Clonus: beats provoked by the application of a rhythmic force

E. GEOFFREY WALSH

From the Department of Physiology, University of Edinburgh, Edinburgh

SYNOPSIS (1) Clonus has been elicited by using a printed motor in nine patients with sustained ankle clonus. (2) When a dorsiflexing biasing force was applied to the foot the amplitude, but not the frequency, of the clonus varied according to the strength of the force. (3) When the biasing force was withdrawn there could be, for some seconds, continuing EMG evidence of a rhythmic discharge. (4) The clonus did not synchronise with an externally applied rhythmic force. In all relevant observations beats were set up between the clonus and the applied force. (5) When clonus was started by the abrupt application of bias the waveform in successive trials was fairly closely repeatable. (6) Beats were also established in two cases of wrist clonus. (7) It is concluded that clonus is not due to the self re-excitation of proprioceptive reflexes but is dependent on a spinal generator, the rate of beating of which is normally independent of peripheral circumstances, although it may be switched on and its activity maintained by appropriate events.

Clonus is a common neurological sign and one which is at times disturbing to the patient. It has, however, been the subject of very little study. The rhythmic action is usually regarded as the result of self re-excitation of hyperactive stretch reflexes. This view has a long history (*cf* Noica, 1917, 1919) and there was *prima facie* support from some experiments on the silent period in decerebrate cats by Denny-Brown (1929). Sherrington himself does not appear to have studied clonus but accepted Denny-Brown's interpretation. It is expressed in the 'little red book' of the Oxford School (Creed *et al.*, 1932) and by Sherrington himself (1939). The self re-excitation hypothesis is plausible, for clonus may often be set off by a single tendon tap and with Sherrington's support the view does not appear to have been challenged. The existence of a silent period may, however, play a stabilizing role if the timing of the quiescence is appropriate for the delays in the system (Merton, 1951).

It is a characteristic of oscillatory systems that their frequency can normally be changed by the appropriate application of a rhythmic signal close to the frequency of oscillation. Accordingly, it may be argued that rhythmic force

applied to the foot of a person with clonus should 'entrain' the rhythm to that of the applied frequency. The study of entrainment has a long history. It is related that Huygens (1629-1695) reported that two clocks which were slightly out of step when hung on a wall became synchronized when fixed on a thin wooden board (Minorsky, 1962). The synchronization effect can readily be observed in electronic circuits (Appleton, 1922) and may be expected in appropriate experiments on neurological feedback loops.

For the present study, use has been made of a 'printed' motor (Evans, 1972). This device is admirably suited to convert an electrical current into a force for biomechanical studies. Supplied with a steady biasing current a torque can be generated at the ankle leading to dorsiflexion and bringing out clonus in susceptible subjects. By superimposing, in addition, a rhythmic torque an attempt has been made to entrain clonus. The results have been the opposite of those predicted by currently accepted theory. No entrainment has been seen; on the other hand, slow rhythmic fluctuations in the amplitude of the waves occur and are evidently beats set up between the biological oscillation and the

rhythmic force. The paper also deals with some effects of varying the degree of bias so as to vary the steady dorsiflexion force, electromyographic evidence, and some observations on wrist clonus. An account of this work at a preliminary stage was communicated to the Physiological Society (Walsh, 1971).

METHODS

Nine of the patients had sustained ankle clonus. The ages ranged from 11 to 55 years. In three of the cases there had been spinal cord trauma and in one there had been a severe head injury several years before. In one patient a spinal tumour had been removed. Two patients had disseminated sclerosis, one cervical spondylosis, and another had suffered from transverse myelitis. Some observations are also included on two patients, aged 20 and 39 years, with a sustained clonus of the wrist. One had a spastic arm after a cerebral abscess and the other had cervical spondylosis.

Some of the patients attended the Commonwealth Spastic Games in Edinburgh in 1971. One of the

subjects, J.B. (Figs 2, 3, and 4) was a champion in the weightlifting class. The procedure was undisturbing, one patient even falling asleep during the investigation.

The printed motor uses an armature of flat copper wires in a computer-designed configuration attached to both sides of a disc of heat resistant plastic. The inertia is very low so the biomechanical properties being tested are changed minimally. The inductance of the armature is almost negligible so that the device can transmute rapid electrical changes into corresponding mechanical alterations. The armature rotates in the field generated by permanent magnets and the torque is proportional to the current. There is no perceptible 'cogging'.

