EVALUATION OF ELECTROCARDIOGRAPH MACHINES

LAURENCE W. PILLER, *Principal Technician, Cardiac Clinic, Groote Schuur Hospital, Cape Town*

It is possible that there are more than 100 manufacturers of electrocardiographic apparatus in the world today and the physician wishing to purchase such an instrument for use in his general practice, hospital or specialized cardiac laboratory is often bewildered at the vast array of equipment available. He is often guided by a physician friend who has had, for many years, faultless service from a particular machine. Unfortunately such guidance does not necessarily mean that the physician is in possession of an accurately reliable machine.

It is the purpose of this paper to explain in principle the operation of the electrocardiograph machine and to point out some of the more important features and characteristics which should not be overlooked when purchase is contemplated, thereby ensuring that it will continue to give reliable and accurate records.

The accuracy to which the electrocardiogram is recorded is dependent upon the combined efficiency of both the operator and the instrument and it must be assumed that the reader is familiar with the techniques of applying the electrodes and leads to the patient, the recording and the prevention of artefacts and such interference as alternating current and tremor. This subject has been adequately covered.[1]

The electrocardiograph machine is an instrument that electrically amplifies and presents as a permanent written record, the resultant cardiac potentials emitted from the skin surfaces of the body. The final method of presentation may be any of the 3 following systems: (1) Direct writing, (2) optical, or (3) some form of electrical storage.

Because over 90% of available apparatus utilizes a direct writing method of presentation, only this system will be discussed, and although it is accepted that the optical systems using mirror galvanometers or cathode ray oscilloscopes have many technical advantages over the direct writing method, their main disadvantage is that they require laborious photographic processing before evaluation of the ECG can be made. For this reason they are not commonly used for routine studies. Electrical storage systems make use of magnetic tape on which the electrocardiogram, superimposed on a high-frequency carrier signal, is stored. Replay is made by demodulation and detection of the stored signal on a cathode ray tube or galvanometer recorder.

Fig. 1 shows a block diagram of an ECG machine. Basically it consists of a signal amplifier, the first stage of which is commonly termed the pre-amplifier. The pre-amplifier is AC coupled to the direct-coupled signal amplifier whose output is in turn connected directly to the driver amplifier, which provides the necessary current to operate the galvanometer recorder. Common to all these sub-assemblies is the power supply which supplies the direct-current source which operates the thermionic valves and/or transistors.

The incoming signals from the patient consist of 2 forms of electrical current. One is a complex alternating signal of

approximately 1 mV amplitude—the electrocardiogram. The other is a direct-current signal of ± 30 mV amplitude above zero potential, commonly known as the 'skin potential'. Both types are of variable amplitude dependent upon lead selection influenced by cardiac abnormality and skin impedance.

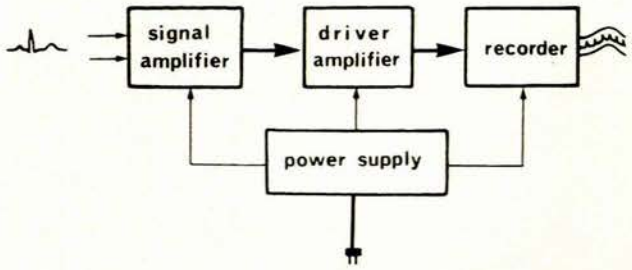

Fig. 1. Schematic diagram of the electrocardiograph assemblies.

Fig. 2 illustrates how the input signal is applied to the amplifier. The ECG signal may be imagined as an alternating generator whose output is superimposed on a direct-current voltage of some 30 times its value. In order to electronically amplify such a signal a method must be used

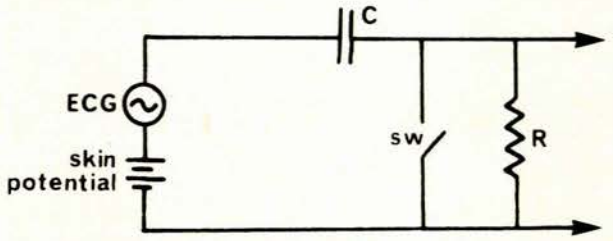

Fig. 2. The input potentials of the ECG machine. See text.

