Recording Mandibular Movement: Technical and Clinical Limitations of the Sirognathograph

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It is essential to know the limitations of any equipment used for research or clinical purposes. Clinical electronic equipment is commonly sold for "black box" use without specification of artifacts. This study tested the technical and clinical limitations of the Sirognathograph, which is a device used for recording mandibular movement. From a technical point of view, the Sirognathograph's slow sampling speed and sample artifacts have been shown to be the system's main limitations; however, it was possible to eliminate sampling artifacts by using a customized pulse generator and software for controlled data acquisition. Clinically, the Sirognathograph appears to have some inherent limitations in its accuracy. The effect of cranial movements during mastication can cause a baseline drift with consequent errors in the recording of mandibular position. This problem was controlled in this study by using a headband to stabilize the cranial movements during mastication. Also, the spatial relationships between the aerial and both the cranial base and the magnet were found to be critical for repeatability of the recordings.
J OROFACIAL PAIN 1994;8:165–177.

Through the years, improvement in systems used for recording jaw movements have followed advances in science and technology. Recently, certain systems, which involve computerized data collection and analysis, have been found to be easy to use and noninvasive. These include the Selspot (Selspot AB, Partille, Sweden), Kinesiograph (Myotronics, Seattle, WA), and Sirognathograph. The limitations of the Selspot and Kinesiograph have been reported previously.[1–4]

The Sirognathograph is now widely used for research tracking of mandibular incisor movement, but reports on its limitations are few.[5–10] This jaw-movement recording equipment was developed over several years,[11–14] and the final version (Model D-3175, Siemens, Bensheim, Germany) was introduced by Lewin[5] in 1985.

Sensitivity and Linearity of the Sirognathograph

It has been reported that the calculated distortion of this device, within the normal range of movement, was 1% or less.[6] A later paper has stated different distortion values; 7% at gapes of 20 to 25 mm and negligible distortion for gapes less than 20 mm.[7] The latest value was reported to be 1.5%.[8]

The initial calibration of the Sirognathograph used in this study showed differences in sensitivity from the manufacturer's specification and from that reported in other studies. Although some of the reasons for the artifacts have been described,[5,7,8] they have not been reported in sufficient detail for the design of future studies. Moreover, no solutions have been offered to overcome these distortions. It was therefore considered desirable to analyze these limitations in detail and, as a consequence, develop methods to obtain a higher degree of accuracy.

Clinical Reproducibility of Sirognathograph Recordings

Only three studies have considered the importance of reproducibility of the Sirognathograph.[7,10,15] The earliest of these recorded six subjects' chewing movements on 3 separate days and analyzed movements up to 10 mm below the level of centric occlusion. Their test foods were chewing gum and salami sausage. Because opening, closing, and lateral chewing movements had standard deviations of less than 1 mm, it was concluded that the reproducibility of movement recording by this system was high. In the second study,[10] 5-mm protrusion and 23- and 43-mm opening in one subject were measured in two different trials. The frame and magnet were removed and repositioned between tests. Results showed that the Sirognathograph was reproducible for 5-mm protrusion movement and 23-mm opening. Even the 43-mm opening was said to be reproduced with negligible differences between tests. From these figures the general pattern does appear to be satisfactory, but no numerical analysis was provided. The largest number of subjects (n = 9) studied in detail in relation to repeatability of the Sirognathograph recordings has recently been reported.[15] The aim of this study was to look for the core of chewing cycles by eliminating the extreme chewing cycles. Only 9 out of 120 variables were found to be significantly different between the two different recording sessions.

Although high clinical reproducibility was reported,[7,10] it has been stated that reproducibility with this type of system depends upon the positioning of the magnet and/or aerial and the technique of the user.[15] It was therefore considered worthwhile to provide further validation of the limits of accuracy of this widely used system.

Cranial Movement

Cranial movement is part of the normal mastication motion. It is especially noticeable when masticating hard foods and during wide opening; as much as 10 degrees of tilting of the Frankfort plane has been reported.[16]

Preliminary research showed that cranial movement affects the mandibular movement records as evidenced by base line drift (Fig 1). Although the importance of cranial stability during recording has been stated in some studies,[5,7-9,13] there has been no description as to how to effectively prevent this movement or how to take it into account when expressing the accuracy of the system.

Materials and Methods

Technical Specifications of the Sirognathograph

An aerial is employed to detect changes in the magnetic field using eight Hall effect devices, four in each side. These devices are positioned so that their output provides the basis for analysis of three-dimensional movements of a magnet that is temporarily attached on the labial surface of the mandibular incisors. The magnet weighs 1 g and has a field strength of 10 gauss. The circuits are designed to minimize the effect of environmental magnetic fields on the output.

Technical Analysis

To evaluate the speed of response of the Sirognathograph's output, a square wave change in the magnetic field was generated for bench experiments. This was produced by a simple coil that

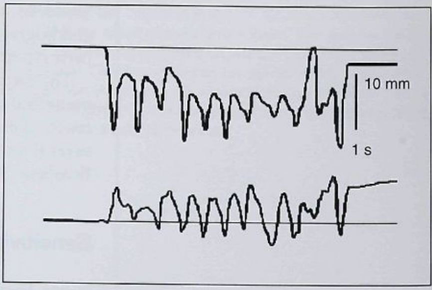


Fig 1 A mandibular movement record from a subject during the chewing of gum (top trace is vertical, bottom trace is lateral movement). At the beginning and end of the experiment the subject was instructed to keep the maxillary and mandibular teeth together (straight line). During chewing the subject tilted his head downward and to the right side (shown by a shift of the base line of more than 5 mm at the end of the experiment).

was placed close to one of the Hall effect transducers of the aerial (5 MHz sweep generator, Model 184, Wavetek, CA). The output was recorded at 200 kHz with a digital storage oscilloscope (Gould 20 MHz Digital Storage, Type 1425, Essex, UK).

