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A VERSATILE RECORDING SYSTEM FOR STUDIES OF MASTICATION*†

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Abstract—A versatile instrumentation system for research on the physiology of mastication is described. Tooth contact signals from miniature radio transmitters in dental bridgework are combined with electromyographic data from the muscles of mastication. Flexibility in signal processing utilizing a multi-channel FM tape recorder is emphasized to accommodate the needs of varying research programs.

1. INTRODUCTION

RECENT studies utilizing this system have already contributed to a better understanding of the physiological processes of mastication (POWELL, 1963 and ADAMS and ZANDER, 1964). Of particular interest have been determinations of the time duration of contacts between specific areas of opposing teeth (not only during mastication but in sleep as well) and the temporal relations of these contacts to the electromyographic waveforms of the associated muscles. To conduct studies of such a wide variety unique instrumentation was needed. Flexibility was to be the most prominent feature of the system in order to accommodate the variations and constantly changing research directions required by emerging data. Research budgets are not flexible enough to constantly tear down and renew instrument systems. The systems to be described in this paper were conceived to fulfil the above demands and to meet the technical specifications for adequately recording and displaying the various signals. In order to keep costs at a minimum, the components were of commercial manufacture as far as possible, with custom fabrication only for those items required to integrate the major units and to provide the desired versatility.

The instrumentation accomplishes the recording, playback, and display of tooth contacts via miniature radio transmitters in the teeth along with six channels of electromyography and the necessary event marker and timing reference marks.

Tooth contact information from the radio transmitter is detected by a receiver and after processing in an audio discriminator is injected into the overall recording system as one of the eight active channels. Preamplifiers for the six electromyographic channels are incorporated in the eight-channel paper recorder, from which signals are extracted and tape-recorded for playback and analysis at a later time. On playback the signals can be either displayed on the paper recorder or subjected to any other electronic processing desired. The eighth channel is assigned to timing and event-marker signals.

2. THE TOOTH CONTACT CHANNEL

The tooth contact data are needed to provide precise information as to the occurrence and duration of tooth contacts. To generate this information, a miniature transmitter is packaged in a dental bridge fabricated of acrylic to replace a missing tooth. On completion of the bridge, with its enclosed radio transmitter, it is cemented

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in place on the abutment teeth. It is switched on and off by the contact of the teeth: two electrodes brought to the surface of the bridge are connected at the moment of tooth contact by a small gold inlay in the crown of the opposing tooth. Figure 1 shows a completed transmitter *in situ*.

The transmitter itself uses a single transistor in a "squegging" oscillator circuit (see Fig. 2) which generates a carrier frequency of about 2 Mc/s while simultaneously switching itself on and off at an audio rate (see Fig. 3). The carrier frequency is determined by L1 and C2, while the interval between the bursts of carrier is con-

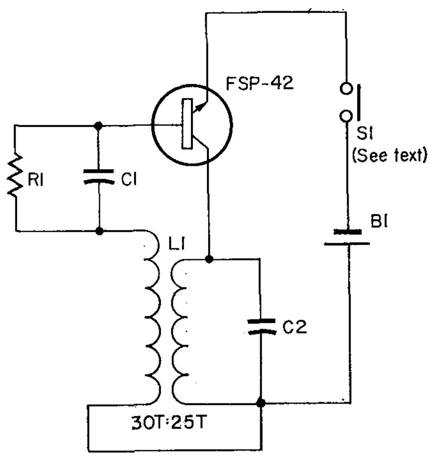

FIG. 2. Circuit of tooth transmitter. B1—1·4V mercury cell; C1—0·01 μF; C2—500 pF; L1—tank coil, approximately ¼ in. dia., two superimposed close-spaced windings # 40 AWG copper wire (enameled); R1—typically at 220 KΩ.

trolled by R1 and C1. Ultraminiature components are used to make the small finished product possible. The Fairchild transistor has no case, but is epoxy sealed to a molybdenum chip about 0·05 in. square. The battery is a hearing aid type 1·4 V mercury cell and will power the transmitter for over an hour of actual operation.

Because of the pulsing nature of the transmitted signal, it occupies a very wide spectrum—much wider, in fact, than the changes in carrier frequency which are caused by the motion of conductive tissues (e.g., the tongue) near the transmitter. Therefore, critical tuning of the receiver is not required, and an inexpensive two-band portable transistor radio has proven entirely adequate to receive these signals. Because the radiated power from the transmitter is extremely small, it is necessary to place the receiver within two or three feet of the patient to ensure reliable pickup. The patient and the receiver are inside a shielded room, so interference from local broadcast stations is not a problem.