The motor has been supplied by a transistorized power amplifier. The current through the motor is sensed by the voltage drop in the lead returning to earth and is used to provide feedback so as to regulate the torque provided according to the input from a waveform generator.

A motor type G16M4 supplied by Printed Motors Ltd has been used for the studies on ankle clonus. The arrangements are shown in Fig. 1. Some of the earlier results used the same motor but this was fixed to a tubular metal frame and was held below rather than above the ankle. That system has been illustrated previously (Walsh, 1974). A smaller motor, type G9M4, was used for the study of wrist clonus. The apparatus has been illustrated elsewhere (Gillingham *et al.*, 1972).

The spindles are double ended. One end of the shaft is coupled to a conductive plastic potentiometer which records motion. Velocity is obtained by the use of an operational amplifier in a pseudo-differentiator circuit. The other end of the shaft is coupled to the foot through a lever to which is fixed a curved metal plate fitting under the ball of the foot. This splint is attached to the limb by Velcro strapping. A Mingograph ink jet recorder has been used to display signals corresponding to torque, position, and velocity. Other channels were fed from conventional electromyographic amplifiers. Suction cup surface electrodes have been used. The time marker of the recorder displayed intervals of one second.

A phase sensitive detector was also available. This was a dedicated on-line hybrid computer that gave cycle by cycle plots of the phase relationship between the waveform generator and the velocity of the motion. The generator had two outputs at 90°. Each was multiplied by the velocity signal and fed to an integrator that was reset each cycle. Immediately before being reset the integrator voltages were switched to sample and hold devices so that they were retained for one cycle. The angle whose tangent was the ratio between the voltages in the sample hold

FIG. 1 Arrangements for studying ankle clonus in their final form.

modules was computed and displayed. The method of display will be seen from Fig. 5 and is described in the legend.

RESULTS

Ankle clonus

EFFECTS OF BIAS In all of the patients a dorsiflexing force was needed to bring out the clonus which differed in rate between different patients but was never slower than 5.5 Hz or faster than 8.0 Hz. The bias on the motor was thus used to duplicate the manoeuvre of a clinical examination where the physician presses upwards on the ball of the foot. The torque needed is much less than that exerted on the ankle during normal walking. If the bias is applied gradually the clonus may not start at once but take some seconds to build up and mechanically the first few beats may be erratic (Fig. 2). If the conditions are held constant, clonus then continues with each beat closely following the pattern of its predecessors. In this almost machine-like regularity, clonus differs from tremor which, even at its most uniform expression, varies

significantly in amplitude. Clonus is more jerky than a rhythmic voluntary act, it is difficult to see it as the 'release' of normal neural activity. Similarly, the clonus that can sometimes be elicited at the ankle in normal subjects seems capable of performing no biologically useful function. The contraction of clonus is abrupt, the onset and cessation of electromyographic activity being more clear than, for example, in the tremor of Parkinsonism. It has been shown that the amplitude, and indeed even the shape, of the mechanical motion vary widely according to the level of bias applied. In Fig. 3 the bias follows a slow triangular waveform. By thus varying the force, the mechanical conditions in the muscle can be subjected to substantial alterations. With wide variations in bias there was no shift in frequency. As long as the clonus could be detected its frequency was invariable. This easily reproduced observation suggests that clonus is due to the operation of a central pace-maker rather than to the effect of self-excitatory reflexes involving the limb.

Further information has been obtained by observing the electromyographic disturbances

FIG. 2 Dorsiflexing bias, manually controlled. Two examples, in both electrical evidence of clonus outlasts mechanical oscillations when the bias is withdrawn. J.B., male, aged 23 yr. Mid-thoracic lesion, traumatic, complete. Right ankle.

FIG. 3. *Slow variation of bias. Dorsiflexing torque varies in triangular manner. Size of pulsations of clonus varies, as do configurations of waves but frequency is unchanged. Time marks—1s. J.B., male, aged 23 yr. Mid-thoracic lesion, traumatic, complete. Right ankle.*

FIG. 4 *Beats between clonus and a rhythmic force. Beats may be slow and the envelopes may repeat time and time again with similar shape. Time marks 1 s. Second line torque, third line position, J.B., male, aged 23 yr. Mid-thoracic lesion, traumatic, complete. Right ankle. (Tracing.)*

associated with clonus. If the biasing force is withdrawn, the mechanical motion at the ankle ceases at once. It may often be observed, however, that rhythmic bursts of electromyographic potentials from the calf continue for a variable period (Fig. 2). The amplitude of the potentials is reduced but the rate remains the same as that of the preceding clonus. If the skin over the muscle be observed at this time, small fluctuations in the contours can often be observed that evidently correspond to the electrical changes. The persistence of this 'subclinical clonus' also speaks for the existence of a central pacemaker, for the mechanical conditions in the limb have changed widely and yet the rate of beating remains unchanged.