For the purpose of excluding the artifacts produced by the Sirognathograph, a 50-Hz mains lock pulse generator was custom designed for this study. The relevance of this device will be discussed below.

Sensitivity and Linearity Tests

A plastic vernier calliper was used to effect movement of the magnet a distance of 5 mm for calibration purposes. The magnet was moved in the frontal, sagittal, and horizontal planes. This calibration procedure was performed three times.

For conventional denture wearers, jaw movement can be recorded from the mandibular denture, but it may tip during use. To examine the possible effects of this movement, the effect of rotating and tilting the magnet on its long axis was recorded at 10 and 20 degrees.

Reproducibility of Magnet/Aerial Relationship

The occlusal border movement of a 28-year-old male subject was recorded. This subject had canine guidance on the right side and group function on the left side of his articulation. The subject was initially asked to traverse the occlusal border movement while maintaining intermaxillary tooth contact. Following this, a 20-mm bar was placed between the first molar region to provide a controlled gape, and a recording was made to verify this degree of opening. The subject repeated these experiments five times on two recording sessions, so that the effect of removing and relocating the magnet and aerial could be tested.

Data were plotted in the frontal (YZ) and sagittal planes (XZ). Vertical movement was measured at 1-mm intervals in both lateral and anterior directions for each trace.

Cranial Movements

Dentate subjects (7 women and 7 men; mean age 24.8 ± 3.3 years, range 18 to 29 years) were employed for this experiment. All subjects were fully dentate, had Angle Class I occlusion, and were free of any orofacial discomfort or pathology.

The output from the Sirognathograph provides a recording of apparent mandibular movement. The effect of cranial movement in relation to the aerial gives an artifact that will effect recordings of mandibular movement. This effect is termed ECM and was assessed by experiments with the magnet situated on the maxillary incisors. Four test foods were chosen to provide different hardness during chewing: a single almond (weight between 1.0 and 1.2 g, Sainsbury's Bleached almonds, J. Sainsbury, London, UK); a piece of chewing gum (weight approximately 1 g, Freedent Chewing Gum, Wrigley, London); a single sweet (weight between 4 and 5 g, Sainsbury's boiled sweet, J. Sainsbury); and a quarter of a biscuit (weight between 3.3 and 3.5 g, Mcvitie's Digestive biscuit, United Biscuits, Middlesex, UK). The subjects were also asked to perform wide open-close and border movements. The range of cranial movement was calculated for each individual mastication experiment.

Instructions and Requirements for the Cranial Movement Study

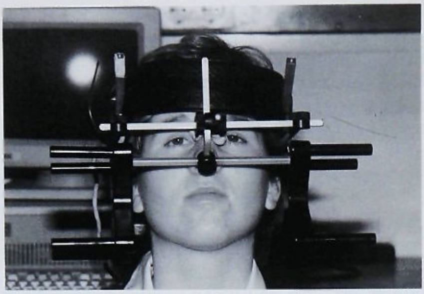
During the recording procedure the subjects were seated in a chair of nonferromagnetic material to prevent interference with the magnetic field. A rubber-padded, aluminum headband was constructed to provide cranial stability during mastication (Figs 2a and 2b). This headband was developed to allow smooth adjustment in two dimensions. This is essential to achieve a natural sitting posture for the subjects. The tightness of the band can be adjusted to achieve a compromise between comfort and restriction that allows subjects to maintain stability. Some voluntary restraint by viewing a horizontal line complements the physical restriction.

Further essential features of the design were: *(a)* a strap over the cranium to support the weight of the aerial, and *(b)* the use of viscose putty (Blu-tak, Bostik, Leicester, UK) between the nose and the "nasal support" of the aerial to improve comfort and stability.

To evaluate cranial movement, the magnet was fixed on the labial surface of the maxillary incisor teeth. All necessary instructions were then given to the subjects to minimize the ECM. The first 10 seconds of each mastication sequence was recorded.

Statistical Analysis

Wilcoxon signed-rank and Mann-Whitney U tests were applied to reveal significance between the test foods.



Figs 2a and 2b Frontal *(left)* and lateral *(right)* view of headband being used to stabilize cranial movement.

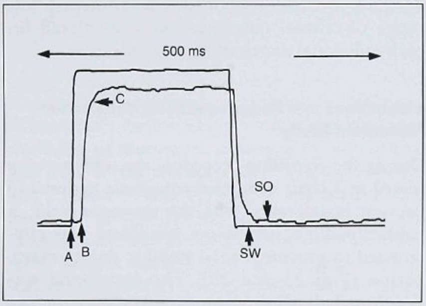


Fig 3 Sampling frequency testing showing sirognathograph output (SO) produced by a step wave change in magnetic field (SW); delay of the response (A-B) in this case was 14.5 ms. Output reached 93.7% of the correct value after 20 ms (C).

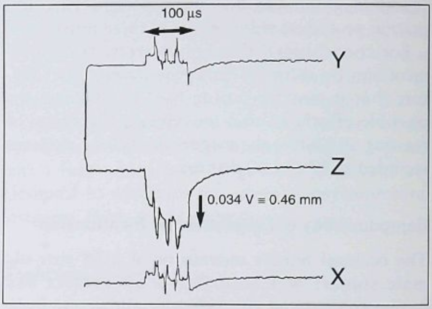


Fig 4 Sirognathograph output: a high sampling rate (200 kHz) showed sampling artifacts on all 3 channels. Spikes occurred every 20 ms and lasted 100 µs. They were consistently larger on Z than on Y and X. The artifact on channel Z in this instance was equal to 0.46 mm.