Because of the audio frequency pulsations of the transmitter, the receiver output signal consists of an audio pulse train. An Audio Discriminator (RF Communications, Model AD-100) is used to sense these pulses and provide a d.c. output for the duration of the contact. The discriminator consists basically of four stages: a pulse shaper, a univibrator, a timing capacitor with its charging and discharging circuits, and a detector-amplifier (Fig. 4). The shaping circuit amplifies, differentiates, and limits the incoming signal and triggers the univibrator stage to produce a positive- and negative-going pair of pulses of known, constant duration and amplitude, in contrast to the amorphous pulses from the receiver which vary in amplitude and duration. In the timing stage, these two known pulses control the charging of a capacitor such that constant-current charging occurs during the "off" cycle with a rapid discharge taking place during the "on" time. The voltage across the capacitor, therefore, is a sawtooth whose amplitude varies with the period (inversely with the frequency) of the incoming pulse train. A d.c. voltage equal in amplitude to that of the sawtooth is generated by the peak detector and amplifier connected to the timing capacitor. This d.c. voltage is the output of the discriminator; its presence at other than its rest value is an indication of a signal at the input and, therefore, is an indication of a tooth contact. It will be noted that the d.c. output level will vary as a function of the audio frequency being received; this makes possible the identification of more than one transmitter, a feature presently being exploited in this laboratory (SCHÄRER and STALLARD, 1965).

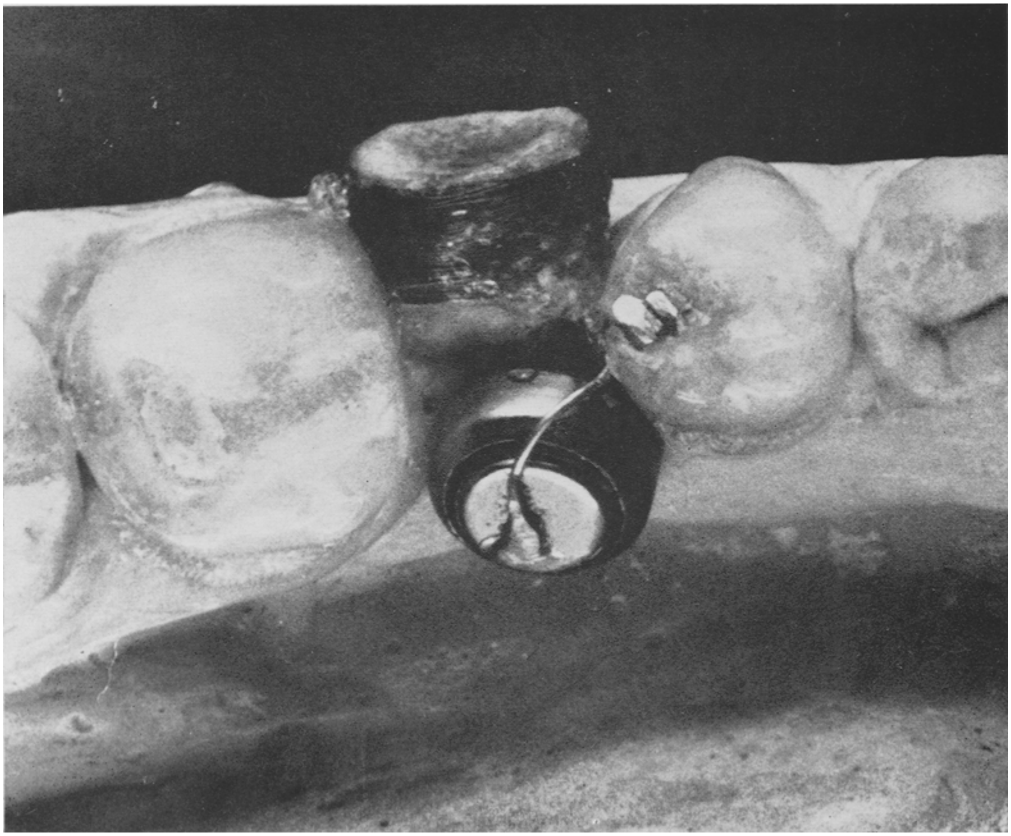

FIG. 1. Partially assembled tooth transmitter showing coil and battery prior to encapsulation in acrylic. The two contacts are visible in the crown of the adjacent tooth.

