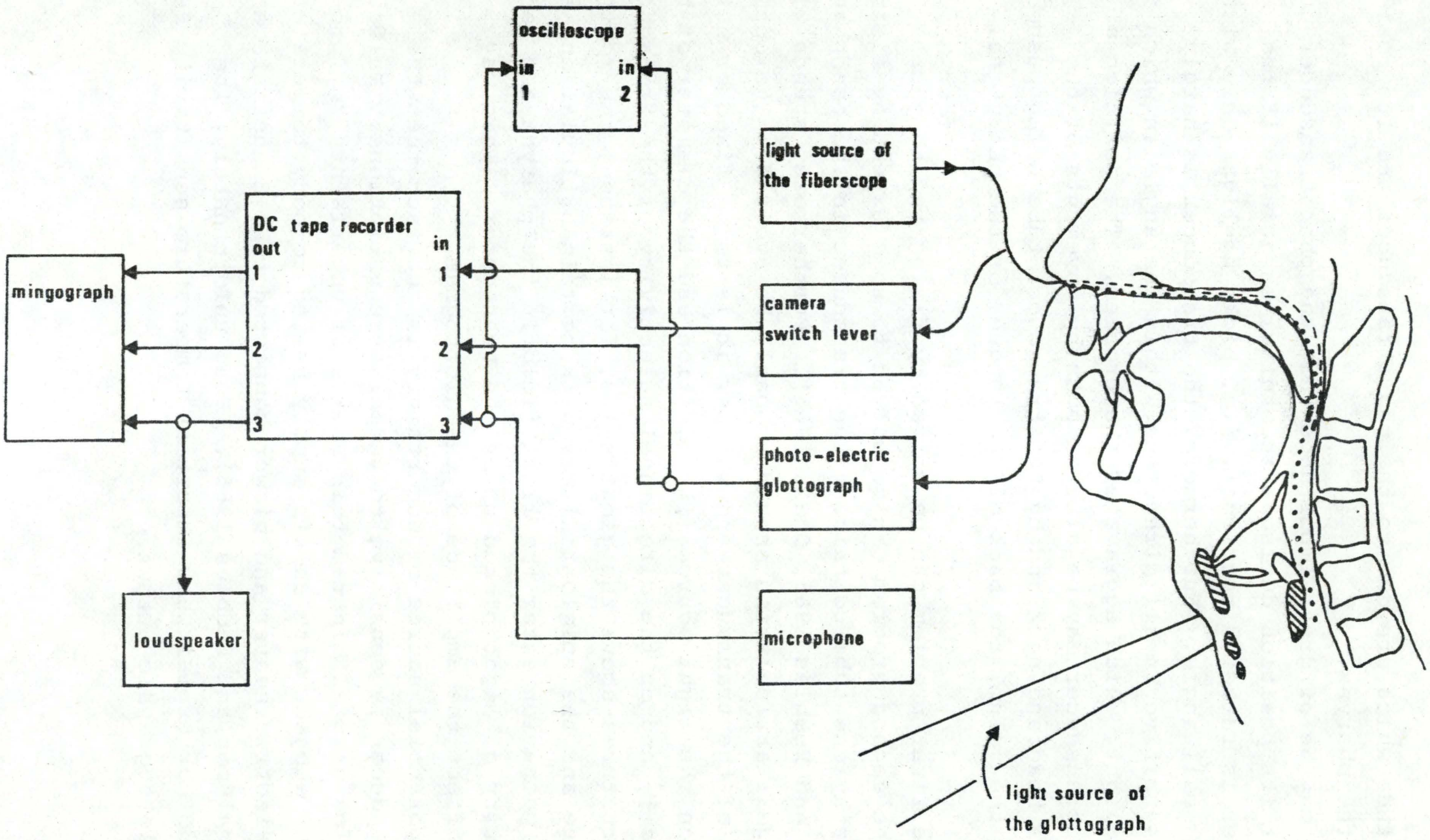

Figure 1

The instrumental set-up.

3. A study of the relationship between the amplitude of the glottogram and glottis aperture

The study I am going to survey here covers only a small fraction of the complex of problems mentioned in the above section.

3.1 The purpose of the study

I chose to approach the problem of the relationship between the amplitude of the glottogram and glottis aperture by studying fairly large glottis apertures, i.e. apertures of such dimensions as may be found in the case of long unvoiced consonants in syllables with emphatic stress. The reason for this choice being that under these conditions it was possible, with our outfit, to take photographs of the glottis which would serve to determine the glottis aperture - viz. by means of a fiberscope connected with a still camera. As there was no possibility of photographing successive variations of the glottis aperture, the study was made on the basis of three fixed glottal positions and synchronous glottographic recordings. At best, this study will show whether it is possible, on the basis of the amplitude of the glottogram, to obtain information about the relative size of rather large glottis apertures.[1]

3.2 The instrumental set-up

The central components of the instrumental set-up, which is shown in fig. 1, are the photo-electric glottograph and the fiberscope with a still camera connected to it.

The glottograph of this study is a modified version of the photo-electric glottograph described by Frøkjær-Jensen (1967, 1968). The light from a light source fed with DC current is led

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1) One cannot, by this approach, get any absolute information on the glottis aperture, since the photo-electric glottograph cannot be calibrated with living larynges (van den Berg 1968).

to the larynx through a 40 cm long, conic plastic rod. The diameter of the rod is 1 cm at the larynx end.[1] The phototransducer (Texas Instruments LS 400) is contained in a protecting polyethylene tube with an outside diameter of 3 mm. The transducer is inserted through the nose into the pharynx. In order to secure the transducer in a relatively stable position in the pharynx it is fixed at a distance from the lower end of the transparent protecting tube which is swallowed into the oesophagus. The tube containing the transducer is, furthermore, fixed to the subject's cheek. The glottographic signal is led partly to the oscilloscope (Tektronix 5103 N), partly to the DC tape recorder (Lyrec TR 86). The fiberscope (Olympus VF, type 4A) is described by Sawashima and Ushima (1971). The diameter of the optic cable is 4.6 mm, and the angle of the lense is 42^{o}. It should be mentioned here that it is difficult to fix the fiberscope tube in a quite stable position during the articulation. The M-X synchronizing switch lever of the still camera attached to the fiberscope was used to synchronize the glottogram and the picture of the glottis. Furthermore, a microphone signal (Neuman KM 56) was recorded. After the recordings mingograms were made of the three signals: glottogram, synchronization pulse, and microphone signal (paper speed: 100 mm/sec).

3.3 Measurements on the synchronization and input-output characteristics of the set-up[2]

3.3.1 Synchronization

The pulse from the M-X synchronizing switch lever (set at M) was used to synchronize the photographs and the glottograms.

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1) This diameter of 1 cm is an arbitrary choice, since we have not yet made a careful study determining the preferable diameter of the light conducting rod.

2) These recordings were made without human subjects.

As the switch lever and the shutter of the camera are not synchronous, the time offset between the movements of these two parts was measured. In a special set-up the photo-electric glottograph was used to determine the open period of the shutter. The transducer - placed in a cardboard tube - and the light conducting rod were placed on either side of the objective and the shutter. With this set-up the duration of the period during which light was passing the objective could be registered, as well as its temporal relation to the pulse from the switch lever. The switch lever pulse and the "shutter pulse" were led to a storage oscilloscope, the screen of which was photographed. The time offset between the two pulses was determined on the basis of these pictures. As it could not be taken for granted that the offset was the same, irrespective of exposure time, it was measured for different exposure times. The difference in time between the start of the pulses was about 13.0 ms, irrespective of exposure time, the shutter lagging behind the switch lever pulse. In some cases it was difficult to determine the moment of cessation of the switch lever pulse, but it ended about 4.0 ms later than the shutter, regardless of exposure time.

3.3.2 The input-output characteristics of the glottographic set-up

It is important to know whether a non-linear relationship between the amplitude of the glottogram and glottis aperture might be due to the input-output characteristics of the glottographic set-up.

The sensitivity of the transducer to variations in illumination[1] was checked. In a darkroom a set-up involving the photoelectric glottograph, an enlarger, and a voltmeter was assembled. The transducer was fixed in a stand and placed below the diaphragm and the bulb of the enlarger. Care was taken to position the

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1) Or, properly speaking, "luminance".