Results

Sampling Frequency and Distortion

The Sirognathograph reproduced 3-Hz square waves with minimum distortion. However, at higher frequencies the output became progressively more distorted. Analyses showed the delay between stimulation and initial response to be between 0 and 20 ms, thus confirming that the Sirognathograph samples at a rate of 50 Hz (Fig 3).

Pulse Artifact

Any magnetic measuring device is subject to artifacts from stray magnetic fields. To overcome this, the Hall effect devices were used in the Sirognathograph sample for a short period once every mains cycle (50 Hz, UK mains frequency). To increase the sensitivity of the device, an energizing pulse is passed through the Hall effect transducer at a rate many times higher than the maximum mean current for the device. Recording the consequent artifacts at 200 kHz showed that pulses are 100 µs long and equivalent to approximately 1 mm of displacement (Fig 4). If this pulse artifact occurred during real recording it would be unacceptable in a study dealing with small distances. The error will be greater in relation to first and second derivative traces (Fig 5).

It is obviously important not to record during these pulse artifacts (Fig 6, point C). It is also necessary to sample the output voltage when it is not changing rapidly. This occurs shortly before the artifact where the output amplitude is becoming asymptotic with the true value for that 20-ms interval (Fig 6, point B). It must be noted that the time at which that magnet position was sensed was actually

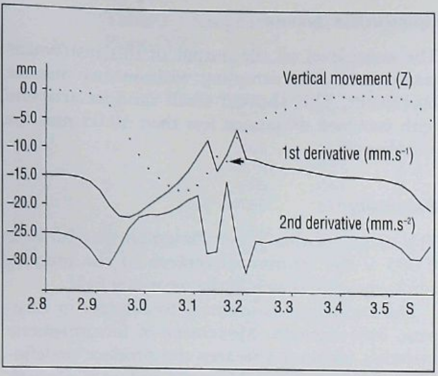


Fig 5 Artifact (arrow) was registered with other samples during closure of the mandible, which caused first and second derivative traces to show sudden dramatic changes that are similar to jaw movement at the moment of food fracture. (First derivative trace is reduced 20 times and offset –15 mm. Second derivative trace is reduced 400 times and offset –25 mm).

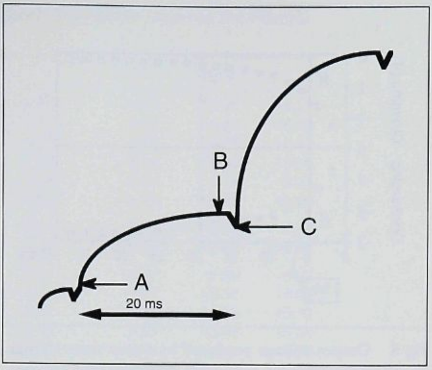
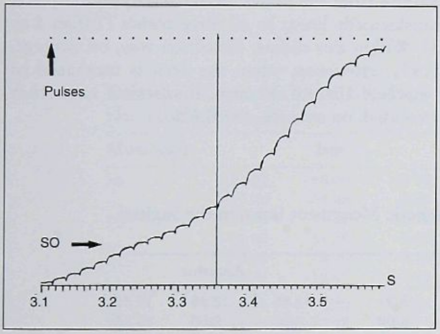


Fig 6 Diagrammatic representation of a spike artifact seen at 1 kHz: note the need to sample where asymptotic at B but clear of spike artifacts C. True point B records the position of magnet at time A.



Figs 7a 50 Hz mains-locked pulses and artifacts; SO of vertical movement sampled at 1 kHz shows capacitance effect. Software selection of corresponding (50 Hz) points on traces (X, Y, and Z) produce artifact-free data.

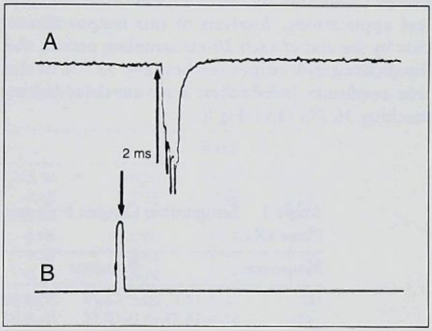


Fig 7b Closeup of relation between an artifact (A) and pulse (B) (voltage against time).

during the spike at the beginning of that interval (Fig 6, point A). It is appropriate to relate any data from other equipment to the correct time (A not B).

The analog-to-digital converter (ADC) used in this study cannot be mains-locked. To overcome this difficulty a 50-Hz mains-locked pulse generator was designed and used for this experiment. The position of this pulse on the mains cycle can be adjusted, as can the width of the pulse (Fig 7a). The pulse was adjusted to 2 ms before the Sirognathograph artifact because the mains frequency can drift +0.1 Hz (Fig 7b). As a result, the recorded voltage is always free from spike artifacts and is where the capacitive effect is minimized (Fig 6, point B and Fig 8). This 2-ms time shift of recorded data thus subtracts from the 20-ms interval (Fig 6), but it must be noted that any movement will have occurred at some time during the preceding 20 ms.

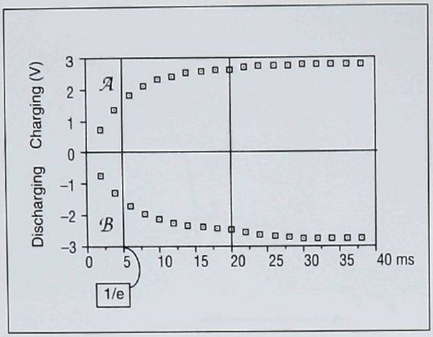


Fig 8 Output voltage produced by a step wave change in the magnetic field when *(A)* charging and *(B)* discharging. This capacitance effect is uniform for movement in any direction. The time constant is 5 ms.