that will 'back-off' the relatively high unwanted DC component on which the ECG signal is superimposed. The capacitor C in the circuit performs the function and permits the alternating ECG component to pass the circuit; at the same time it will block the residual DC component. It charges to a level equal to the value of the skin potential of the patient. Because of the varying values of the DC potential when a change of ECG lead is made, the charge on C will also vary, which, when subsequently amplified, will cause gross drift of the recording galvanometer stylus. (Such a condition is experienced when the operator changes lead selection without depression of the blocking switch, termed 'instomatic' by some manufacturers.) To overcome this disturbance the blocking switch SW is incorporated. Its action is to permit the capacitor C to be charged directly from its source instead of via resistor R so that a new value of charge may be quickly attained. It also protects the circuit when connecting the patient or when leads are changed. On many machines blocking is automatically carried out between lead selector positions, although several still utilize a separate manually-operated switch for this purpose.

The 'pure' electrocardiograph signal is amplified by means of thermionic valves and/or transistors throughout its journey to the galvanometer recording system. It is worthy of mention that no machine should be judged by the number of thermionic valves it contains nor by the presence of transistors—whether it be wholly transistorized or a hybrid type of machine, employing both valves and transistors. An important consideration may be the total weight of the machine, especially when it is required to be continually carried by the physician. Most of the fully transistorized or hybrid types have this great advantage due to the much smaller physical dimension of the transistor as compared with the valve and also to modern printed circuit and modular techniques which are easily adaptable to the transistor circuit.

The recording mechanism consists of a direct-current D'Arsonval galvanometer in which a rectangular coil, pivoted between the poles of a magnet, reacts within a magnetic field, producing a torque. The degree through which the coil rotates is a direct measurement of the current flowing through the coil and the deflection is observed by movement of a pointer or stylus connected to the coil. There are a number of ways in which a direct write-out recording may be obtained. The stylus may be in the form of a fine tube, through which ink under high pressure is allowed to spray as a jet on the recording paper, or the stylus tip may be electrically heated and made to contact specially prepared wax paper on which a black impression is made. Other methods, e.g. employing pressure of the stylus on a carbon paper or ribbon, which gives an impress reading on paper, are less commonly used.

For the electrocardiograph machine to faithfully present the electrical pattern emitted from the heart, it must possess the following qualities:

(*a*) Linearity
(*b*) Stability
(*c*) Balance
(*d*) Adequate frequency response

and tests quoted will enable the physician to check these parameters. It is not uncommon for any one of these qualities to affect the remainder and it is therefore essential that a complete check be made on any one machine at regular weekly intervals.

Linearity

The word linear describes the relation between 2 varying quantities when one varies in direct proportion to the other, so that the resultant graph produced is a straight line. In the electrocardiograph machine the 2 variables concerned are voltage and stylus excursions—thus, if a given voltage of x units causes the stylus to deflect y centimetres, each incremental increase or decrease of voltage should produce a proportional increase or decrease of pen excursion over the entire paper recording width, i.e. $dx = dy$.

Study of a linear response pattern of the machine will indicate (*a*) whether or not the ECG complex will be accurately reproduced in amplitude over the entire recording range and (*b*) the extent to which the stylus can traverse without cutting off the signal.

Before checking this and subsequent parameters, it is important that the machine be switched on and allowed to warm up for 5 minutes. The lead selector switch should be set at the standardization position.

Check for linearity as follows:

1. Adjust stylus to centre of recording paper and accurately calibrate deflection of 1 cm. with 1 mV standardization button (or switch).

2. With one hand controlling the stylus-centering knob, switch on the paper drive mechanism at speed of 25 mm./sec.

3. Adjust the stylus to a position 1 cm. from the top edge of the paper and inject 1 mV signals at ½ cm. levels, simultaneously deflecting the stylus towards the bottom edge of the paper (Fig. 3a). Study of the amplitude of each square wave will reveal any alinearity present. Each initial square wave rise should be of 1 cm. amplitude. Cut-off appearing at the extreme edges of the chart will indicate a non-linear area. Effective linear excursion can be guaranteed between any 2 adjacent wave forms of equal amplitude.