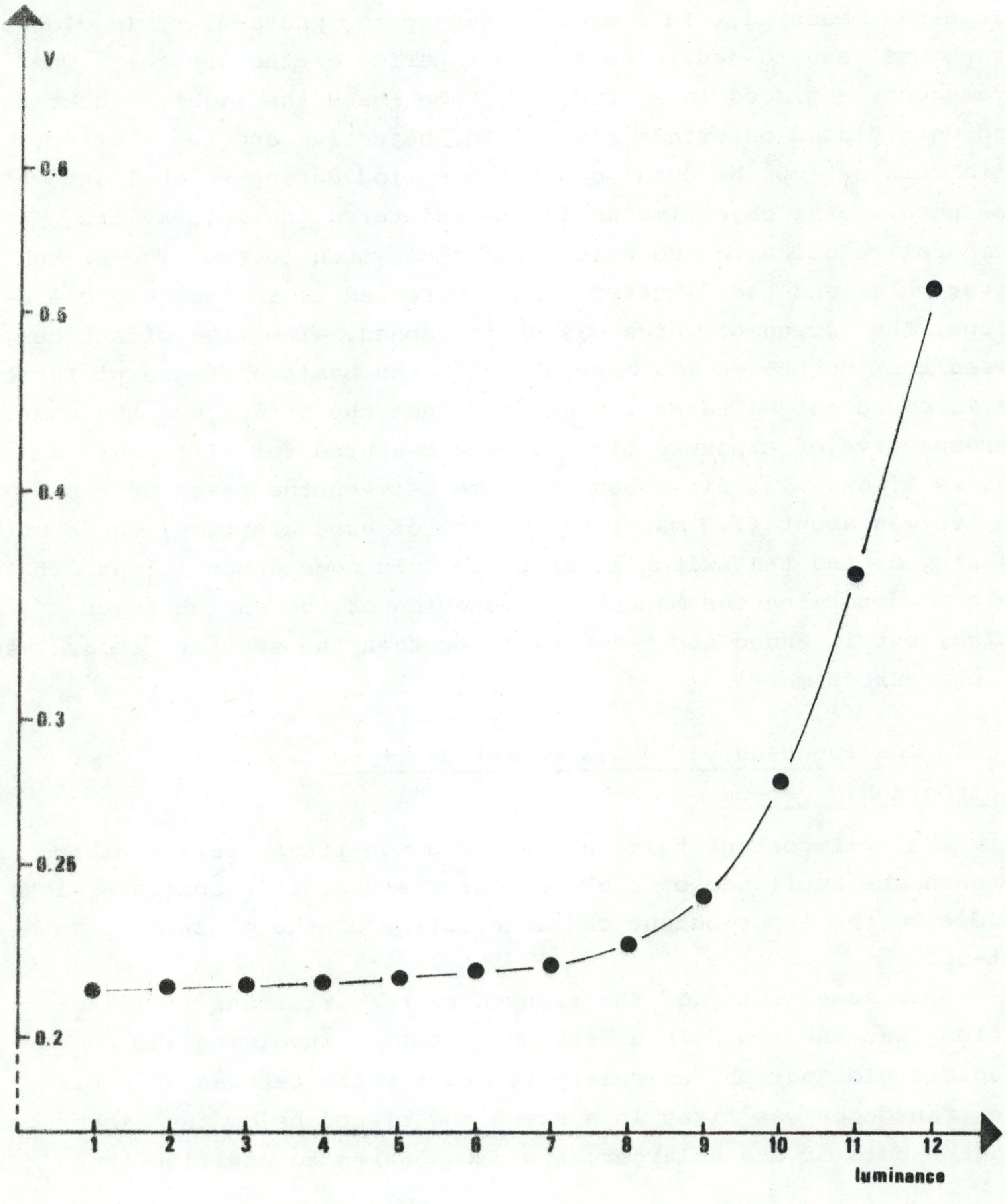

Figure 2

The characteristic curve of the glottographic set-up - with setting 6 - for variations in luminance. The division of the abscissa corresponds to steps in the aperture of the diaphragm, every step corresponding to a doubling of luminance.

transducer so that the whole angle within which the transducer was sensitive was inside the cone of light, irrespective of the aperture of the diaphragm. The aperture of the diaphragm was varied, i.e. the illumination was varied in well defined steps, and the corresponding voltage for each step of the diaphragm was read off. In order to obtain enough steps the measurements were performed with two different distances between transducer and diaphragm, the greater distance being chosen so that the voltage for the greatest aperture of the diaphragm with this distance was equal to the voltage for the smallest aperture of the diaphragm with the smaller distance. These measurements were performed for settings 1 to 8 of the glottographic amplifier. The light picked up by the transducer in the pharynx is diffuse light, and the light used for these measurements was diffuse light, as well. In an earlier experiment the transducer was checked for sensitivity to white and red light because the glottographic light in the pharynx belongs to the red part of the spectrum. There being no noticeable difference between the characteristic curves for white and red light, the subsequent measurements were made only for white light.

In fig. 2 the voltages are shown as a function of illumination with setting 6 which is the setting used in the recordings (the division of the abscissa corresponds to steps in the aperture of the diaphragm; every step corresponding to a doubling of the luminance).

It seems evident that the glottographic set-up for setting 6 has a non-linear characteristic curve in the lower end of the voltage range, which means that the relationship between glottis aperture and the amplitude of the glottogram cannot be linear in this lower end of the voltage range (unless this non-linearity happens to be neutralized by other factors). - These findings imply that, in fact, the voltage ranges occurring in each of the glottographic recording sessions dealt with in the following sections should have been measured, in order to reveal whether the voltage range for a given recording was within a linear range or not. Unfortunately, I did not realize this at the time when the recordings were made.

Furthermore, the performance of the transducer at different angles of incident light with two different degrees of rotation was measured. The transducer was ground at the free end and the black paint had been removed in order to make it less directional. The position of the transducer was varied within an angle of 180^{o} in relation to an immovable light source, and the output voltages were read off the glottograph. Two series of measurements were made, where in the second series the transducer was rotated 180^{o} around its longitudinal axis relatively to its position in the first series. In fig. 3 output voltage is shown as a function of the angle of incident light. It is seen that the transducer picks up light within an angle of at least 150^{o}, and that its sensitivity depends on the position of the transducer relatively to the light source. Furthermore, it is evident that the output voltage varies when the transducer is rotated around its own longitudinal axis, but such a rotation is not possible when the lower end of the protecting tube is swallowed into the oesophagus. On the other hand, the non-uniform sensitivity of the transducer as dependent upon the angle of incidence of light may influence the amplitude of the glottogram. Therefore, whenever light source and transducer change their position relatively to each other, it cannot be taken for granted that there is a linear relationship between the amplitude of the glottogram and glottis aperture, even if the transducer picks up the same quantity of light. Furthermore, in the case of two glottis apertures of different sizes, a linear relationship is not to be expected, even if the glottographic light is of equal density across the illuminated area of the glottis.

I have not checked whether the sensitivity of the transducer to variations in heat caused by the inhalation and exhalation of air, seriously affects the performance of the glottographic set-up used in these experiments.

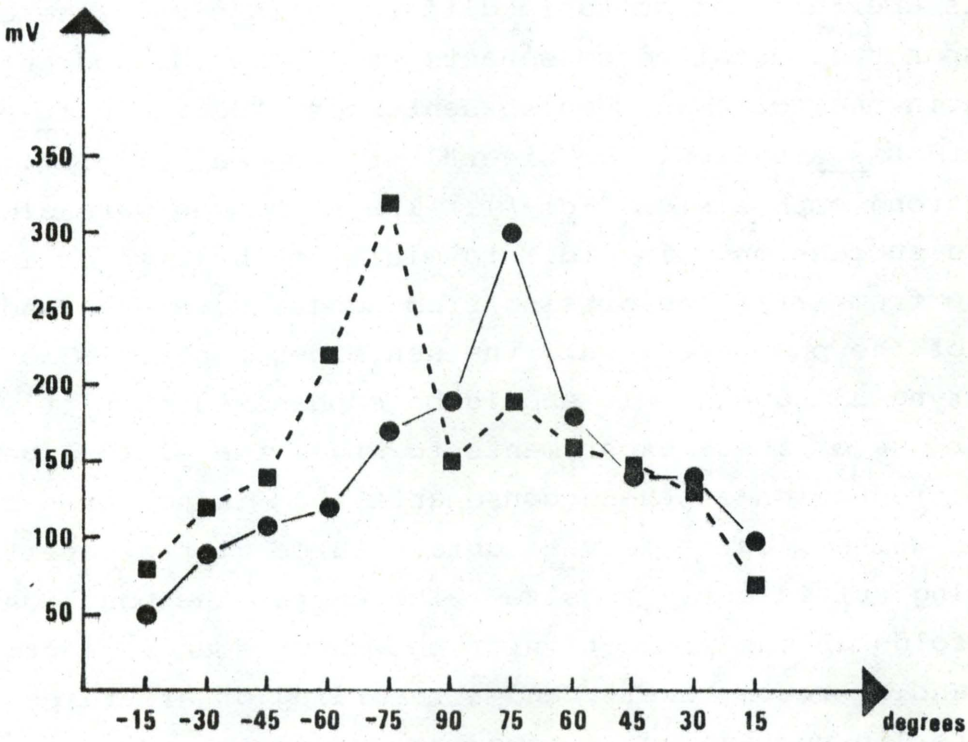

Figure 3

The performance of the phototransducer at different angles of incident light for two different degrees of rotation.

3.4 The material

As mentioned above (section 3.1), this study of the relation between the amplitude of the glottogram and the aperture of the glottis is based on recordings of glottis apertures of such dimensions as may be found in long unvoiced consonants in syllables with emphatic stress. In order to obtain information about this relationship it is necessary to record at least three glottis apertures of suitable difference in size. The choice fell upon the sustained consonants [b̥::], [s::], and [ç::] embedded in the following Danish sentences: "De viste Ib billetten. De viste Lis sibyllen. De higer" (pronounced [d̥i ˈç::i:ʌ] with very strong emphasis on "-hi-"). The sentences were always said in this succession. In order to minimize the risk of interference from artifacts arising from tongue movements and movements of the pharyngeal wall the sentences contained no velar or pharyngeal sounds. It should be emphasized that it was not the purpose of these experiments to study the glottal behaviour in the production of these consonants ([ç] is not even found in normal Danish), but solely to obtain three glottal apertures differing sufficiently in size. Therefore, the position of the vocal folds in the production of the three sounds is called a, b, and c, respectively, and a recording of all three glottis apertures in succession is named an abc-series.

3.5 Subjects

Two phoneticians, highly experienced in experimental phonetics, acted as subjects: JR and BFJ. For subject JR 54 abc-series were recorded over three sessions, for subject BFJ 53 abc-series were recorded over two sessions.

3.6 Light and exposure time

Owing to the synchronous recording of the glottograms and the photographs the light source of the fiberscope set-up had to be switched off. The pictures were taken by the light from the glottograph passing the glottis slit from below. Consequently, these photographs do not show the actual structures of the larynx, but only the contours of some part of the glottis. Therefore, in order to control the position of the fiberscope pictures of the glottis were taken before and after each abc-series by the fiberscope light, i.e. with illumination from above. For these "control pictures" the subject articulated a sustained [s::]. The two [s::]'es are indicated by S and S^+, respectively. If the control pictures of an abc-series were not identical - indicating that the fiberscope had altered its position - it was the intention to reject the series since the pictures of the glottis aperture within one abc-series can only be compared if they are taken under identical conditions.[1] When taking the control pictures the glottographic light was, in most cases, also switched on in order to observe how the light from this source was passing through the glottis slit.