Capacitance Effect

A capacitance is used in the Sirognathograph's circuit to reduce the artifacts between samples and produce smoother two-dimensional traces for clinical applications. Analysis of this output shows that by the end of each 20-ms sampling period, the Sirognathograph output reaches only 93.7% of the true amplitude. Indeed there is a 5-ms delay before reaching 36.7% (1/e) (Fig 8).

Noise in the System

The noise level on the output of this instrument was recorded by sampling without any magnet movement. This showed small random artifacts with standard deviations less than ±0.05 mm for any channel.

Sensitivity

The output of this Sirognathograph was 0.747 ± 0.005 V for 10-mm movement of the magnet across the central area of the recording field.

The instrument is sensitive to changes in magnetic field strength. Movement of ferromagnetic materials within a 1-m area can produce undefinable artifacts. Even the static presence of such material within this 1 m can disturb the magnetic field and consequently the sensitivity.

Linearity

The Sirognathograph output showed that when movements of the magnet occur within a radius of 15 mm from the center of the aerial, the output is satisfactorily linear in all three planes (Tables 1 to 3). Within this radius, distortion was, on average, 5.9%. However, when the area is increased to between 20 and 30 mm, distortion is further increased, on average, to 10.6%.

Table 1 Sirognathic Output Following Magnetic Movement (mm) in the Sagittal Plane (XZ)

Movement		Posterior				Anterior	
15	14.7	13.75	13.65	13.91	13.65	13.55	13.35
	−14.77	−10.17	−5.97	−0.66	4.36	9.06	13.26
10	9.45	9.36	9.16	9.36	9.26	9.23	8.99
	−14.43	−9.96	−5.80	−0.49	4.52	9.15	13.35
5	4.76	4.64	4.48	4.70	4.50	4.61	4.41
	−14.24	−9.68	−5.57	−0.36	4.72	9.32	13.58
Z	0.14	0.08	−0.21	0.00	0.00	−0.21	−0.53
X	−13.88	−9.38	−5.31	0.00	4.92	9.35	13.45
−5	−4.86	−4.84	−4.86	−4.77	−4.96	−4.96	−5.28
	−13.85	−9.28	−5.22	0.13	4.99	9.52	13.55
−10	−9.71	−9.54	−9.78	−9.52	−9.74	−10.00	−10.00
	−13.82	−9.19	−5.05	0.29	5.12	9.78	13.78
−15	−14.23	−14.42	−14.40	−14.10	−14.30	−14.4	−14.81
	−13.75	−9.09	−4.95	0.49	5.42	10.01	14.11
−20	−18.89	−18.53	−18.72	−18.59	−18.75	−18.72	−19.04
	−13.75	−9.02	−4.85	0.62	5.65	10.17	14.31
−25	−22.73	−22.69	−22.69	−22.50	−22.59	−22.78	−23.09
	−13.65	−8.99	−4.75	0.82	5.78	10.44	14.53
−30	−26.27	−26.02	−26.21	−25.98	−25.98	−26.24	−26.57
	−13.61	−8.89	−4.66	0.92	6.01	10.60	14.76

Table 2 Sirognathic Output Following Magnetic Movement (mm) in the Frontal Plane (YZ)

Movement		Left				Right	
15	15.03	14.74	14.51	14.09	14.68	14.91	15.29
	−14.24	−9.00	−4.42	0.04	6.22	11.23	16.30
10	9.95	9.69	9.79	9.53	9.73	10.22	10.47
	−13.78	−9.33	−4.48	0.04	5.14	10.87	15.65
5	4.68	−4.61	4.79	4.69	5.01	5.14	5.23
	−13.58	−9.00	−4.45	0.62	5.14	10.57	15.20
Z	−0.09	−0.10	−0.10	0.00	0.01	0.00	0.00
Y	−13.65	−9.46	−4.68	0.00	5.14	10.44	15.06
−5	−6.09	−5.47	−5.18	−5.01	−4.81	−4.88	−4.07
	−13.65	−9.39	−4.78	−0.01	5.17	10.38	15.02
−10	−11.39	−10.87	−10.15	−9.92	−9.89	−10.12	−10.22
	−13.97	−9.72	−4.94	−0.13	5.27	10.48	15.38
−15	−16.56	−15.69	−15.03	−14.71	−14.68	−14.84	−15.29
	−14.60	−10.08	−5.17	−0.16	5.27	10.74	15.74
−20	−21.09	−20.27	−19.46	−19.07	−19.07	−19.49	−19.98
	−15.48	−10.57	−5.10	−0.36	5.66	11.01	16.13
−25	−25.32	−24.24	−23.43	−23.10	−22.97	−23.43	−24.40
	−16.07	−10.96	−5.30	−0.49	5.40	11.42	16.85
−30	−29.12	−28.11	−27.13	−26.65	−26.74	−27.04	−27.98
	−16.43	−9.10	−5.46	−0.16	5.63	11.62	17.45

Table 3 Sirognathic Output Following Magnetic Movement (mm) in the Horizontal Plane (XY)