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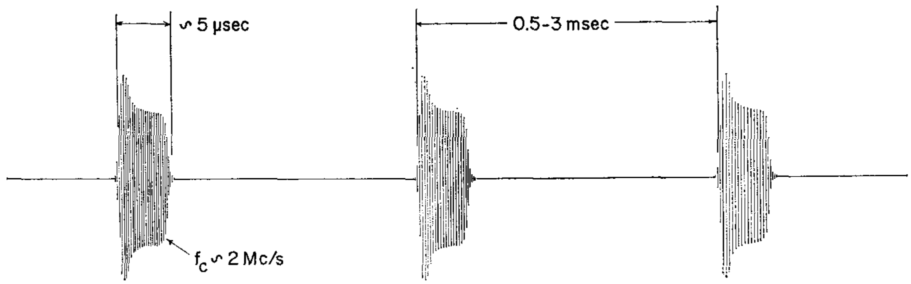

FIG. 3. Waveform of tooth transmitter. Pulse interval depends on choice of time constant of resistor and capacitor in base circuit of transistor.

The injection of this channel of information into the remainder of the system is described later.

3. THE ELECTROMYOGRAPHY CHANNELS

It was recognized from the outset that conventional systems employing moving film cameras, pen recorders and the like as the sole recording medium, would be inadequate to permit full information to be recovered from the patients. Instead, recordings have been made on an FM tape recorder with subsequent playback for display on a paper recorder at the convenience of the researcher.

Electromyographic (EMG) signals from the patient are fed first to the sensitive preamplifiers of an eight channel strip-chart recorder. These signals can then be directly recorded on the paper, or routed (after further amplification) to the FM tape recorder for permanent "live" storage on magnetic tape. On tape playback the signals are once again fed to the strip-chart recorder, but because of the variety of playback speeds available the data can be displayed either faster or slower than real time, permitting both detailed analysis and search for gross effects, according to the needs of the study at hand. Calibration of the EMG channels is accomplished by the monitor console, which also provides for generation of timing pulses and multi-level event markers, as well as switching of the monitor oscilloscope to any signals in the system. A block diagram of the completed system is presented in Fig. 5.

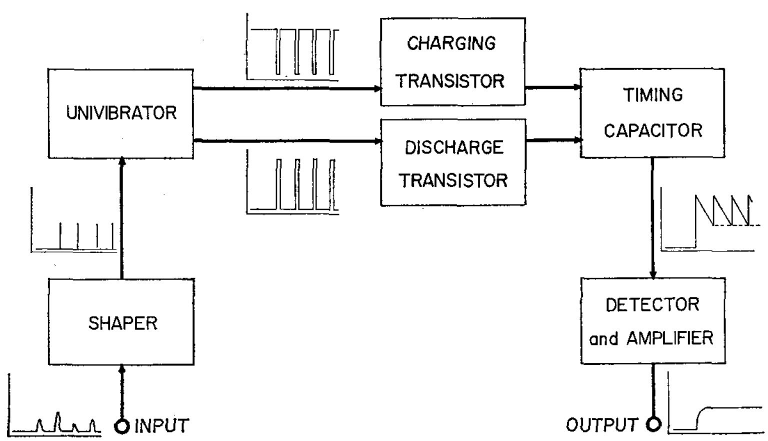

FIG. 4. Audio discriminator block diagram.

The patient sits in a shielded room to prevent pickup of extraneous signals on either the highly sensitive EMG circuits or on the radio receiver which monitors the tooth transmitter. The shielded room is constructed of tightly abutting panels of galvanized iron screening for maximum low frequency attenuation, with a door of similar construction rimmed by a continuous row of spring contacts to ensure complete shielding integrity.

The electrodes which pick up the electromyographic impulses from the skin are connected via shielded cables to a plug panel on the inside wall of the shielded room to permit any desired distribution of signals among the various channels of the recording system. The signals are routed through a multicontact connector and cable to the monitor console where calibrating voltages can be inserted, and thence to the preamplifiers in the pen recorder. The exterior connector is mounted in a heavy brass panel soldered on all four sides to the screening. All major units of the system are grounded to this panel, which is in turn earthed through a heavy cable to a nearby ground rod.