The exposure time of the abc-series was 1/60 sec. The same exposure time could be used for the control pictures with an appropriate adjustment of the fiberscope light.

The film was a Kodak TX 135-36.

3.7 Positioning of fiberscope, transducer, and light source

In the recordings described here the tip of the fiberscope was positioned rather close to the glottis in such a way that the glottis slit took up as much as possible of the field of vision. This was done in order to maximize the accuracy of measurement. But, consequently, it happened rather often that

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1) It should be mentioned that even if the control pictures are identical this is no guarantee that the fiberscope has not moved back and forth, or up and down, during the abc-series, but this can be checked only by means of a synchronous X-ray recording.

a minor part of the glottis escaped the visual field owing to movements of the speech organs. Thus, the position of the fiberscope had to be readjusted fairly often.

In two recordings (JR 29/5 and JR 22/7) the light conducting rod of the glottograph was placed in such a way that the light entered the neck slightly below the cricoid cartilage. In this position the light passes primarily through the central part of the glottis slit. As for the position of the transducer of the glottograph the maximum voltage range was obtained when the distance between the transducer and the outer nostril was 16 cm.

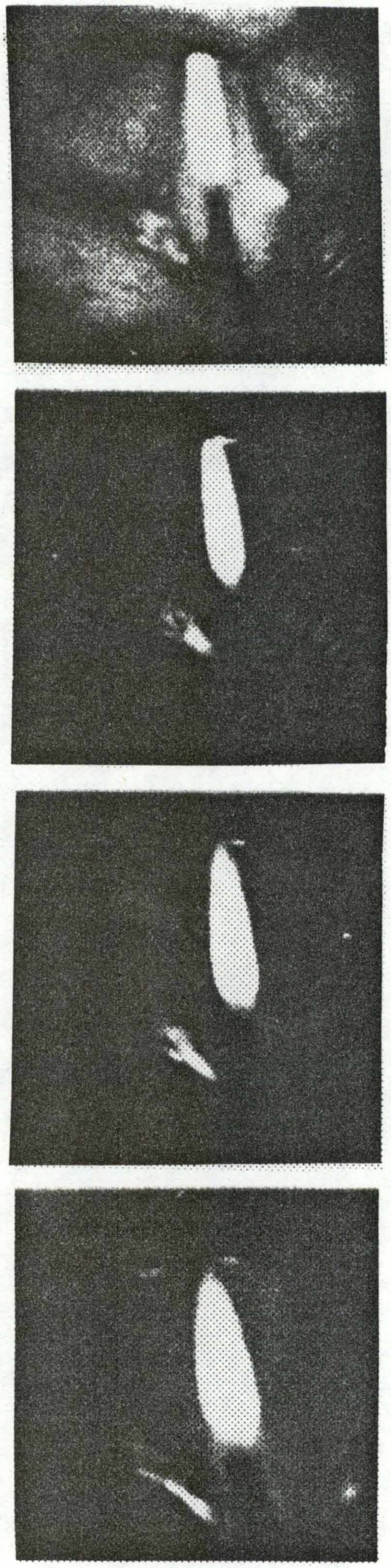
In all other recordings the rod was placed in such a way that the light entered the neck between the thyroid cartilage and the cricoid cartilage. In this position the light passed primarily through the anterior part of the glottis and the maximum voltage range was obtained when the distance between the transducer and the outer nostril was 14 cm.

3.8 Measurements of the glottis aperture and the amplitude of the glottogram

The negatives were converted into contour drawings by tracing a projection with a magnification of the order of 30:1. A microfiche viewer was used for this purpose.

As the fiberscope cannot be calibrated (at least no such calibration has been described), the pictures yield information only about the relative size of the glottis aperture. The distance between the vocal processes is generally referred to as a measure of the glottis aperture. This distance is directly proportional to the glottis area, provided that the glottis is a triangle in which the baseline and the line drawn between the processes are parallel.

The distance between the vocal processes could not be used in this study, partly because the light source illuminates only part of the entire glottis slit (in its longitudinal direction)



Control picture [s::]

a [ɮ̥::]

b [s::]

c [ç::]

<u>Figure 4</u>

Photographs of one abc-series including one of the two control pictures. The glottographic light passes the anterior part of the glottis.

if the cartilaginous glottis is open, and partly because the abc-pictures reveal only the contour of the glottis. Therefore, another line, parallel to the baseline of the glottis triangle, was used. As this relative measure of glottis aperture is to be used for a comparison, the line has to be drawn at the same distance from the anterior commissure of the glottis in all photographs. In order for the contour of the anterior commissure to be observable the light must pass the anterior part of the glottis; if it does not, the commissure must be determined by extrapolation. In some cases the extrapolation method was applied. In certain other cases I employed a constant distance from the upper limit of the field of vision. This method, which may be even more inaccurate than the extrapolation method, implies that the glottis has a fixed position in relation to the upper limit of the field of vision throughout the recording of an entire abc-series.

It should be borne in mind that the basic prerequisite for a comparison of glottis apertures on the basis of photographs taken through the fiberscope is that the distance between the glottis and the lens of the fiberscope is kept constant during the recording. As mentioned above (footnote to section 3.6), this cannot be taken for granted, even in the case of identical control pictures.

Fig. 4 shows photographs of the glottis contour for one abc-series and for one of the control pictures. The glottographic light is positioned in such a way that the light passes through the anterior part of the glottis.

From the control pictures it is obvious that some transillumination of the vocal folds occurs. How much cannot be determined on the basis of the photographs because of the saturation threshold of the film (cf. footnote to section 3.9). However, the error caused by the transillumination is probably the same for the three measurements of the glottis aperture within one abc-series.[1] Another problem is whether the addition to the amplitude of the glottogram, caused by the transillumination of the vocal folds, is constant - irrespective of the glottis aperture - which is probably not the case. So, here we may have another source of uncertainty to the glottographic method.

The amplitude of the glottogram was measured 10 ms after the start of the switch lever pulse. As mentioned before, the exact time lag between the start of this pulse and the shutter was 13 ms. But truly precise determination of the start of exposure seems to be rather meaningless, considering the inaccuracy introduced by other parts of the adopted procedure. When the amplitude of the glottogram varied no more than 1 mm during the exposure, the average was measured. The glottogram was rejected if the variation exceeded 1 mm. The zero-line level was arbitrarily determined, but it is, of course, fixed within each abc-series.

3.9 Results

Out of 107 abc-series 64 series were rejected for one or several of the following reasons:

1) The picture had been taken too soon or too late in relation to the consonant
2) The glottographic signal was overloaded
3) The fiberscope was not in a stable position
4) Both the amplitude and the relative glottis area differed very little, i.e. 1 mm or less, from a to b or from b to c (i.e. the series is not sufficiently informative)
5) The variation of the glottographic curve exceeded 1 mm during the exposure.

It is obvious that one rejected recording within an abc-series entails a rejection of the whole series.

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1) Since the difference in size between the observed light spot and the illuminated part of the glottis slit seems to be considerable, it is obviously desirable to develop a different procedure in which the pictures are taken with light from above, the glottographic light being intermittently switched off, triggered by the camera.

Actually, the requirements were satisfied only in a few cases, inasmuch as the position of the fiberscope (or of the larynx) changed in most cases during the recording of an abc-series. Still, if there was only a slight disturbance, the series was included among the usable material. There is reason to suppose that the inaccuracy of measurement caused by minor displacements of the fiberscope does not exceed the inaccuracy of other parts of the procedure.

It must be emphasized that measurements of amplitude and aperture can only be compared within one series, as it is only during this short sequence that attempts have been made to keep the recording conditions constant. The fiberscope may have been readjusted between series. Furthermore, the films sometimes reveal unintentional disturbances of the glottographic light during a recording session. It cannot be taken for granted that the light (from the kind of light source employed in this study) will remain in a stable position during a recording.

In the table and the figures identical control pictures are indicated by $S=S^+$, almost identical control pictures are indicated by $S(=)S^+$. The measures of aperture and amplitude (both in mm) are called A and GL, respectively.

The results from the serviceable series are seen in table 1. In figs. 5-9 GL is shown as a function of A. It is seen that the three points in most cases deviate more or less from a straight line, and in one third of the cases there is even a negative correlation between the glottis aperture and the amplitude of the glottogram.

Minor deviations from a straight line may be explained by the inherent characteristics of the glottographic set-up (see section 3.3.2 above), i.e. by the characteristic curves showing the output voltage as a function of varying illumination (luminance) and as a function of variations in the angle of incidence of light. As previously mentioned, the output voltage range of the glottographic recordings were not measured for each session, since I did not realize until later that that was necessary in order to know whether the voltage range for a given recording was within a linear range or not. If the voltage range for a given recording lies in the low, non-linear range the curve would bend off "to the right", provided that the glottographic output were influenced by that factor only. But since several factors may simultaneously influence the amplitude of the glottogram it is impossible to propose one single explanation for each deviation from the straight line. There is another essential source of error, viz. that the transducer and/or the glottographic light may have moved during the recording of a series. To judge by the films (see footnote to section 3.6), the light does not seem to have moved during the recording of any of the series which show only minor deviations from a straight line. In order to find out whether the transducer may alter its position during the production of [ɮ::], [s::], and [ç::] X-ray pictures of those sounds were taken for subject BFJ, the transducer (and the fiberscope) being positioned as during the actual recordings. The X-ray pictures show that the transducer was pushed slightly downwards during the articulation of [s::]. As only one picture of each sound was taken it cannot be proven whether this varying location of the transducer is random or systematic. But according to my experience, minor displacements of the transducer will not influence the glottographic output very much. Also, the transillumination of the vocal folds could explain part of the deviation from a linear correlation. Of course, the applied procedure for measuring the glottis aperture causes a certain inaccuracy of the measurements.