These observations may sometimes be paralleled in the clinic with no special apparatus. First, it may be observed that the intensity but not the rate of clonus is modified according to the pressure applied to the ball of the foot. Secondly, when the pressure is withdrawn and the calf observed, rhythmic alterations in the muscle form may be seen.

On the one occasion on which muscle activity was studied by an intramuscular electrode, the discharge of a motor unit was seen for each cycle of the clonus. No double discharges were seen.

EFFECTS OF RHYTHMIC FORCES In five patients rhythmic forces were added to a constantly applied force. When the rate was close to but not identical with that of clonus, it was possible to set up beats. To get clearly defined maxima and minima for the beat cycles it was necessary to adjust the amplitude of the rhythmic component of the force to an appropriate level. This was not a difficult procedure and could usually be

accomplished by trial and error in a short time. A sinusoidal waveform was usually used, but square waveforms and pulses too proved quite effective. As soon as the rhythmic force was applied, the steady pulsations of the clonus were replaced by pulsations which, while of the same rate, varied in amplitude in a slow and systematic manner (Fig. 4). The rate at which the envelopes of the waveform varied depended on the difference in frequency between the clonus and the applied force. Even when slow, the beat envelopes were usually, although not universally, symmetrical. The period during which the amplitude increased was equal to that during which it decreased. One oscillating system may influence another to an extent short of synchronization. This lesser influence may be suspected if the beat frequency observed is significantly less than that calculated. Data from one patient are shown in Table 1. The figures observed are reasonably close to those predicted, allowing for experimental error; in particular, there may be minor variations of clonus frequency. As the applied force is moved in frequency from the rate of the clonus in either an increasing or decreasing direction, so the rate of beating increases in agreement with theory.

The electromyographic potentials recorded from the calf show changes corresponding to the beats, for the amplitude of the massed muscle activity is greater when the swings are large rather than when they are small. It seems probable therefore that as the physical interaction proceeds, additional motor units may be recruited by reflex mechanisms.

In one patient, observations were made using the on-line phase detector (Fig. 5). The signals from the signal generator reached the detector together with those corresponding to velocity even when the motor was not switched on. With a steady clonus, there were naturally rhythmic shifts in phase around the full 360° as the clonus and the generator moved into step, out of step, and then into step again. This rhythmic fluctuation of phase indicated clearly the beat frequency predicted by simple theory. When the current from the generator was fed to the motor, beats were set up and here too there was a rhythmic fluctuation of phase. Predictably, this did not amount to 360° unless the amplitude of the force closely matched the clonus. It will be seen

TABLE 1
FREQUENCY OF BEATS

Applied torque (Hz)	Predicted beat (Hz)	Observed beat (Hz)
4.5	2.2	2.0
5.0	1.7	1.5
5.5	1.2	1.3
7.0	0.7	0.7
8.0	1.3	1.6

* M.L., aged 11 yr. Old head injury. Left ankle clonus frequency 6.7 Hz.

FIG. 5 Phase changes between wave generator and velocity signal. When the two signals are in phase, output of detector corresponds to 0 level as indicated; when 180° out of phase the trace corresponds to ' π '. When the velocity leads the force the trace is automatically thickened (an oscillator is switched on). J.A.B., male, aged 46 yr. Transverse myelitis. Left ankle.

that the two frequencies differ, if at all, only marginally. This evidence thus strongly suggests the existence of an internal clock for the clonus that is uninfluenced, as a rule, by peripheral events.