Movement		Left				Right	
15	−17.92	−16.08	−15.15	−15.36	−14.80	−14.23	−14.37
	−15.70	−11.48	−6.05	−0.65	5.54	10.08	15.28
10	−12.54	−11.00	−10.16	−10.00	−10.37	−9.54	−9.48
	−15.06	−11.70	−5.69	−0.65	5.60	10.01	14.82
5	−6.49	−5.73	−5.28	−4.92	−5.32	−4.49	−4.19
	−14.62	−10.47	−5.36	−0.19	5.33	10.28	14.82
X	−1.35	−0.30	−0.04	0.00	0.00	0.35	1.08
Y	−14.30	−10.16	−5.17	0.00	5.14	10.34	15.02
−5	4.66	5.12	4.96	5.06	5.25	5.51	5.38
	−13.64	−9.91	−4.61	0.04	5.42	10.60	15.38
−10	10.20	10.11	9.88	9.88	10.40	10.51	11.06
	−14.13	−10.04	−4.64	0.17	5.63	10.90	15.90
−15	15.60	15.03	14.60	14.51	14.83	14.50	15.98
	−14.39	−10.14	−4.48	0.33	5.51	11.23	16.52

Table 4 Tilting Effect of Magnet

	10° tilt		20° tilt	
	x (mm)	± SD	x (mm)	± SD
Tilting north pole (right)				
AP	0.27	±0.10	0.04	±0.05
Lateral	1.30	±0.33	1.50	±0.48
Vertical	0.80	±0.12	0.80	±0.13
Tilting south pole (left)				
AP	0.23	±0.01	0.15	±0.10
Lateral	0.38	±0.03	0.77	±0.34
Vertical	0.28	±0.10	0.90	±0.30
Tilting orientation in anterior direction				
AP	0.08	±0.02	0.26	±0.08
Lateral	0.06	±0.04	0.11	±0.06
Vertical	0.05	±0.02	0.17	±0.02
Tilting orientation in posterior direction				
AP	0.02	±0.01	0.12	±0.02
Lateral	0.07	±0.30	0.10	±0.05
Vertical	0.03	±0.01	0.07	±0.04

AP = Anterorposterior.

Tilting Effect of the Magnet in Relation to Its Long Axis and Orientation

Rotating the magnet about its long axis by 10 and 20 degrees did not seriously affect the output, nor did tilting its long axis by 10 and 20 degrees from its correct orientation. The worst effect was equivalent to 1.5 ± 0.48 mm, which occurred with the north (red) pole tilted 20 degrees from its correct axis (Table 4).

Clinical Reproducibility of Occlusal Border Movements

The general appearance of these border movements within the sessions showed relatively little variability in the frontal plane. However, on the left-hand side, standard deviations were increased as the mandible moved further from the intercuspal position (Fig 9). On this side, maximum variation occurred in the second recording session at 8 ± 0.41 mm of lateral movement. On the right-hand side, remarkably low variations were seen except in the middle portion of the curve. The highest variation was again in the second session but at 4 mm ± of lateral movement (Table 5). In the sagittal plane, the overall variation was quite low except for the first session at the 1-mm protrusive position (±0.55 mm) (Fig 9, Table 6). Higher variations were found in the second session during "wide gape" experiments (±2.60 mm) (Table 7).

Differences Between Sessions

Average differences between sessions were small in the frontal plane. Differences between the sessions were negligible for the left-hand side; the highest difference was 0.14 mm. For the right-hand side, the middle portion of the curve showed the highest differences (0.24 mm), and this subject concluded his border movement with a remarkable target point at the same point in both sessions and with no standard deviation. The overall average differences between the sessions were 0.08 mm for the left side and 0.12 mm for the right side (Fig 9, Table 5).

In the sagittal plane, differences between the experimental sessions increased with the distance from the intercuspal position (ICP). The highest difference was 0.62 mm at 6-mm anterior movement, and the overall mean difference was 0.31 mm. Wide gape exercises also showed negligible variability for a large movement; the average difference between sessions was only 0.85 mm (Fig 9, Table 7).

Effect of Cranial Movements (ECM) During Mastication Experiments

The success of cranial restraint is shown by the very small mean value of ECM for each experiment (±0.005 mm). Thus, it exhibits freedom from systematic bias; approximately 60% of the values were zero. Therefore, the range of the ECM has been analyzed for each experiment, by type of experiment and by subject.

All the subjects showed some cranial movement. For all experiments there were significant differences between the directions of head movement (Tables 8 and 9). The highest movement was seen in the lateral direction (0.99 mm) and the smallest was in the anteroposterior direction (0.62 mm). On average, the ECM was ≤ 1 mm movement during chewing or exercising (Table 8). Differences between chewing experiments and exercises were negligible, and no significant differences were found. Both highest and lowest ECM occurred in the anteroposterior direction (0.03 to 4.15 mm) (Table 8).

An analysis of the results of the ECM per experiment and per patient showed that, on average, the maximum cranial movement occurred in anteroposterior (0.81 mm) and vertical directions (0.96 mm) during wide opening. The highest lateral ECM was found during the chewing of sweets (1.3 mm) (Fig 10).

Some differences were noted when the directions of movement were compared within subjects.

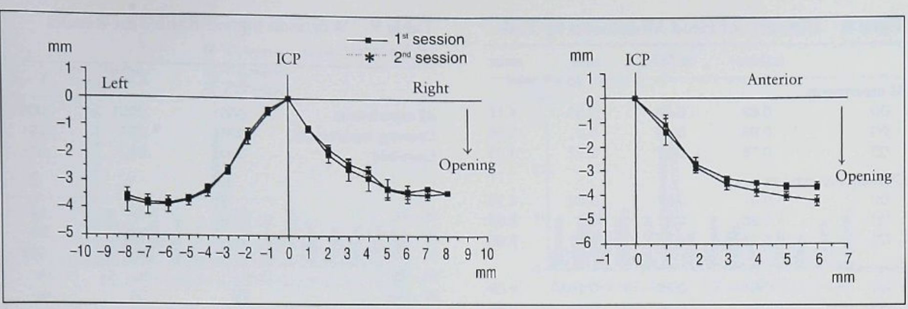


Fig 9 Reproducibility of the mandibular movements in frontal *(left)* and sagittal *(right)* planes. Vertical bars are ± SD (n = 5).