Each electrode circuit consists of a pair of wires to the preamplifier input. Each circuit is shielded separately throughout its entire length, with no contact permitted either between adjacent shields or to any other ground points except directly at the preamplifier inputs; thus each shield is carried through the exterior connector and in and out of the calibrator on a separate contact. The shields are not grounded inside the screen room. The only ground connection between the screen room and the pen recorder is the heavy lead installed between the ground plate on the screen room and the amplifier chassis. This extreme care is taken to avoid breaching the shielding of the screen room by setting up "ground loops"—paths where circulating currents can be induced from nearby power lines resulting in 60 c/s interference. That the shielding incorporated in the system is adequate is indicated by the fact that typical interference (power line plus random noise) does not exceed 10 μV peak–to–peak referred to the input when the skin electrodes are replaced by a 5000 Ω resistor; this is considerably lower than the signals to be recorded.

The Offner Dynograph Type R eight-channel recorder was chosen to accomplish both the preamplification of the EMG signals and the paper write-out. Of particular importance in this instrument are its low noise level (2 μV pp max referred to shorted input), very low drift (the circuitry is exclusively solid-state), versatility in recording speeds (1–250 mm/sec in seven steps), and the availability of post-amplifiers to boost the preamplifier output sufficiently to drive the tape recorder. The standard connection between the preamplifiers and the pen driver amplifiers is maintained to permit direct paper readout should this be desired, although we generally use paper read-out only on playback from the tape recorder. (The connection used during tape playback is shown in Fig. 5). The pre- and post-amplifiers exhibit a flat response between 10 and 3000 c/s, which is adequate for EMG recording, while the d.c. to 200 c/s response of the pens and their drivers accommodates the tooth contact and event marker signals which do not require preamplification. The preamplifiers are equipped with integrators which can be switched in if desired in the analysis of total muscle activity. To avoid spattering ink when recording high frequency signals, yet still retain maximum frequency response, an electric-arc writing version of the recorder was specified.

The tape recorder, a Honeywell LAR-7400, is equipped for eight channel operation with provision for expansion to fourteen channels. Because the input signals frequency-modulate individual channel carrier oscillators which in turn are recorded on the tape (rather than feeding the original signals directly to the recording head), a response to d.c. is made possible. This capability is necessary for two reasons: the tooth contact and event marker waveforms have d.c. components which must be preserved, and the low frequency components of the EMG signals would, on slow playback, be reproduced at frequencies below the capabilities of a conventional recorder. The upper frequency