4. If the machine is provided with automatic selection of half and double sensitivities, a check should be made to ascertain linearity of signal deflection. Adjust the stylus to deflect exactly 2 cm./mV on double sensitivity setting and then switch to normal and half sensitivities. Inject 1 mV signals on each position and study resultant wave forms. These should be successively halved in amplitude (Fig. 3b).

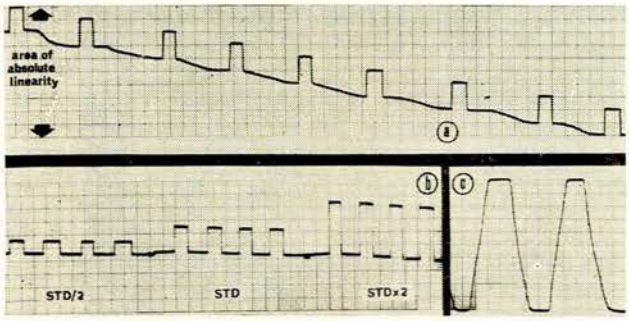

Fig. 3. (*a*) = Linearity check. (*b*) = Calibration setting check. (*c*) = Stylus deflection check.

5. Reset the sensitivity to normal 1 cm./mV position and deflect stylus with the centering knob over the entire paper width. There should be no electrical or mechanical cut-off of the stylus within the range of recording (Fig. 3c).

Stability

This refers to movement of the stylus under conditions of zero input, and may be checked as follows:

1. Set lead selector switch to STD position.
2. Turn sensitivity to maximum and adjust stylus to centre of paper.
3. Using a conductive terminal bar, short-circuit the pins of the patient cable. (This may be adequately done by gripping the terminal pins in a vice.) Connect the patient cable to the machine.
4. Release the 'instomatic' blocking button and record at speed of 25 mm./sec. There should be no drift of stylus.
5. Switch lead selector throughout its complete range. There should be no appreciable movement of the stylus when this manoeuvre is carried out. Should no drift occur, the system is said to be stable.
6. Switch off paper drive.

Balance

An amplifier is 'in balance' when there is electrical equilibrium in the entire circuit. Most electrocardiograph machines operate with balanced (push-pull) amplifiers in which there are 2 identical signals connected to operate in opposite phase and with input and output connections 'balanced' to ground. Such a circuit has a high rejection to alternating and unwanted currents. Out-of-balance may be caused by normal ageing of certain components which need not necessarily require replacement. Many instruments have balance controls which can be manually adjusted.

Test as follows:

1. With selector switch on STD position, adjust sensitivity control to minimum position.
2. Adjust stylus to centre of paper chart.
3. Rotate sensitivity control to maximum clockwise position and return to minimum anti-clockwise position. Record changes.

There should be not more than ½ cm. stylus deflection difference between max. and min. settings. Fig. 4 illustrates an example of an out-of-balance condition.

Frequency Response

This refers to the variation with frequency to the gain or loss of amplitude. It may be considered as a measurement of the recording sensitivity to various applied frequencies. It is obvious that any system of oscillation is capable of responding to a maximum frequency, dependent upon its mass and inertia. The less the mass the higher is the frequency at which the system will oscillate and conversely the higher the mass the lower its frequency. Therefore if a sinusoidal current of constant amplitude is applied to the input of the electrocardiograph machine and the frequency of current increased from zero to, say, 500 cycles per second, because of the large mass of the stylus, a point would be reached where the galvanometer would no longer respond to such rapid vibrations in a linear fashion. In other words, its amplitude would decrease and continue to do so until it reached zero movement. The frequency at which the stylus amplitude begins to decrease is generally referred to as its 'flat' response.* In other words, the amplitude is constant up to that instant.