Table 5 Variations in Clinical Reproducibility of Occlusal Border Movements (mm) in the Frontal Plane

Intervals right, (–) left	1st (left) opening ± SD	2d (left) opening ± SD	1st (right) opening ± SD	2d (right) opening ± SD
1	–0.40 ± 0.00	–0.54 ± 0.09	–1.12 ± 0.11	–1.10 ± 0.10
2	–1.30 ± 0.17	–1.44 ± 0.22	–2.04 ± 0.27	–1.82 ± 0.13
3	–2.60 ± 0.14	–2.62 ± 0.16	–2.58 ± 0.40	–2.36 ± 0.17
4	–3.28 ± 0.11	–3.36 ± 0.21	–2.90 ± 0.42	–2.66 ± 0.20
5	–3.68 ± 0.11	–3.72 ± 0.18	–3.24 ± 0.34	–3.28 ± 0.39
6	–3.82 ± 0.13	–3.86 ± 0.29	–3.38 ± 0.25	–3.46 ± 0.32
7	–3.78 ± 0.11	–3.88 ± 0.36	–3.27 ± 0.05	–3.50 ± 0.18
8	–3.60 ± 0.14	–3.72 ± 0.41	–3.40 ± 0.00	–3.40 ± 0.00

Table 6 Clinical Reproducibility of Occlusal Border Movements (mm) in the Sagittal Plane

Intervals anterior	1st (opening) ± SD	2d (opening) ± SD
1	–1.40 ± 0.55	–1.10 ± 0.40
2	–2.70 ± 0.27	–2.84 ± 0.23
3	–3.32 ± 0.05	–3.54 ± 0.21
4	–3.50 ± 0.07	–3.80 ± 0.25
5	–3.62 ± 0.13	–4.02 ± 0.18
6	–3.60 ± 0.14	–4.22 ± 0.22

Table 7 Clinical Reproducibility of Occlusal Border Movements (mm) at Wide Gape

	1st experiment	2d experiment
Z	–38.10 ± 0.96	–37.25 ± 2.60
Y	–1.90 ± 0.60	–1.00 ± 0.43
X	–3.60 ± 0.80	–2.40 ± 0.73

Higher average ranges were found with lateral movements than with vertical movements for 12 of the 14 subjects during chewing and 11 of the 14 subjects during exercising. One subject showed exceptionally high ECM, from 1.47 to 2.77 mm, while other subjects showed approximately 1 mm or less (Fig 11). Wilcoxon signed-rank tests revealed the direction of ECM between test foods (Table 9). The results show that cranial movement appears to be highly significantly different in the lateral direction (Y), but all these differences disappeared in the anteroposterior direction (X) between test foods.

Discussion

Sensitivity

Both the manufacturer's specification and a recent report[8] stated the sensitivity of the Sirognatho-

Table 8 Direction of Head Movements by Task

	x (mm)	± SD	min	max
All experiments				
(X)	0.62	0.69	0.03	4.15
(Y)	0.99	0.44	0.3	3.56
(Z)	0.76	0.57	0.12	4.33
Chewing experiments				
(X)	0.6	0.67	0.03	4.15
(Y)	0.98	0.47	0.3	3.56
(Z)	0.71	0.48	0.12	2.96
Exercises				
(X)	0.64	0.75	0.11	4.05
(Y)	1.0	0.39	0.3	1.85
(Z)	0.85	0.74	0.28	4.33
Biscuits (BI)				
(X)	0.78	1.0	0.06	4.15
(Y)	1.07	0.29	0.72	1.66
(Z)	0.9	0.7	0.44	2.96
Sweet (SW)				
(X)	0.66	0.77	0.08	3.22
(Y)	1.3	0.73	0.36	3.56
(Z)	0.71	0.49	0.38	2.34
Almonds (AL)				
(X)	0.52	0.4	0.2	1.82
(Y)	0.84	0.21	0.36	1.18
(Z)	0.64	0.29	0.12	1.42
Chewing gum (CG)				
(X)	0.44	0.29	0.03	1.29
(Y)	0.71	0.16	0.46	1.06
(Z)	0.59	0.29	0.24	1.33
Border movement (BM)				
(X)	0.47	0.26	0.13	1.19
(Y)	0.82	0.36	0.3	1.51
(Z)	0.74	0.29	0.28	1.32
Wide opening (OP)				
(X)	0.81	1.02	0.11	4.05
(Y)	1.17	0.35	0.48	1.83
(Z)	0.96	0.99	0.36	4.33

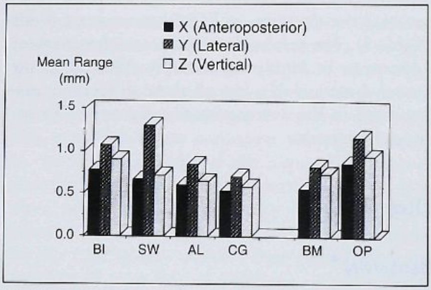


Fig 10 Mean range of cranial movements per food and exercise.