For a large part of the series the results deviate very much from a linear correlation, and, as mentioned above, one third of all series show a negative correlation (all but one instances of negative correlations are found with subject BFJ). This cannot just be due to the characteristics of the glottographic set-up.

Table 1

Results of the measurement of glottis aperture and amplitude of glottogram.

Recording JR 29/5

	A (mm)	GL (mm)
1. $S(=)S^+$		
a	15.0	9.5
b	22.0	14.0
c	27.0	19.5
2. $S(=)S^+$		
a	14.0	8.0
b	21.5	16.0
c	25.5	23.5
3. $S=S^+$		
a	17.0	14.0
b	26.0	27.0
c	21.5	22.5
4. $S(=)S^+$		
a	17.0	12.5
b	22.0	22.0
c	21.5	20.0
5. $S(=)S^+$		
a	16.5	12.0
b	21.5	17.0
c	23.5	24.0
6. $S(=)S^+$		
a	17.0	12.5
b	21.0	18.5
c	24.0	25.5
7. $S=S^+$		
a	14.0	10.0
b	19.0	13.5
c	22.5	21.5
8. $S(=)S^+$		
a	15.0	12.0
b	21.0	17.5
c	21.0	23.0
9. $S(=)S^+$		
a	15.0	11.0
b	18.5	17.5
c	22.0	26.0
10. $S=S^+$		
a	15.0	13.0
b	20.0	22.5
c	21.0	24.5
11. $S=S^+$		
a	10.0	4.0
b	20.5	8.0
c	22.0	6.5
12. $S=S^+$		
a	16.0	7.0
b	20.0	8.5
c	22.0	12.0

Recording JR 22/7

	A (mm)	GL (mm)
1. $S=S^+$		
a	11.0	5.0
b	16.5	9.0
c	26.5	16.0
2. $S=S^+$		
a	12.5	22.0
b	15.0	26.0
c	20.5	34.0
3. $S=S^+$		
a	13.0	17.5
b	16.0	26.0
c	22.5	33.0
4. $S=S^+$		
a	11.5	19.0
b	16.0	32.0
c	20.0	33.0
5. $S=S^+$		
a	10.5	15.5
b	15.0	26.0
c	19.5	33.5

Recording JR 28/8

	A (mm)	GL (mm)
1. $S(=)S^+$		
a	10.5	5.0
b	11.5	7.5
c	14.5	18.0

Table 1
(continued)

Recording BFJ 18/9

	A (mm)	GL (mm)
1. S(=)S$^+$		
a	6.0	13.0
b	8.0	15.0
c	9.5	29.5
2. S(=)S$^+$		
a	5.5	5.5
b	9.5	10.0
c	16.0	16.0
3. S(=)S$^+$		
a	7.0	8.5
b	11.5	12.5
c	16.0	21.0
4. S(=)S$^+$		
a	6.0	6.5
b	11.0	9.5
c	14.0	15.5
5. S(=)S$^+$		
a	6.0	7.5
b	11.5	9.0
c	18.5	19.5
6. S(=)S$^+$		
a	6.5	5.0
b	11.0	8.0
c	14.0	10.5
7. S(=)S$^+$		
a	7.0	6.5
b	10.5	7.0
c	18.5	15.5
8. S(=)S$^+$		
a	12.0	18.0
b	13.0	12.0
c	21.5	21.0
9. S=S		
a	12.5	14.5
b	15.5	15.0
c	19.5	20.0
10. S(=)S$^+$		
a	12.5	17.5
b	16.0	18.0
c	17.0	23.0
11. S=S		
a	9.5	14.5
b	16.5	17.5
c	18.5	11.5
12. S(=)S$^+$		
a	11.5	11.5
b	16.5	14.5
c	19.5	12.0
13. S=S$^+$		
a	12.5	13.0
b	17.5	18.0
c	24.5	18.0
14. S(=)S$^+$		
a	10.5	11.0
b	17.0	16.0
c	21.5	14.0
15. S(=)S$^+$		
a	11.5	12.0
b	17.5	19.5
c	26.0	20.0
16. S=S$^+$		
a	10.5	14.5
b	19.5	22.0
c	24.5	21.5

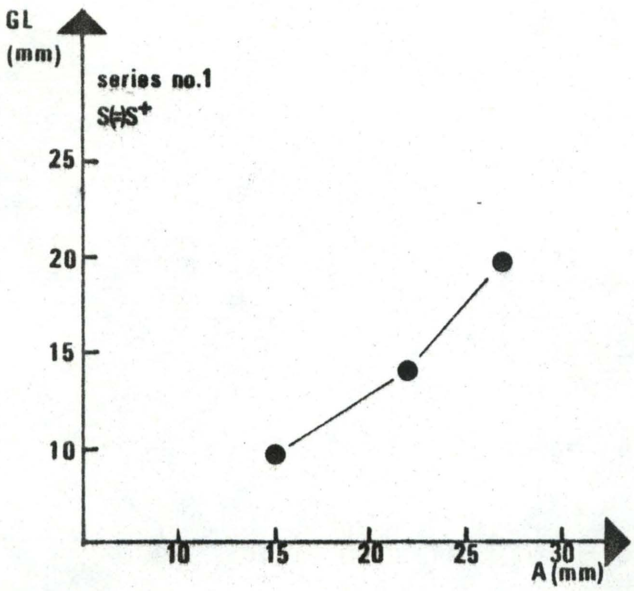
Recording BFJ 14/10

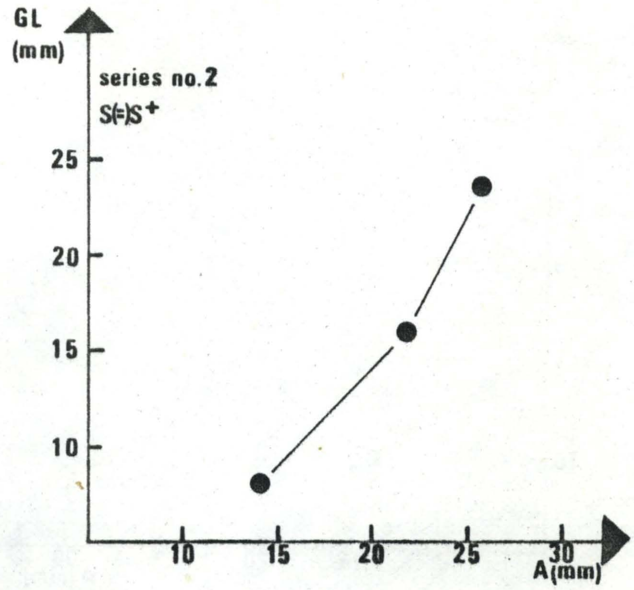
	A (mm)	GL (mm)
1. S(=)S$^+$		
a	8.5	10.5
b	12.0	15.0
c	12.5	13.0
2. S(=)S$^+$		
a	9.5	10.0
b	12.0	13.0
c	14.0	12.5
3. S(=)S$^+$		
a	8.0	9.0
b	12.5	16.0
c	13.5	13.5
4. S(=)S$^+$		
a	8.0	7.0
b	9.5	10.5
c	16.0	13.0
5. S(=)S$^+$		
a	8.5	8.0
b	11.5	10.5
c	16.5	13.0
6. S(=)S$^+$		
a	8.0	7.0
b	12.0	12.0
c	14.5	11.0
7. S=S$^+$		
a	11.5	8.5
b	13.5	13.0
c	17.5	13.5
8. S(=)S$^+$		
a	8.5	8.0
b	13.5	11.0
c	13.5	6.0
9. S(=)S$^+$		
a	8.0	9.5
b	12.5	14.0
c	15.5	16.0