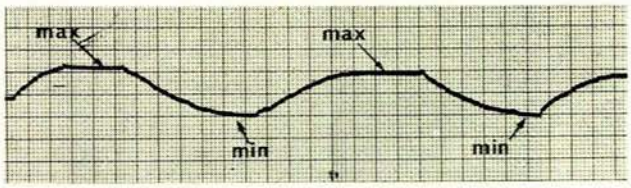

Fig. 4. Balance check showing maximal and minimal settings of sensitivity control. The variation of over ½ cm. between these settings indicates an out-of-balance amplifier.

It is estimated that frequencies of over 2,000 c.p.s. are contained in the human electrocardiogram and Langer[2] has suggested that the ECG recorder should have a frequency response relatively flat to over 330 c.p.s. and probably much higher to faithfully record the electrocardiogram. Although the necessary frequency response characteristics of ECG machines have not been definitely specified, some writers feel that 200 c.p.s. is a minimum flat frequency requirement.[3,4]

Many present-day instruments utilizing the hot stylus method of write-out have a 'flat' response of 40 c.p.s., which seems adequate for general diagnostic evaluation of the electrocardiogram and although few manufacturers give reference to the response characteristics of their machines, some have cut-off frequencies in excess of 70 cycles per second. It is probable that the lack of response, suggested by many writers, could not be overcome without greatly increasing costs of both design and manufacture.

Fig. 5 shows a response curve of one particular make of instrument. The upper tracing portrays the ability of the machine to respond to various frequencies of equal signal amplitude from 10 to 100 c.p.s. The lower graph is a log/linear plot of the curve (B). It can be clearly seen that up to a frequency of 40 c.p.s. the response is flat and the amplitude of the injected signal does not change. However, beyond the frequency of 40 c.p.s. the amplitude gradually decreases and is some 70% of its original value at a frequency of 70 c.p.s.: 70 c.p.s. is therefore termed the *cut-off frequency* of that particular machine. Both these figures are acceptable for limited accurate recording of the electrocardiogram. Lines A and C show the pattern of overdamped and underdamped systems respectively. In the underdamped system (C) it will be noticed that severe resonance has occurred at a frequency of 50 c.p.s. In either faulty conditions the electrocardiogram would be grossly inaccurately recorded.

*The term 'flat' is purely relative and in engineering practice a frequency of 100 c.p.s. would have a response of 70·7% at 100 c.p.s., 70·7 being the value of $1\sqrt{2}$ of the maximum value, i.e. 3db down, commonly termed the 'cut-off' frequency.

It is not usually possible for the physician to check absolute response of his recorder by application of a variable sine wave current from an audio-signal generator, but close study of the simple square wave will give him a good indication of how his machine will respond to both slow and fast-moving changes.

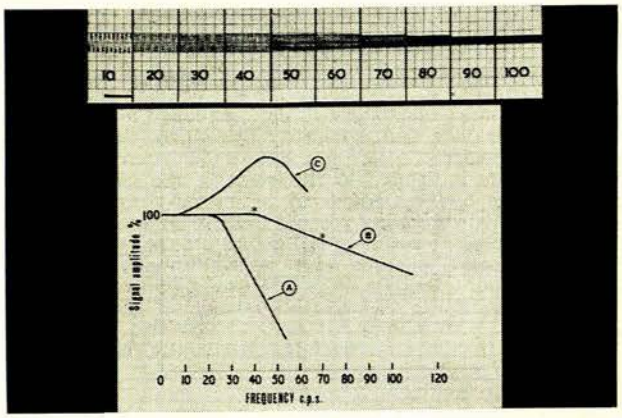

Fig. 5. The frequency response curve of one particular model of ECG machine. The *upper* recording shows the decrease of signal amplitude after the application of a sine wave potential, varying between 10 and 100 cycles per second, to the input of the amplifier. *Below* is illustrated the response pattern in graphical form of the recording (B). The asterisks show the 'flat' and 'cut-off' frequencies respectively of the recording. Curves A and C are typical patterns of over- and underdamped systems which would produce faulty ECG tracings.