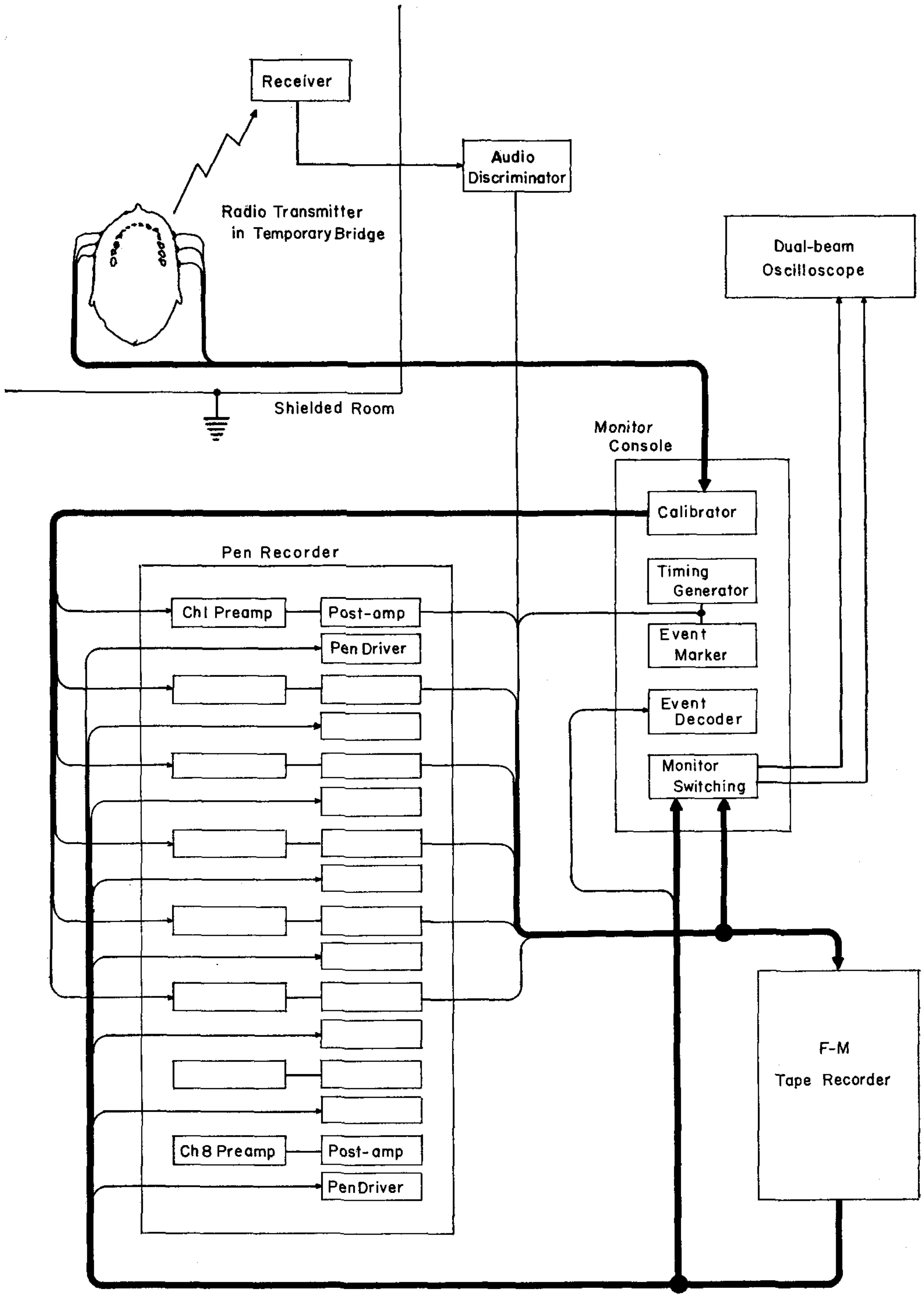

FIG. 5. Block diagram of entire recording system.

limit varies with tape speed to a maximum of 20 kc/s. Six tape speeds from $1\frac{7}{8}$ in/sec to 60 in/sec are available, permitting up to a 32:1 compression or expansion of data depending on the information sought.

The tape recorder is, in a sense, the heart of our system. Data recorded from a patient (e.g., during a sleep study) can be played back time after time for observation on an oscilloscope, making chart recordings, or any other analyses which may be desired. The advantage here lies in the fact that the tape recorder, in putting out the data in electrical form, actually substitutes for the patient in producing "live" data, and in being able to reproduce that data identically time after time as often as required by the research project.

4. THE MONITOR CONSOLE

The Monitor Console, custom designed by RF Communications, Inc.*, provides numerous ancillary functions which contribute greatly to the utility and versatility of the system. A simplified schematic diagram of the console is presented in Fig. 6. The calibrator section (Fig. 6a) permits injection of known voltages into the preamplifiers for gain checks. The multi-pole 3-position switch (S1) normally is set to connect the EMG electrodes to the pre-amplifiers; in the "connect patient" position, the preamps are shorted to prevent damage to either the pens or the preamps themselves, while in "calibrate" a common calibrating voltage is applied to all channels simultaneously. Calibrating voltages are available in seven steps from 10 μV to 10 mV peak-to-peak, 60 c/s. Very complete shielding is provided to prevent noise or hum pickup while recording.

A timing generator and multi-level event marker are combined in a single unit (Fig. 6b). A synchronous motor and chopper disc permit a burst of light to fall once per second on a photo-conductive cell which, in turn, activates a transistor amplifier. The resulting voltage spikes are superimposed on a d.c. pedestal whose amplitude is varied in five levels by the event marker push buttons; that is, pushing a given button produces a particular change in the d.c. level. These steps are readily recognizable on the paper recording. The event decoder (Fig. 6c) senses these changes (during tape playback) with five voltage comparator circuits which operate their associated relays when the input voltage exceeds their preset trigger levels. Numbered indicator lamps operated through the relay contacts provide a visual readout of the event marks independent of the paper recorder. The relays are required to insure that only one lamp lights at a time.

Switches are incorporated in the monitor console to connect a dual beam oscilloscope (Tektronix 502) to the tape recorder inputs or outputs, displaying any of the eight channels on either beam of the oscilloscope. This permits instantaneous monitoring by the researcher of all signals during both recording and playback.