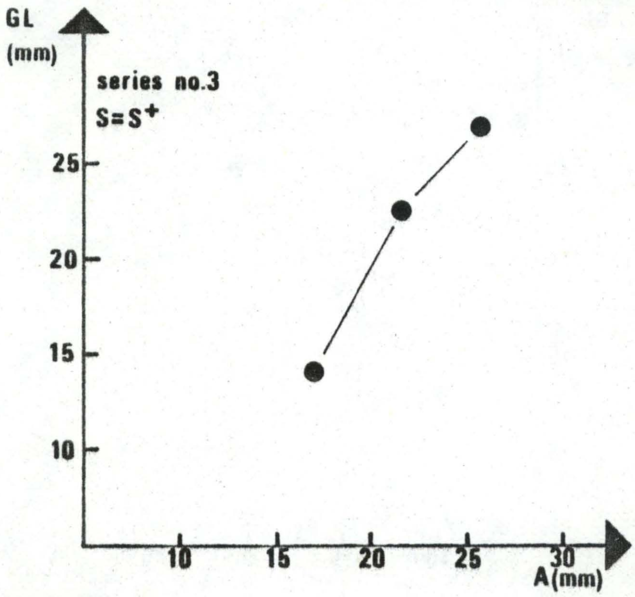
Figure 5

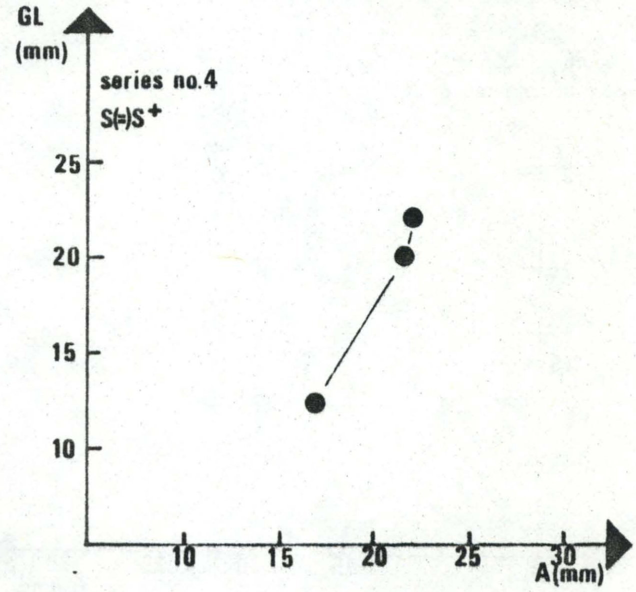
Recording JR 29/5

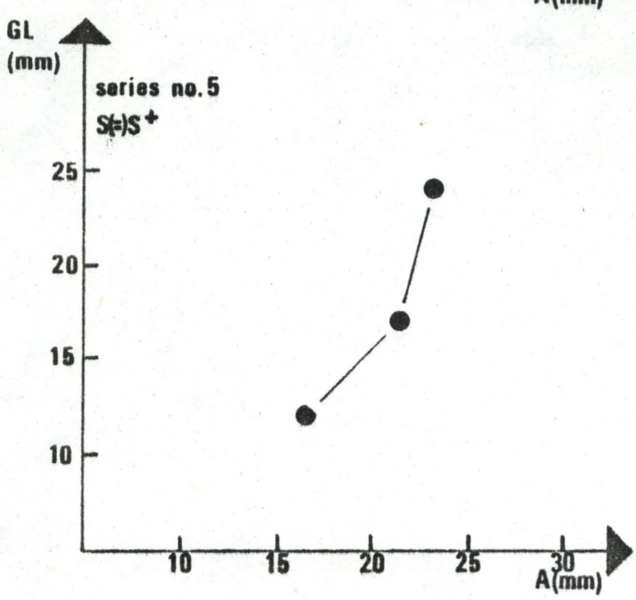
Amplitude of the glottogram, GL, is shown as a function of the glottis aperture, A. Identical control pictures are indicated by $S=S^{+}$, almost identical control pictures are indicated by $S(=)S^{+}$.

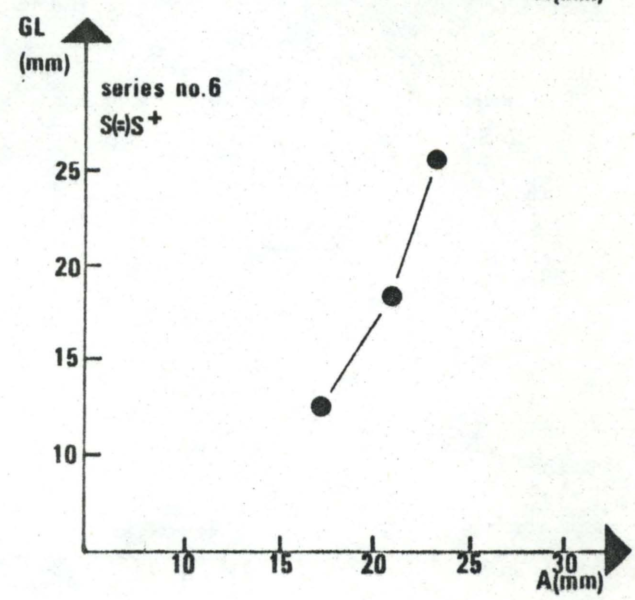

GL
(mm)
series no.1
S(=)S+
25
20
15
10
10
15
20
25
30
A(mm)


GL
(mm)
series no.2
S(=)S+
25
20
15
10
10
15
20
25
30
A(mm)


GL
(mm)
series no.3
S=S+
25
20
15
10
10
15
20
25
30
A(mm)


GL
(mm)
series no.4
S(=)S+
25
20
15
10
10
15
20
25
30
A(mm)


GL
(mm)
series no.5
S(=)S+
25
20
15
10
10
15
20
25
30
A(mm)


GL
(mm)
series no.6
S(=)S+
25
20
15
10
10
15
20
25
30
A(mm)

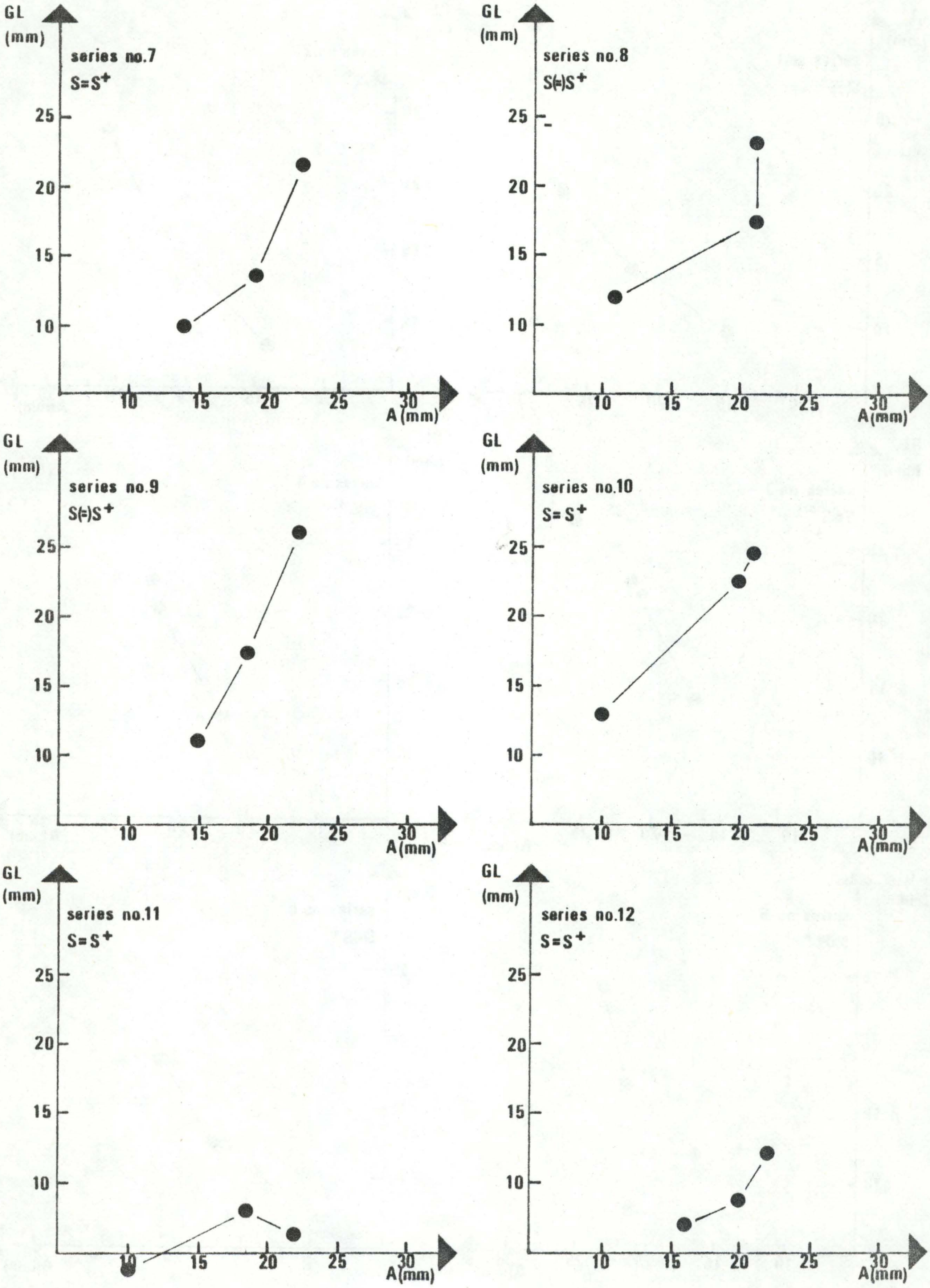


Figure 5 (continued)