Fig. 6 illustrates the 3 degrees of damping of the square waves mentioned above. In the upper tracing the 1 mV signal is applied to the recorder and the amplitude is calibrated to exactly 1 cm. stylus deflection. The left-hand recording shows an overdamped response which is characterized by the roundness of the corners and slow rise time of the deflection. Such a situation would give rise to a roundness of the ECG wave form and slurring of the high frequency components. The middle recording is the ideal wave form which has a fast rise time, completely 'square' corners and flat right-angled top and bottom. The rise time indicates that the high response is adequate and the flat portions that the low frequency response is acceptable. The extreme case of underdamping shown in the upper right-hand recording is presented by a large overshoot of the stylus. This condition would cause the fast-moving QRS components of the ECG to be grossly exaggerated.

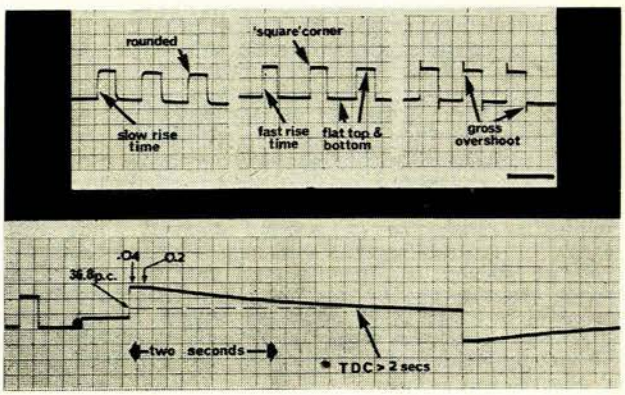

Fig. 6. Upper: The 3 degrees of damping. The left-hand recording shows moderate overdamping characterized by rounded 'shoulders' and slow rise time of the stylus. In its severe form the rise time may be extended to 0·2 seconds or more with corresponding extension of the fall time. The *centre* recording illustrates optimal damping in which any decrease in the amount of damping will result in an underdamped or periodic situation. It is the ideal square wave response for accurate reproduction of the ECG. In the right-hand recording underdamping is present, characterized by overshoot of the stylus. The *lower* recording shows the normal decay curve extending beyond 2 seconds. Such a recording is made by prolonged depression of the millivolt switch.

Other factors apart from electrical maladjustments also contribute to the frequency response of the recording system. Stylus pressure on the recording chart may greatly influence upper frequency response. It is therefore important that pressure of the stylus be set at a level recommended by the manufacturers, for if it is too great severe overdamping will occur. There are machines which make use of this variant in order to control damping of the recording mechanism.

Temperature of the stylus will also affect response and care must be taken to adjust the heat to a level that will cause minimal drag. Wax deposits from the recording paper on the stylus and knife edge (on which the stylus tip rests) will cause drag and subsequent loss of response.

Time Decay Constant

This is the time required for an electrical quantity to rise to 63·2% (or 1—1/e) of its final value or to fall to 36·8% (1/e where e=the exponential function 2·718) of its initial value. By study of the prolonged square wave of the recorder, the physician is able to judge more accurately the lower frequency response of the system. Evaluation is made on the time taken for the curve to decay to a level 36·8% of its initial value after depression of the 1 mV button. The time decay constant should exceed 2 seconds. Fig. 6 (lower tracing) shows such a record.

COMMENT

Certain minimal requirements for electrocardiograph machines have been reported.[5] The response of the instrument at 0·2 seconds after the application of a direct current of 1 mV should not deviate more than 10% from the response at 0·04 seconds. Most recorders meet this demand.

It is unfortunate that there is no international control of the requirements of medical electronic apparatus and one wonders how much misdiagnosis is made because of inadequacies of certain electrocardiograph machines. On some of the current models it is impossible to carry out such tests as linearity and frequency response without the use of additional electronic test equipment.

The user of any electrocardiograph machine should be familiar with the instrument and know its limitations. Physicians and technicians alike should demand that their machine meets with the most stringent requirements wherever it is necessary for repairs to be effected. In my opinion, maintenance should only be carried out by the representative of the manufacturing company who is in possession of a copy of the official maintenance manual for that particular instrument.