5. DISCUSSION

Fundamental to the successful operation of the EMG portions of the system for the research at hand is the discrimination of signals from specific areas on individual muscles. Essential to this is the use of a differential input circuit, whereby the signal is detected between a pair of electrodes at the site of interest. This is not possible with a conventional single-ended electrode configuration in which one electrode is located over the muscle and the circuit returned to a neutral (or indifferent or ground) electrode at a location unrelated to the activity being investigated, since in this configuration signals will be detected from all the muscles in the area between the two electrodes, resulting in an indication of overall activity rather than the selective activity of the one site. With a truly differential input circuit (featuring a high common-mode rejection) a given channel accepts only those signals generated between its two electrodes while rejecting activity from other areas. It is necessary only that the electrodes and

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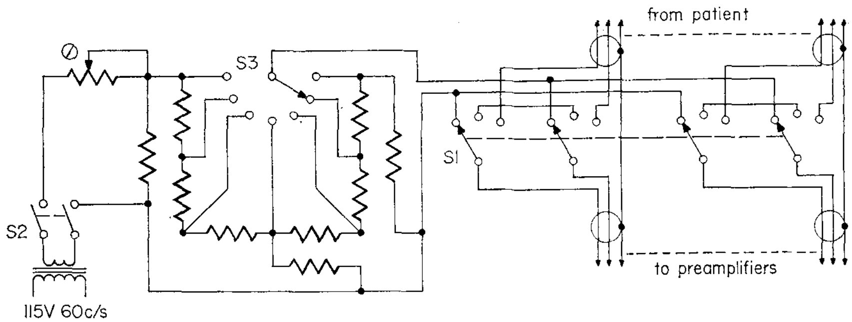

FIG. 6(a).

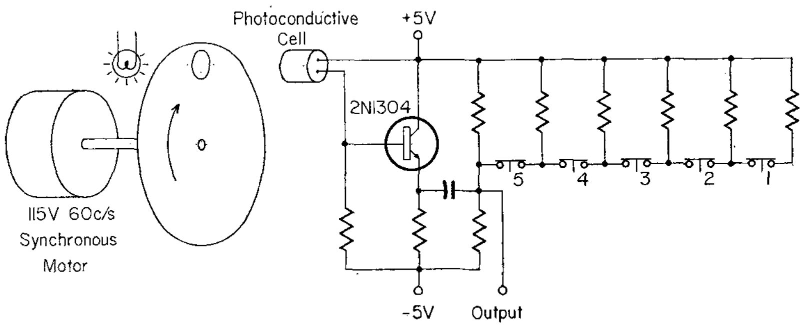

FIG. 6(b).

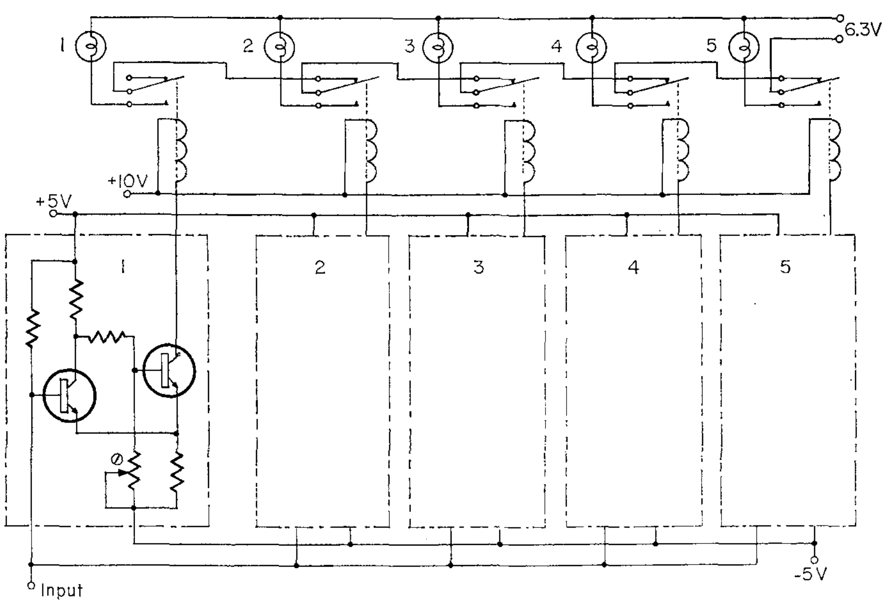

FIG. 6(c).