Table 9 Wilcoxon Signed-Rank Test Results (P Values)*

	X - Y	X - Z	Y - Z
All experiments	.0001	.0001	.0001
Chewing experiments	.0001	.003	.001
Exercises	.0003	.002	.03
	X	Y	Z
BI - AL	ns	.007	.04
BI - CG	.03	.0006	.01
BI - SW	ns	ns	.005
BI - OP	ns	ns	ns
BI - BM	.03	.04	ns
AL - CG	ns	.03	ns
AL - SW	ns	.02	ns
AL - OP	ns	.004	ns
AL - BM	ns	ns	ns
CG - SW	ns	.0009	.03
CG - OP	ns	.0008	.03
CG - BM	ns	.05	.02
SW - OP	ns	ns	ns
SW - BM	ns	ns	ns
OP - BM	ns	ns	ns

*P < each value; ns = nonsignificant.

graph to be 1 V/10 mm movement. In this study, 10 mm of movement was found to be equivalent to 0.75 V. Repeated calibrations established that this sensitivity is stable, but it underlines the importance of routine calibration of equipment.

There is an amplitude reduction in the Sirognathograph's output (6.3%) during dynamic recordings due to the output-smoothing "capacitance effect." This could be corrected by software if the movement per interval is critical.

The frequency of normal mastication has been shown to be between 0.7 and 1.2 Hz.[18] This frequency can be followed by the Sirognathograph with minimum distortion.

Linearity

The nonlinearity found in the present study is greater than that reported by three previous studies,[6-8] but it is impossible to consider the source of this difference with the other reports, as they do not include absolute values from the measurements (the data are given in graphs). The 5.9% average distortion found in the present study is close to the value of 6.4% shown in the data presented by Maruyama et al.[9] This later report covered a radius of 15 mm. This relatively high distortion would be important for studies measuring larger distances such as maximum mandibular movements.

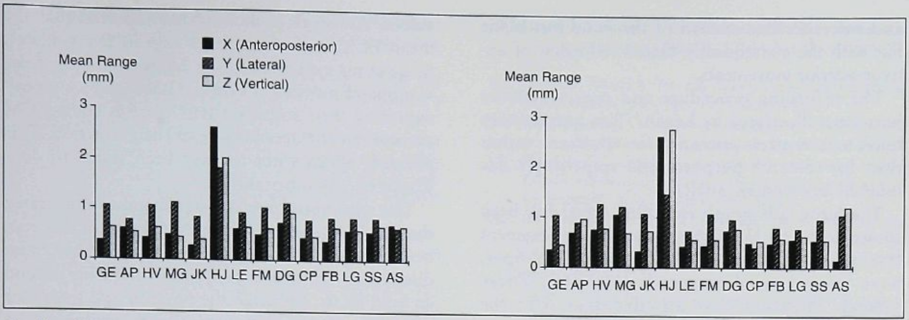


Fig 11 Mean range of the cranial movements per patient during test food mastication *(left)* and wide open and border movement exercise *(right)*.

Because of the severe distortion in the output from a similar system, the Kinesiograph, computer linearization programs have been written.[2-4] The studies that validated the Sirognathograph by mapping magnet movement at 5-mm intervals in all three planes concluded that corrections are not necessary for the Sirognathograph.[7,9] The present study confirms their findings for the central area of most common clinical importance.

Positioning of the Magnet

Due to the finding that the errors increase exponentially beyond 20 mm from a central position, the magnet should be carefully centered. The field error from the magnet being off center by 5 mm means that a further 20-mm movement (25 mm from the center) could increase the existing nonlinearity to approximately 4%. The success of computer linearizing programs for the Kinesiograph also depends upon the magnet being placed in the center of the aerial. Tolerance of the magnet/aerial relationships is claimed to be acceptable up to 5 mm from the center, but no data are reported.[2,3]

Because the initial magnet position will locate the central zone of linearity, it is important to mount the aerial in a way that achieves a central position of the magnet for the area of most interest—usually near the occlusal plane. If large vertical movements are to be recorded accurately there may be an advantage in trading the closest accuracy near the occlusal plane for improved accuracy with wider gapes by positioning the center of the aerial some millimeters below the magnet, as suggested by Maruyama et al.[9]

Clinical Reproducibility of the Sirognathograph

The central concern in the analysis of repeatability of mandibular movement is the additive basis of variance. There are always two principle sources of variance, from the mechanics of the equipment and from biologic sources. The net variance is derived from combining the two.

Although it appears that within- and between-session variability is acceptable, within-session analyses showed that variation does occur even for simple movements. Low standard deviations are seen on the left-hand side up to 5 mm and the first millimeter of right deviation. It thus appears that the mechanical errors are below 0.2 mm. It is possible that the higher variation derives from variable cuspal contact that seems to be occurring at the wider left lateral movement and between 2 and 7 mm right lateral deviation with canine guidance, where intercuspal relationships were less restricted by defined interdigitation.

As illustrated in Fig 9, the remarkable congruity of the 8-mm right lateral excursion is intriguing. It appeared that this subject has a definite "target" end position to this movement. This may be due to mechanical constraints within the stomatognathic system.

Reproducibility was not as high within the sagittal plane as it was in the frontal plane, but the highest difference between the experiments was only 0.62 mm. The Frankfort plane has been suggested as the reference plane for the aerial's side arms.[5] It appears that despite the care taken, it was not possible to define this reference line precisely enough to preclude errors in repositioning the aerial. In some earlier experiments, the Camper line was used as a reference line instead of the Frankfort plane but with the consequently biased reduction of anteroposterior movements.

The recording procedure and possible errors have been illustrated by Lewin.[5] This introductory book was written primarily for clinicians rather than for research purposes and surprisingly has omitted any numeric analysis.