I wish to thank Prof. V. Schrire, Head of the Cardiac Clinic, for his help and encouragement. This work was supported by the South African Council for Scientific and Industrial Research and by a grant from the City Council of Cape Town, and forms part of the work of the Joint University/CSIR Cardiovascular-Pulmonary Research Group.

REFERENCES

1. Bradlow, B. A. (1964): *How to Produce a Readable Electrocardiogram.* Springfield, Ill.: Charles C. Thomas.
2. Langer, P. H. (1952): Circulation, **5**, 249.
3. Kerwin, A. J. (1953): *Ibid.*, **8**, 98.
4. Gilford, S. R. (1949): Paper presented at AIEE-IRE Conference on Electronic Instrumentation in Nucleonics and Medicine, New York, October.
5. Report of Council on Physical Medicine (1947): J. Amer. Med. Assoc., **134**, 455.

gic or toxic effects were seen in any patients among which were 94 clinical cures, 8 improved and 6 unimproved.

Lynch, *et al*[24] in a review of oral antifungal agents used in clinical trials, reports that amphotericin-B in an oral dosage of from 5 to 7 gms. a day, produced no side effects in either the solubilized or insoluble form. In this regard the normal effective antifungal dosage (Amphotericin-B) in MYSTECLIN-V IMPROVED is 0.2 gm. to 0.4 gm. daily.

Amphotericin-B alone or with tetracycline in a ratio of 1 to 5 was extremely well tolerated and did not produce any significant systemic toxicity, or gastro-intestinal disturbance among 109 patients treated 3 to 7 days with a 5 to 1 ratio of tetracycline to amphotericin-B.[14]

Reichelderfer[29] evaluated the efficacy and acceptability of combined tetracycline-amphotericin-B oral therapy in 92 paediatric patients with a variety of infections, ranging in age from new-born to nine years. In his series . . . "No clinical evidence of candidal overgrowth was observed even after prolonged administration".

Another paediatric study[20] showed uniformly good therapeutic results among 53 children with various acute infections treated with a 5 to 1 oral mixture of tetracycline and amphotericin-B. "No candidiasis developed in any of the patients during or after therapy". Among 30 patients with upper respiratory tract infections who received only tetracycline, the yeast count rose during therapy.

". . . there have been many indications for the use of an antifungal agent in conjunction with a broad-spectrum antibiotic. These include many common infections of the respiratory, gastro-intestinal and also genito-urinary systems, which are amenable to tetracycline therapy. Because the addition of an antifungal agent to the broad-spectrum agent may act to prevent monilial overgrowth, it is particularly indicated for those patients who require broad-spectrum antibiotic therapy, but who may be especially susceptible to super-infection with C. albicans. These would include those on high or prolonged dosage, infants (particularly prematures), the debilitated or elderly, pregnant women, diabetics, leukemics, those on concomitant corticoid therapy and those who have developed moniliasis on previous broad-spectrum therapy. And even in those who do not apparently demonstrate an incidence of monilia, the addition of an antifungal agent to the broad-spectrum antibiotic appears to reduce the severity of diarrhoeal side effects".[30]

While Amphotericin-B effectively checks and depresses any tetracycline-induced monilial overgrowth in the gastro-intestinal tract, it does not interfere with the absorption of tetracycline.[14]

Side effects during and after plain tetracycline therapy are not infrequent.[1,27]

A definite clinical cure and a negative smear was obtained in 91% of 241 males with acute gonococcal urethritis treated with tetracycline phosphate complex and Amphotericin-B.[25]

"It is felt at the present time that tetracycline phosphate complex with Amphotericin-B is to be considered a preferred tetracycline in the treatment of many chronic urinary tract infections because of the high degree of tolerance to it, and the absence of severe diarrhoeas."[26]

Caruso,[28] following a clinical trial stated . . .

"We believe that the results of this study indicate that monilial infections of the vagina may be associated with the administration of tetracycline and that the supplementation of tetracycline with the antimycotic Amphotericin-B constitutes an effective measure against secondary infection by Candida albicans."