Recording JR 29/5

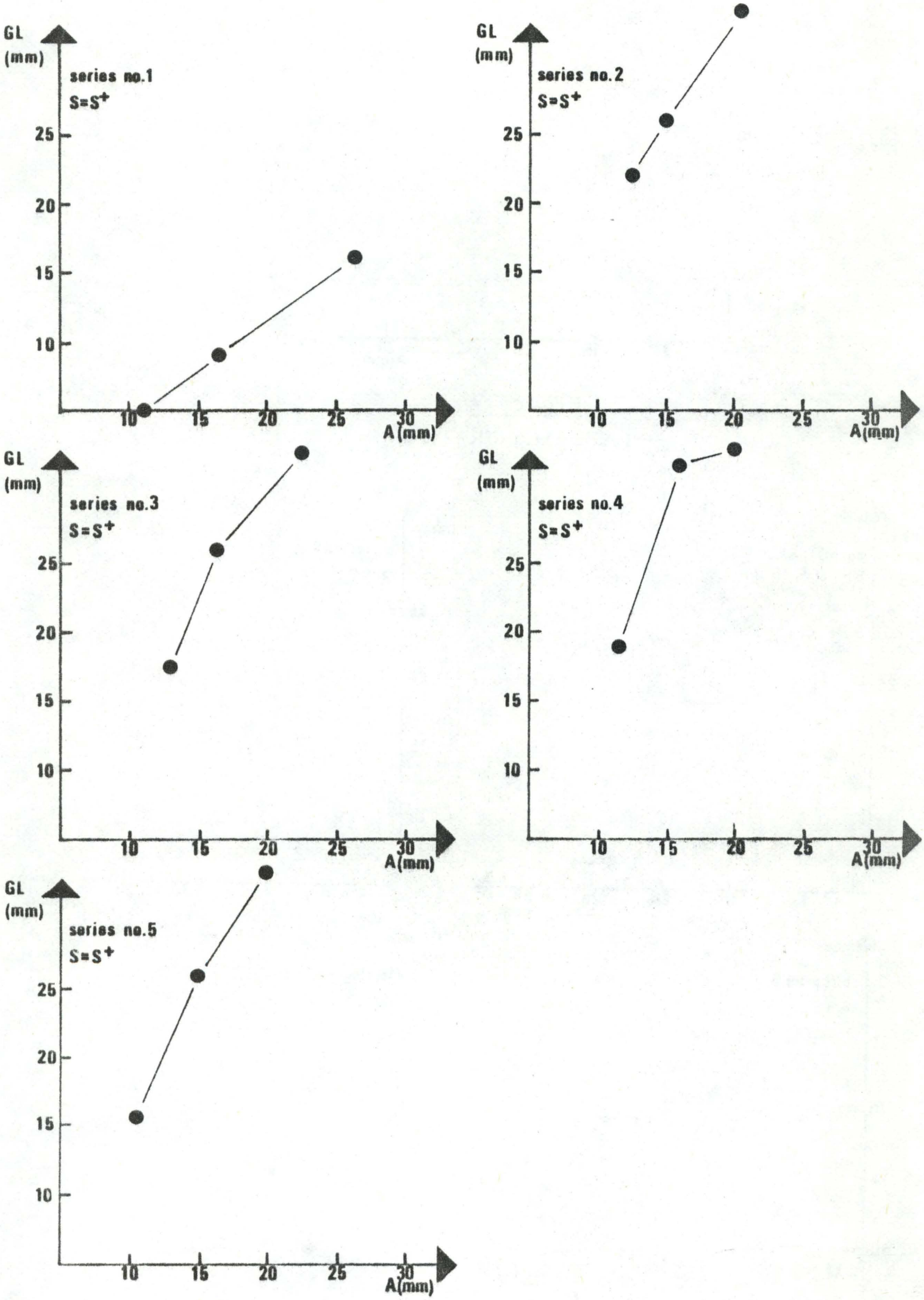


Figure 6
Recording JR 22/7

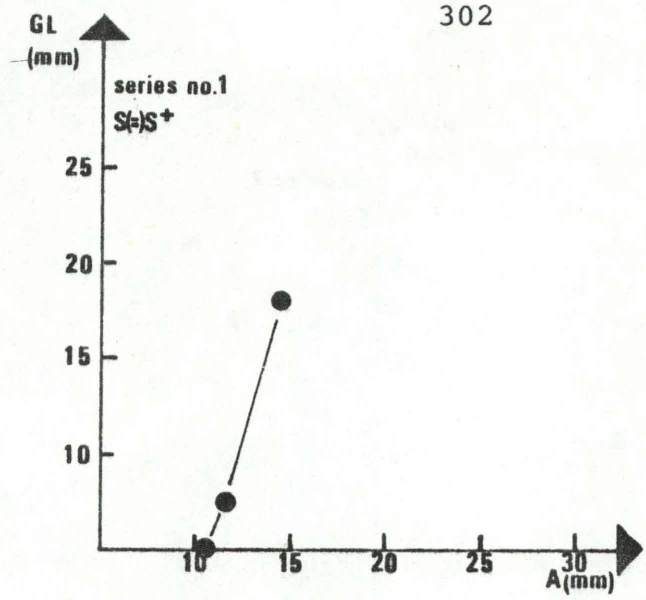


Figure 7

Recording JR 28/8

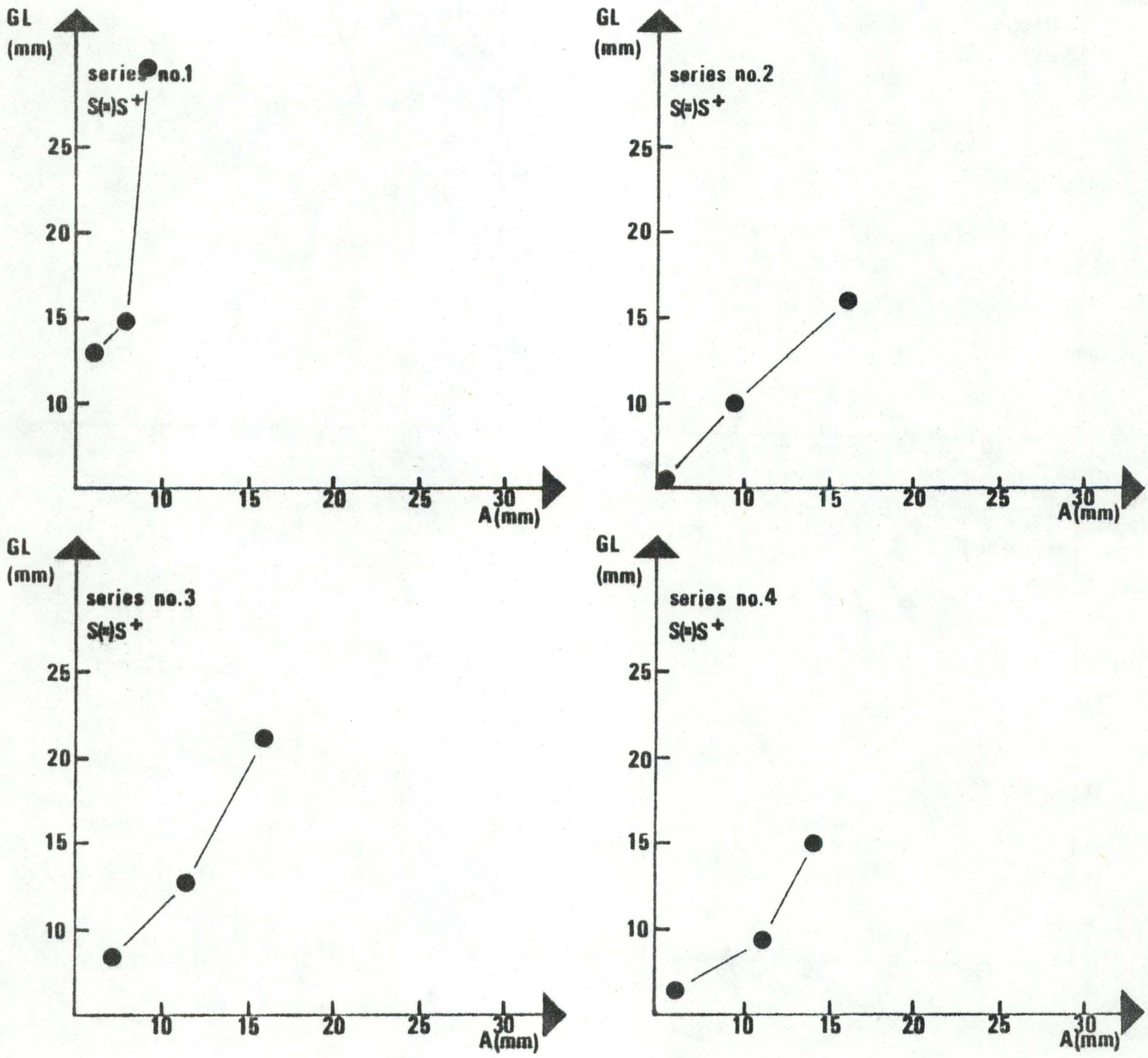


Figure 8