FIG. 6. Elementary diagram of monitor console: (a) EMG calibrator (two channels shown), S1—function selector switch, S2—push-to-calibrate button, S3—voltage selector; (b) event marker and timing generator; and (c) event decoder and lamps—the five voltage comparator circuits are identical.

input circuits be differential; once interfering common-mode signals are rejected the signals can be handled in the conventional single-ended manner (with one side of the circuit at ground); this is done in our system, where single-ended circuitry is used from the post-amplifiers onward.

It has been shown how the EMG signals are channelled from the patient to the tape recorder to the paper read-out. The tooth contact signals and the event marker/timing waveforms are handled in the same manner, except that, since no preamplification is required, these two channels are fed directly to the tape recorder inputs. Should a direct read-out be desired rather than tape recording, a simple interchanging of plugs on the front of the tape recorder applies the timing and tooth contact channels directly to the paper recorder, thus maintaining full versatility.

An example of the recordings obtained with this system is presented in Fig. 7. The first six channels show the electrical activity of three pairs of muscles during jaw closure. The tooth contact on channel seven will be seen to occur near the end of the closing activity. Timing pulses at one-second intervals are evident in channel 8, along with an event-marker step.

The flexibility of the instrumentation which has been described above can be appreciated by considering some of the research which has been performed with the aid of this equipment. Powell (1963) has made sleep studies of tooth contacts and electromyographic activity which involved several hours of night-time recording with each subject. Tape recordings were made at a speed of $1\frac{7}{8}$ in/sec. With playback at 15 in/sec and a paper speed of 1 mm/sec, seven-hour studies were displayed in less than an hour's time on about 10 ft of paper to provide an overall picture of the night's activity. Because of the permanent "live" storage of the data on tape, however, it was then possible to reproduce those areas of particular interest at $1\frac{7}{8}$ in/sec tape speed, that is, reverting to real-time display; paper speeds up to 25 mm/sec were used during the detailed analysis to obtain the desired resolution. It is apparent that without the tape facility, the evening's recording would have had to be recorded in its entirety at a paper speed of 25 mm/sec to obtain the same resolution, resulting in a consumption of approximately 2100 ft of paper. The savings both in terms of paper and in terms of fatigue on the part of the researchers should be obvious.

Adams and Zander (1964), investigating certain characteristics of the occlusal contacts between teeth in mastication, recorded at 30 in/sec. The number of masticatory cycles and tooth contacts were determined from playback at 15 in./sec (tape) and 10 mm/sec (paper), resulting in a display at the rate of 2 cm/sec of real (recorded) time. Subsequently individual tooth contacts were played back at $1\frac{7}{8}$ in./sec and 25 mm/sec for a 20:1 expansion (8:1 on the tape and 2·5:1 on paper, resulting in 40 m/sec, real time); the duration of tooth contacts was determined from these tracings (Fig. 7).

It will be noted that by this last technique, that of slowing the tape for playback, detailed recordings of EMG activity may be obtained on a mechanical pen recorder of limited frequency response. Recording at 30 and reproducing at $1\frac{7}{8}$ in./sec results in a 16:1 reduction of all frequency components in the recorded signal. (Frequency is inversely proportional to time, and the time between successive events is increased by slowing the tape.) Thus, frequencies of 3000 c/s in the original are reproduced at 188 c/s, which is within the 0–200 c/s frequency response of our pens.

By moving the contact points of the tooth transmitter to a succession of locations on the occlusal surface, position-time studies of contacts have been made (Adams and Zander, 1964). The onset of tooth contact was related to the associated bursts of muscle activity recorded for each contact site on the EMG channels, permitting a determination of the time sequence of contacts at these locations.

Other possible uses of this system of telemetry would be to study pH changes in the saliva. Future investigations could also involve modification of the transmitter circuitry to allow