The Sirognathograph recording speed has been shown to be 50 Hz. Other mandibular movement tracking devices, the Kinesiograph and Sel Spot, have faster recording speeds (100 Hz). These systems therefore have an advantage over the Sirognathograph.

Cranial Movements

Although some studies have mentioned the importance of giving instruction to restrict cranial movement, no satisfactory evaluation has been published. In one study, various methods have been described for stabilizing cranial movements during mastication.[19] However, these methods were not practical for the present study, because they employed metal in their construction or were customized for each patient. A cephalostat has been suggested as a means of stabilizing the subject's head.[5] This gives lateral and anteroposterior support and appears to depend on having a neck rest. The success of that system was not validated. Two studies also stated the problem of ECM, but in both the authors only asked the subjects to restrict movements consciously.[8,9]

Although Michler et al[7] achieved high reproducibility on bench tests, they failed to achieve reproducibility during normal mastication and speech, possibly because of cranial movement. It appears from their experimental protocol that they stabilized the subject's cranium with hand support, which was apparently satisfactory for slow opening and closing movements. It is not clear whether cranial movement was eliminated during normal mastication and speech. In the present study, head movement artifacts during mastication were effectively reduced. However, one subject exhibited exceptionally high ECM during mastication of all foods and exercises (subject HJ; Fig 11). This indicates that the headband was probably not tightened sufficiently for this subject during the experiments. A similar observation has been reported elsewhere.[15]

A similar system, the Kinesiograph, has a transducer on top of the frame for recording cranial movement. The main unit subtracts the cranial movement values from the mandibular movement values. Although Jankelson[3] has reported that the mean ECM is less than ±0.1 mm in five subjects, he gives no indication of the range or standard deviations of movement errors. Gibbs and Lundeen[20] expressed their suspicion that there is some ECM on movement traces in spite of the correction. This problem appears not to have been stated or confirmed by any other author.

This preliminary use of a headband demonstrated that the ECM can be effectively reduced. It can even be eliminated, but the necessary pressure may cause discomfort for long experiments extending beyond an hour or so. Although the physical and voluntary restriction of cranial movement will inevitably have some effects on the masticatory process, none of the subjects expressed difficulty or discomfort in completing the experiment.

Conclusion

This study shows that the mandibular movement recording system, the Sirognathograph, is a valuable tool provided that the user is aware of the limitations and errors of this device.

The sensitivity of each Sirognathograph system needs prior calibration by the user. The Sirognathograph is adequately linear (5.9%) within the range ±15 mm in three planes, which is acceptable for many clinical applications. Data must be sampled asynchronously to avoid pulse artifacts. Care must be taken to establish the correct aerial and magnet positions and, particularly, the orientation of the aerial to the Frankfort plane. Cranial stabilization is necessary for accurate recording of mandibular movements with the Sirognathograph, and satisfactory cranial stability can be achieved with a combination of a padded headband and voluntary limitation of cranial movement.

Acknowledgments

The authors would like to thank Drs P. L'Estrange and M.P. Hector for their constructive criticisms. Dr Kazazoglu has been supported by a Turkish Ministry of Education grant during this study.

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Resumen

Limitaciones clínicas y técnicas del sistema Sirognatógrafo para la grabación de los movimientos mandibulares

Generalmente el equipo electrónico clínico es vendido como un sistema desconocido (black box) sin especificar los diferentes artefactos. Este estudio examinó las limitaciones clínicas y técnicas del Sirognatógrafo, el cual es un dispositivo utilizado para grabar los movimientos mandibulares. Descle el punto de vista técnico, se considera que la limitación mas importante del Sirognatógrafo es que cuando toma las muestras lo hace a baja velocidad, además la muestra presenta artefactos. En esta investigación fué posible eliminar los artefactos de la muestra por medio del uso de un generador pulsátil fabricado según especificaciones y de software para la adquisición de la información de una manera controlada. Clínicamente el Sirognatógrafo parece tener algunas limitaciones inherentes en cuanto a su precisión. El efecto de los movimientos craneales durante la masticación puede causar una desviación basal que puede ocasionar errores consecuentemente, en la grabación de la posición mandibular. En el estudio este problema fué controlado por medio de una banda colocada en la cabeza para estabilizar los movimientos craneales durante la masticación. También, se determinó que las relaciones espaciales entre la antena y tanto la base craneal como el imán fueron críticas para la repetición de las grabaciones.

Zusammenfassung

Technische und klinische Grenzen des Sirognathographen zur Aufzeichung der Unterkieferbewegungen

Klinische elektronische Geräte werden üblicherweise als "black box" verkauft, d.h. ohne die Spezifikation von Fehlern. Diese Studie überprüfte die technischen und klinischen Grenzen des Sirognathographen; eines Gerätes zur Aufzeichung der Unterkieferbewegungen. Vom technischen Standpunkt aus gesehen sind die niedrige Abtastrate und die dabei auftretenden Fehler als limitierend zu bezeichnen. Die Abtastfehler konnten durch den Gebrauch eines speziellen Pulsgenerators und spezieller Software für eine kontrollierte Datenerfassung eliminiert werden. Klinisch scheint der Sirognathograph eine Grenze in seiner Genauigkeit zu haben. Die Kopfbewegungen während des Kauens können Grundlinienabweichungen ergeben, die Fehler in der Aufzeichung der Unterkieferposition verursachen. Dieses Problem wurde in der Studie gelöst, indem der Kopf während des Kauens mittels Stirnbandes fixiert wurde. Auch die räumliche Beziehung zwischen der Antenne und der knöchernen Schädelbasis einerseits, dem Magneten andererseits, schien die Reproduzierbarkeit der Aufzeichnungen einzuschränken.