Recording BFJ 18/9

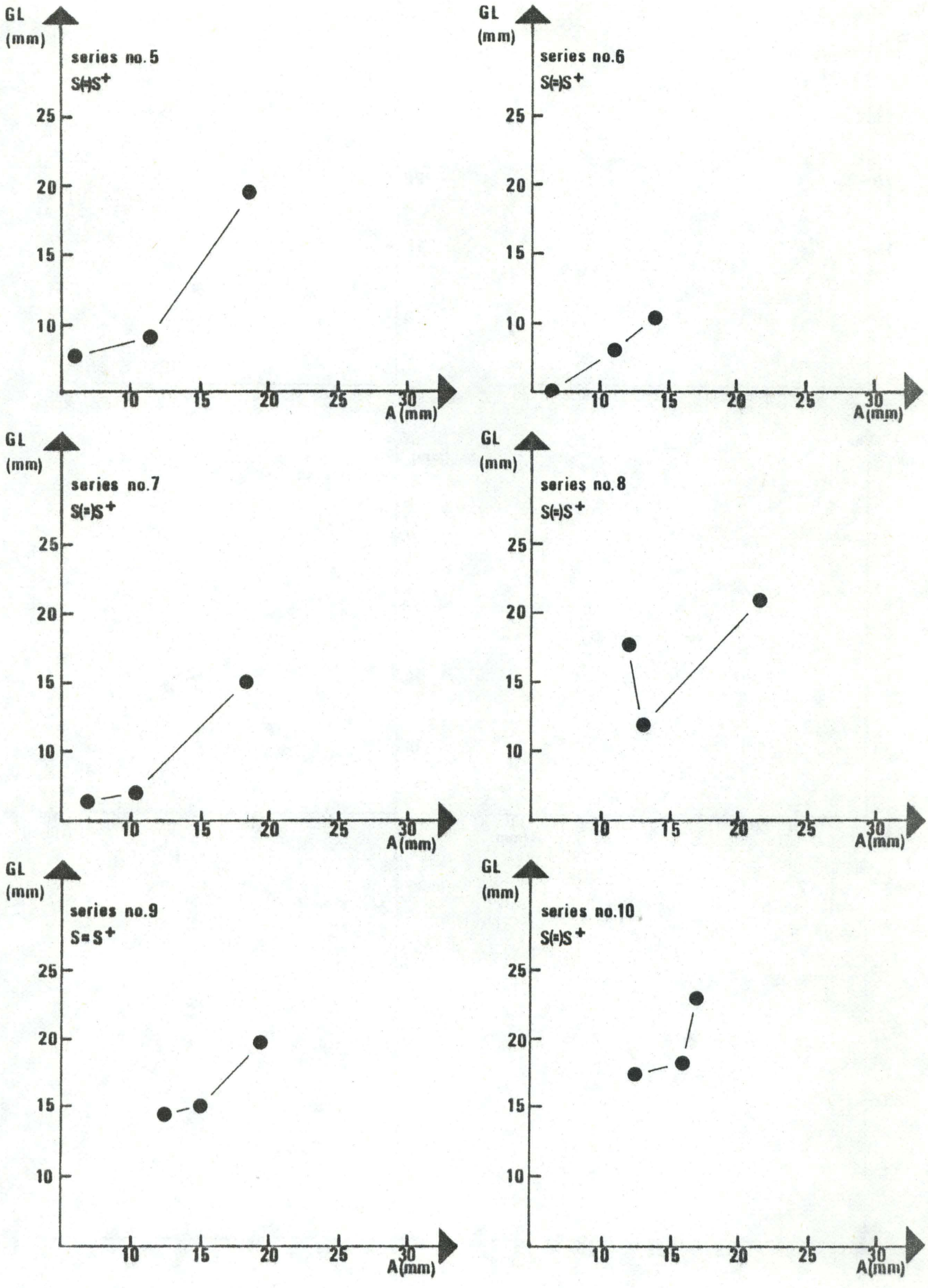


Figure 8 (continued)
Recording BFJ 18/9

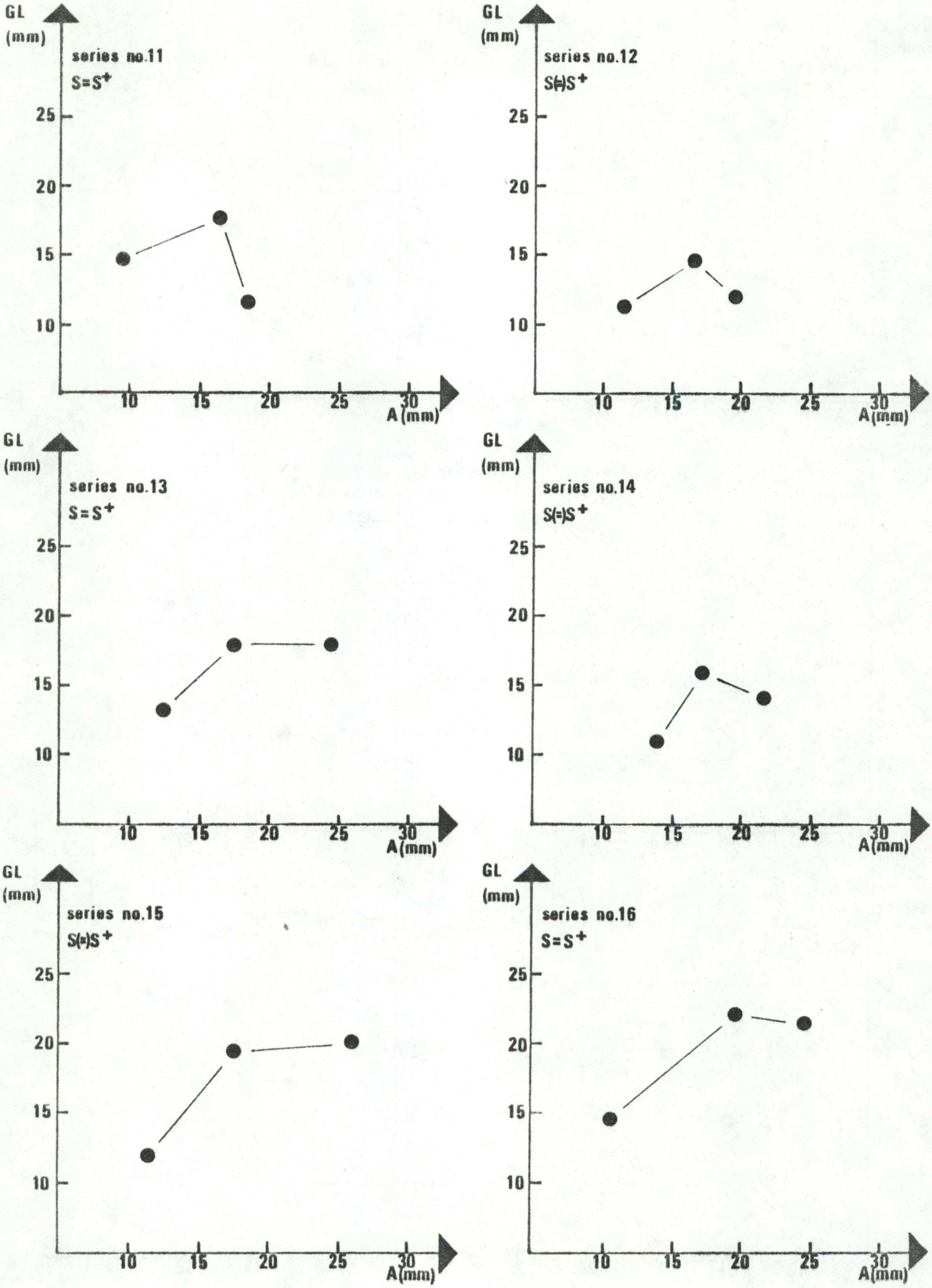
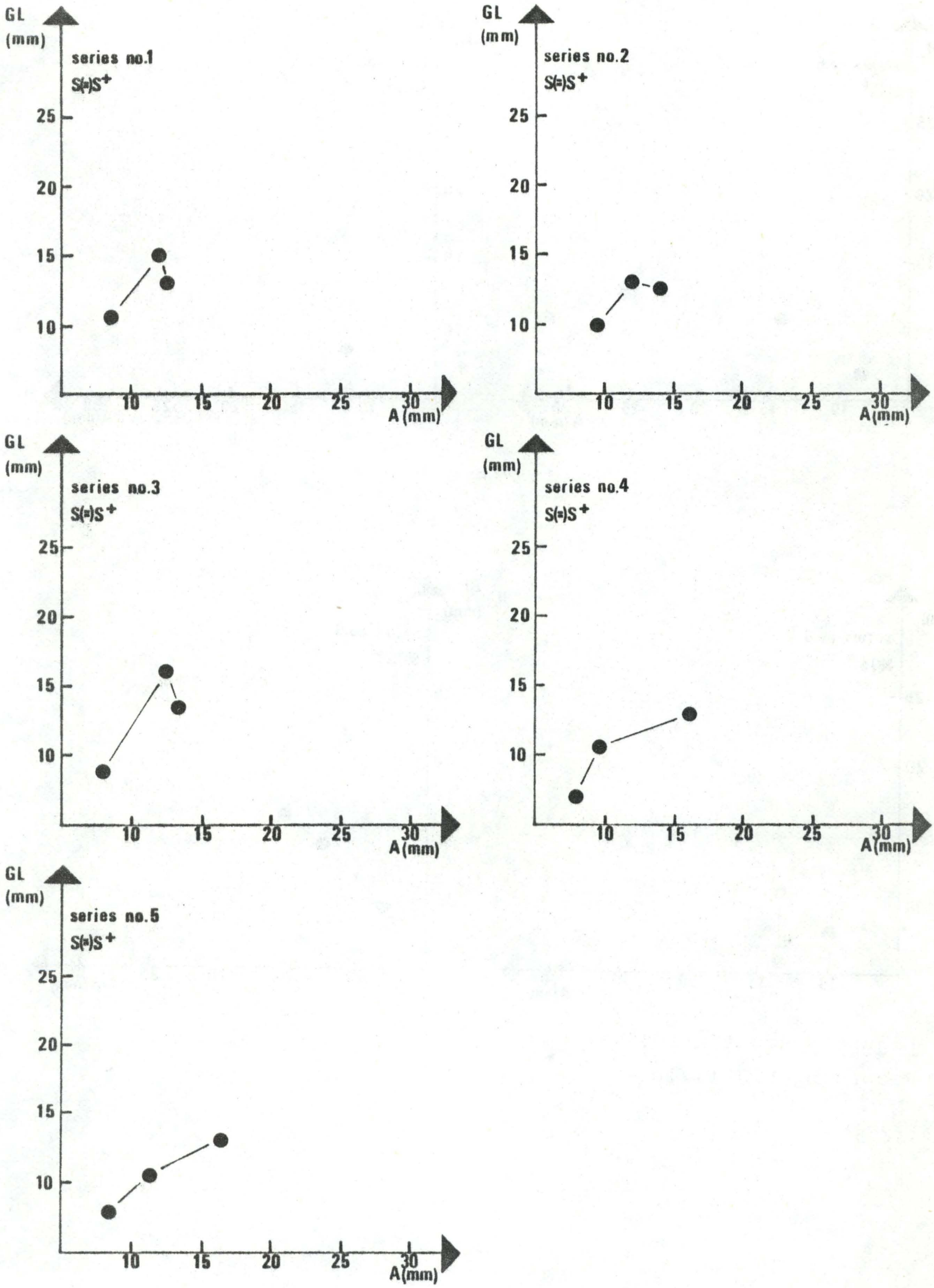


Figure 8 (continued)