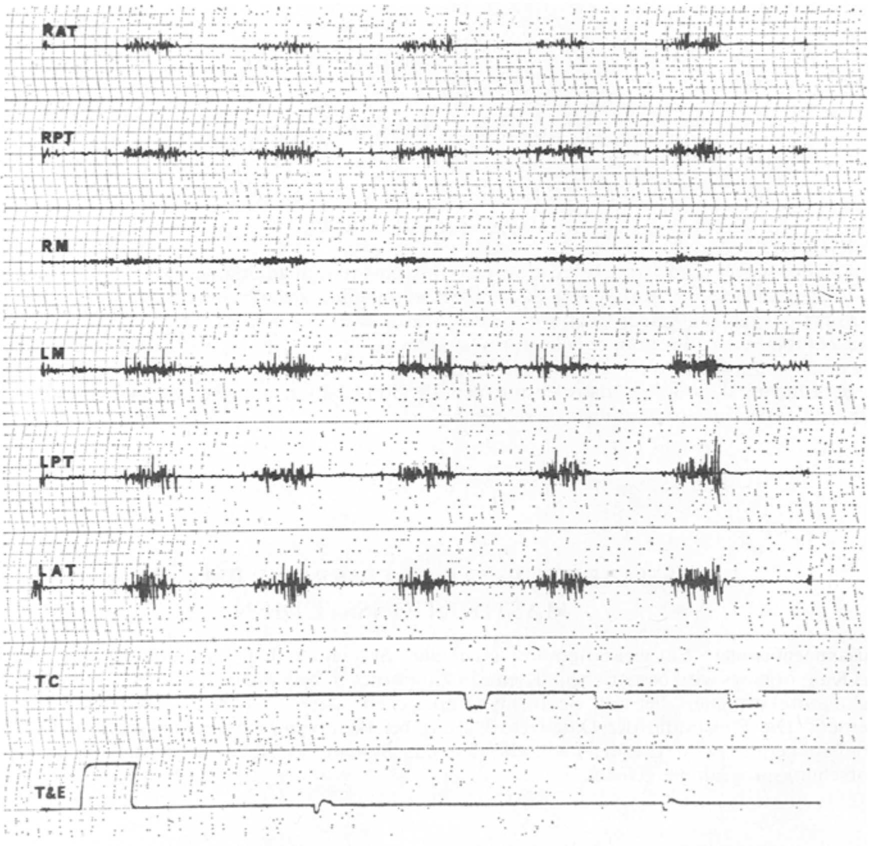

FIG. 7. Example of paper writeout, showing time relations of tooth contact to six channels of electromyography. Channels 1—6, electromyography; (RAT—right anterior temporal muscle, RPT—right posterior temporal muscle, RM—right masseter muscle, LM—left masseter muscle, LPT—left posterior temporal muscle, LAT—left anterior temporal muscle); Channel 7, tooth contact (TC); Channel 8, one second time pulses and event marker step (T & E).

telemetry of pressure transducers to study the forces exerted by the lips and tongue on the teeth and the forces exerted by teeth upon teeth during mastication. We have looked into such alterations but have not as yet succeeded due to the problems of temperature instability of strain gauges.

REFERENCES

ADAMS, S. H. and ZANDER, H. A. (1964) Functional tooth contacts in lateral and in centric occlusion. *J. Amer. dent. Ass.* **69**, 465–473.

POWELL, R. N. (1963) *Tooth Contact* during *Sleep*. Thesis, University of Rochester, Rochester, N.Y., U.S.A.

SCHÄRER, P. and STALLARD, R. E. (1965) The use of multiple radio transmitters in studies of tooth contact patterns. *Periodontology.* **5**, 5–9.

UN SYSTEME D'ENREGISTREMENT POUR L'ETUDE DE LA MASTICATION

Sommaire—Cette étude traite d'un système d'instrumentation adaptable aux différents aspects de la recherche sur la physiologie de la mastication. Des signaux du contact dentaire sont transmis par des miniscules radiotransmetteurs fixés dans des bridges dentaires. Ces signaux sont combinés avec les données électromyographiques transmises à partir des muscles masticateurs. L'utilisation d'un enregistreur à modulation de fréquence et à canaux multiples exige beaucoup de souplesse dans le traitement de l'information en vue d'une meilleure adaptation à la variété des programmes de recherche.

EIN VIELSEITIGES REGISTRIERSYSTEM FÜR MASTIKATIONSSTUDIEN

Zusammenfassung—Ein vielseitiges instrumentelles System zur Untersuchung der Physiologie des Kauvorgangs wird beschrieben. Kleine in Zahnbrücken befindliche Radiosender übertragen Zahnkontaktsignale, die mit elektromyographischen Daten der Kaumuskeln kombiniert werden. Die Flexibilität der Datenverarbeitung bei Benutzung eines mehrkanaligen F.M.—Tonbandgerätes wird betont; dadurch wird das System den Erfordernissen verschiedener Forschungsprogramme gerecht.