There is voluminous clinical evidence to support the use of the tetracycline/Amphotericin-B antibiotic, MYSTECLIN-V IMPROVED—a Squibb product, quality enhanced by the Priceless Ingredient which is the honour and integrity of the maker.

REFERENCES

1. Barber, M., M.D., Prof. Clinical Bacteriology, Post Graduate Medical School of London, The Practitioner, Vol. 194: 37-42 Jan. 1965.
2. Sidransky, H. and Pearl, M.A. Dis. of the Chest **39**: 630-642 June 1961.
3. Chakravarty, S. and Sundhu, R. S. Acta tuberculosea et pneumalogica Sand. **42**: 198-206, 1962.
4. Skinner, C. E. and Fletcher, D. W. Bacteriolog. Rev **24**: 397-416 Dec. 1960.
5. Isenberg, H. D. *et al* Antibiotics & Chemotherapy **10**: 353-363, June 1960.
6. Abbas, T. M. J. Obstet. Gynaecol. Brit. Empire **65**: 430-432, 1958.
7. Brodie, J. and Henderson, A. Scottish M.J. **6**: 146-148, Apr. 1961.
8. Stewart, G. T. Brit. M.J. **1**: 658-660, Mar. 24, 1956.
9. From, P. and Alli, J. H. Antibiotic Med. & Clin. Therapy **5**: 639-648, Nov. 1958.
10. Editorial Section British M.J. **2**: 403 Aug. 17, 1963.
11. MacLean, K. Practitioner (England) **189**: 364-371, Sept. 1962.
12. Dr. H. Welch, Ph.D. Antibiotic Medicine, Vol. 11, No. 2, Feb. 1956, p. 81.
13. Editorial, Journal American Medical Association, Vol. 192: No. 11 June 14, 1965.
14. Stough, A. R., Groel, J. T. and Kroeger, W. H. Antibiotic Med. & Clin. Therapy **6**: 653-661, Nov. 1959.
15. Lechevalier, H. Antibiotics Ann. 1959-1960, New York, Antibiotica Inc. 1960, 614.
16. Quinn, L. Y., Wilbur, R. D. and Catron, D. V.: Antibiotics and Chemo. **10**: 95 (Feb.) 1960.
17. New and Nonofficial Drugs 1960, Philadelphia, J. B. Lippincott Company, 1960, 73 and 137
18. Lehan, P. H. *et al*: Dis. Chest **32**: 597 (Dec.) 1957.
19. Newcomer, V. D. *et al*: J. Chron. Dis. **9**: 353 (April) 1959.
20. Kozinn, P. J. *et al*: Antibiotic Med. & Clin. Ther. **7**: 749 (Dec.) 1960.
21. Reiss, F. In Muschenheim C., Robitzek, E. H., Vandow, J. E. and Reiss, F. New York State J. Med. **59**: 4187 (4209) (Nov. 15) 1959
22. Campbell, J. B. *et al*: Oral Surg. **13**: 1273 (Oct.) 1960.
23. Karp, A. *et al* E.E.N. & T. Monthly **42**: 72, 76-78, 96, Sept. 1963.
24. Lynch, H. T. *et al* Trans. 20th Research Conf. in Pulmonary Diseases U.S. Veterans Administration 304-308, Feb. 1961.
25. Tiedemann, J. H. Southern M.J. **55**: 852-854, Aug. 1962.
26. Trafton, H. M. and Lind, H. E. Current Therap. Res. **3**: 59-65, Feb. 1961.
27. Textbook of Medical Treatment (1964) Edited by Sir Derrick Dunlop, Sir Stanley Davidson, Prof. Stanley Alstead.
28. Caruso, L. J., M.D., AM. J. Obst. & Gynacae. Vol. 90: No. 3, Oct. 1964.
29. Reichelderfer, T. E. Antibiotic Med. & Clin. Therapy **7**: 541-545, Sept. 1960.
30. Lind, H. E. Am. J. Proctol **13**: 236-242 Aug. 1962.