Recording BFJ 18/9



<u>Figure 9</u>

Recording BFJ 14/10

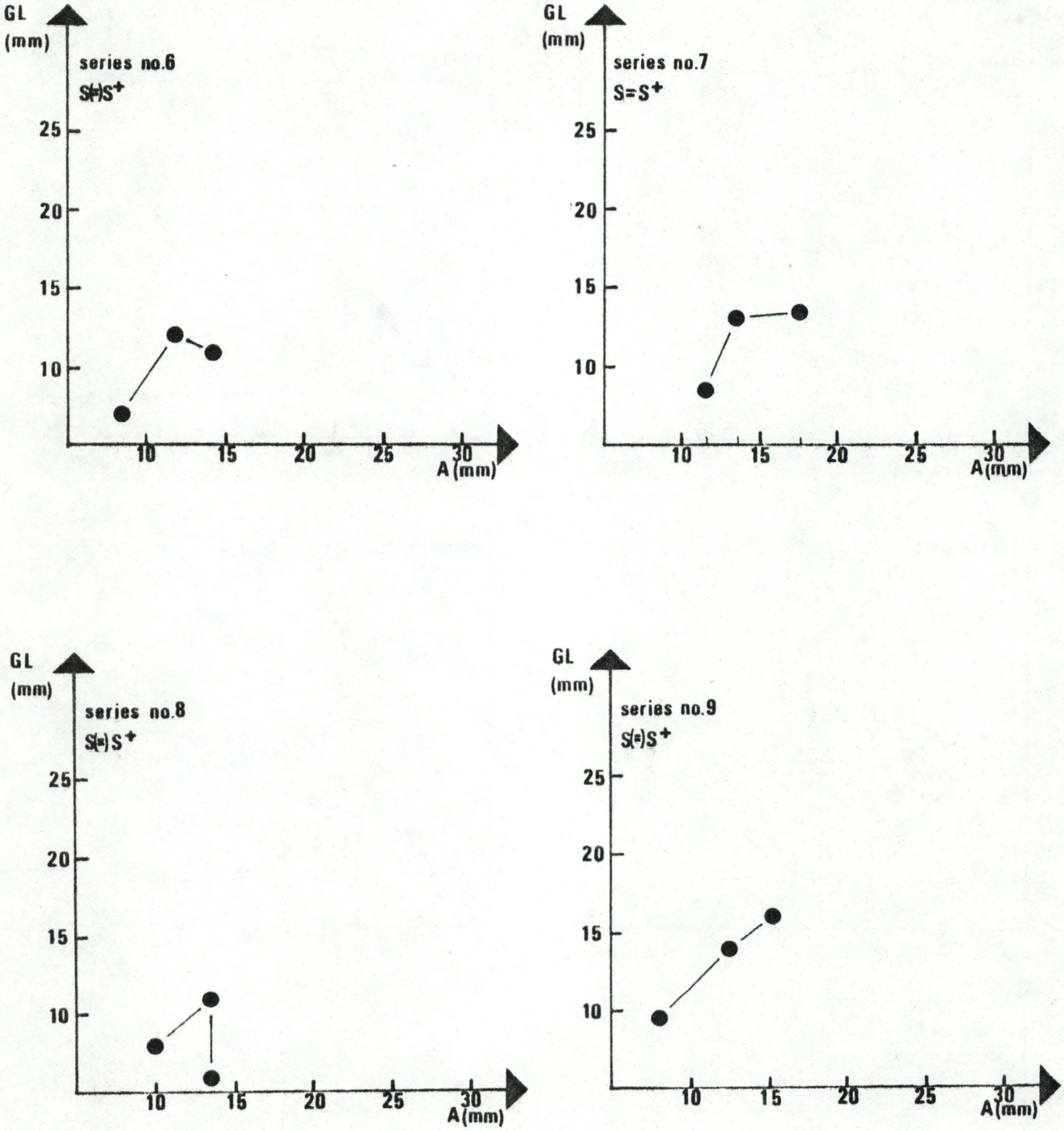


Figure 9 (continued)
Recording BFJ 14/10

It must be brought about by one or several of the following factors:

1) The glottographic light has been disturbed during the recording of the series
2) The glottograph transducer has moved considerably during the recording of the series
3) Something has shaded the glottograph transducer.

The first mentioned factor may explain the negative correlation in JR 29/5 series no. 11. The film shows that the part of the glottis in which the film is saturated is larger for b than for c. The same factor may explain the negative correlation in BFJ 18/9 series no. 8, because the density of the film in the anterior part of the glottis is less for b than for a. In all other cases where the deviation from a straight line is considerable, this explanation does not apply, judging by the films.[1]

It is not possible to say whether the transducer has been considerably moved in some cases since this would have required synchronous X-ray pictures.

The most obvious explanation of the fact that the correlation between a, b, and c is in many cases so far from being linear, and very often even negative, is that something has shaded the transducer. It can hardly be the epiglottis or the tongue root as all the sounds included in the sentences are articulated with an advanced tongue root. It is rather the fiberoptic tube that has shaded the transducer. The negative correlation is most frequently seen for subject BFJ, and it is most often the correlation between b and c that is negative. Therefore, BFJ made a supplementary glottographic recording of 28 abc-series, the light and the transducer being positioned as in the actual recordings, but without the tube of the fiberscope.

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1) It may be problematic to estimate the relative quantity of light passing the glottis on the basis of the films. The film has a saturation threshold, and will thus be saturated at and above a certain light intensity; thus the film shows maximum density irrespective of the light intensity beyond this threshold. Furthermore, the absolute size of the saturated area seen on the film depends partly on the distance between the lens of the fiberscope and the glottis, partly on the angle between the plane of glottis and the plane of the lens.

If it is correct that the fiberoptic tube under certain conditions shades the transducer, this recording made without the tube should show a greater amplitude for c than for b in the vast majority of cases, as the films normally showed a larger glottis aperture for c than for b. This is exactly what the 28 series show: out of 28 series only 2 have a smaller amplitude for c than for b. This result supports the hypothesis that the fiberoptic tube may have shaded the transducer in certain cases.

It seemed methodologically preferable to confine this study to the relationship between the amplitude of the glottogram and the glottis area under the simplest conditions, viz. with articulatory gestures involving the same type of glottis function. Still, I tried to get a hint of the relationship for series involving two different glottis functions. But as the procedure was fairly inaccurate, and the data very limited, this part of the study will not be reported here, except for one observation pertaining to the fiberscope. The recordings comprised, in addition to the three unvoiced consonants, synchronous fiberoptic pictures and glottograms of sustained vowels [i::] and [æ::] (for the vowels it was the maximum glottis aperture during the vibratory cycle that was registered). It appeared from the film that the whole glottis was positioned considerably closer to the upper limit of the field of vision during phonation than during the articulation of unvoiced consonants. This may be due to movements of the velum, pushing the fiberoptic tube about during the recording. The X-ray recording mentioned above showed that the distal end of the tube was bent forward to the greatest extent in the articulation of [b̥::], [s::], and [ç::], less in [i::], and least in [æ::]. This displacement, and the subsequent variation in the relative location of the glottis within the field of vision, may be explained by variations in the velopharyngeal closure depending on the type of sound (Lubker 1968, 1970): the higher the position of the velum, the more the distal end of the fiberoptic tube is bent forward because both the velum and the pharyngeal wall press against the tube.

4. Concluding remarks

In this preliminary study the relationship between the glottis aperture and the amplitude of the glottogram has been examined under rather specific conditions of articulation and with one specific glottographic set-up. I did not have any possibility of studying continuous variations in glottis aperture, which of course would be of interest, too. To mention another limitation, only one type of light source was used. Furthermore, the applied procedure for measurement of the glottis aperture causes a certain inaccuracy of the results. Nevertheless, it is justified to make some concluding remarks.

The results demonstrate that the relationship between glottis aperture and the amplitude of the glottogram is sometimes approximately linear, and at other times far from linear; in many cases even a negative correlation is seen.

The negative correlation found in this study is probably caused in most cases by the fiberoptic tube shading the phototransducer, i.e. it is caused by an artifact stemming from the complex procedure followed in this study and not by an artifact associated with the glottographic method itself. But other factors may give rise to a negative correlation: the tongue root and the epiglottis may shade the transducer and the glottographic light may alter its position during the recording.

It is true of all types of photo-electric glottographs that the linearity of the system has to be established in order to know whether the signal voltages delivered by the glottograph in a given recording are within a linear range or not. In interpreting the data of this study a means to divide the results into two groups would have been desirable, one for which the voltage range is within a linear range, and one for which it is within a non-linear range, in order to preclude that greater or lesser deviations from a linear relationship between amplitude and aperture may be caused by the system's inherent non-linearity for varying illumination. Since I had not realized that such a problem exists at the time when the recordings were made, and hence did not measure the voltage range for each recording session, this is not possible with my data. It can only be stated that one does not very often find a linear correlation between the glottis aperture and the amplitude of the glottogram. Deviations from a linear relationship may be caused by one or several of the factors influencing the amplitude of the glottogram: the characteristics of the glottographic set-up, instability of the light source, shading effects, and so on. The combined effect of these different factors acting simultaneously may sometimes increase and sometimes decrease the deviation from a linear relationship, depending on the factors involved.

The non-linearity of the system is a problem in comparisons between glottographic curves of different sounds, if and when the amplitude is taken to be some kind of measure of glottis aperture. It may, however, also be crucial for the interpretation of the amplitude variations observed in a glottogram of a continuous glottis movement. For one thing, the pronounced non-linearity of the system in the lower voltage range makes it highly dubious to take the "bottom" of the glottogram of a single vocal fold vibration as a realistic representation of the true physiological conditions.

I wish to add that according to my experience it is very difficult to keep the fiberoptic tube stable during articulation. This may be a relevant problem when the fiberscope is used for some sort of quantitative analysis of the glottis area.

As for the glottograph, I venture the general conclusion that the amplitude of the glottogram may be influenced by so many factors that it is hazardous to take for granted - without further proof - that there is a linear relationship between glottis aperture and the amplitude of the glottogram. Therefore, it may be "not only hazardous but invalid in many cases" to draw conclusions about the relative size of glottis aperture on the basis of glottograms.

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