A CONSTANTLY RUNNING CLOCK OR ONE THAT IS SWITCHED ON BY PERIPHERAL EVENTS? Clonus appears only when a biasing force is applied. It is possible that the appearance merely depends on facilitation of pathways from a central

generator which is constantly running. The proprioceptive pathways in susceptible subjects could open neural 'gates' and allow rhythmicity to be displayed which is constantly present. Should this be so, appropriate signs should be expected when the bias is abruptly applied, for the waveform of the first oscillation should vary according to the phase of the internal generator at which the proprioceptive signals were received. Accordingly, observations have been made on the effect of applying a steady bias abruptly

FIG. 6 *Velocity records, onset of clonus as dorsiflexing bias is applied on successive occasions. The main features of the initial waveforms are phase locked to the initial movement. Synchronization may later be lost (cf Table 2). The small initial upward deflection in some of the records is an electrical artefact. The onset of the dorsiflexing force corresponds to the initial downwards movement of the trace. The peak of the first downward swing is limited electrically. A.H., male, aged 45 yr. Mid-thoracic ependymoma. Right ankle.*

using a slow square wave from the waveform generator. In the two patients tested the clonus did appear to be phase locked to the square wave. This suggests a generator which may be switched on by proprioceptive signals. The initial swings were identical in successive trials (Fig. 6). The synchronism was sometimes lost after a number of waves; one possible cause could be minor variations in clock frequency. The EMG findings (Table 2) are similar. After the first and presumably reflex burst the subsequent waves kept well in step at first.

When clonus is present on both sides, the question arises as to the relationship between the

rhythms. In one patient, clonus was generated by a printed motor on one side and by pulling up on the foot with an extension spring on the other side. On the side of the spring, the rhythm was monitored electromyographically. The rates of clonus in the two sides showed small but real differences. The suggestion, then, is that there is more than one rhythmic generator.

SITE OF GENERATOR One of the subjects showing beats had suffered a transection of the spinal cord at C7/T1 segment which was deemed clinically to be complete (Figs 2, 3, 4). It is accordingly presumed that the generator is spinal in site.

Wrist clonus

In the two patients, the hand was normally held in a flexed position, and was stable. When a steady extensor force was applied, the steady beats of clonus occurred at a regular rate in both. There was no difficulty in setting up beats when a rhythmic component was added to the force (Fig. 7). The rate of the clonus in one patient was steady at 6.0 Hz, the rate of the other clonus was 5.7 Hz.

DISCUSSION

CLONUS IN ABSENCE OF ACHILLES TENDON JERK Twenty years ago when the operation of hemispherectomy was being undertaken, Dr J. A. V. Bates (of the National Hospital, Queen Square, London) tested knee jerk, ankle jerk, and ankle clonus in the spastic limb during the induction of anaesthesia. The patients were started on pentobarbitone and continued on gas, oxygen, and a little ether supplemented with pethidine. It was observed that the depression of clonus did not run parallel to the depression of the knee and ankle jerks. Clonus was relatively more resistant to the anaesthetics. In one patient, clonus was clearly demonstrated when the ankle jerk was unobtainable.

Dr P. W. Nathan, also of the National Hospital, has investigated the influence of intrathecal procaine to give a differential block of spinal roots in spastic patients. In one of these patients the left lower limb was lying toneless and flaccid, but was observed going into spontaneous clonus. Dr Nathan has observed the same phenomenon in two decerebrate human subjects being given diazepam.

TABLE 2
DEVELOPMENT OF CLONUS*

	Burst number																			
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Trials																				
1	0	160	320	440	600	720	880	1 040	1 160	1 320	1 480	1 640	1 800	1 920	2 080	2 240	2 400	2 560	2 680	2 880
2	0	160	320	440	600	760	880	1 040	1 200	1 320	1 480	1 640	1 800	1 920	2 080	2 200	2 360	2 520	2 680	2 840
3	0	160	320	480	600	720	880	1 000	1 120	1 280	1 440	1 560	1 680	1 840	1 960	2 080	2 240	2 360	2 520	2 640
4	0	160	320	440	600	720	880	1 000	1 120	1 280	1 400	1 520	1 640	1 760	1 880	2 040	2 080	2 280	2 440	2 600
5	0	160	320	480	600	760	920	1 040	1 200	1 320	1 480	1 600	1 760	1 920	2 080	2 200	2 360	2 520	2 640	2 760
Mean	0	160	320	456	600	736	888	1 024	1 160	1 304	1 456	1 592	1 736	1 872	2 016	2 152	2 288	2 448	2 592	2 744
SD of mean	0	0	0	22	0	22	18	22	40	22	39	53	73	72	92	86	131	121	107	122
Difference between successive means	-	160	160	136	144	136	152	136	136	144	152	136	144	136	144	136	136	160	144	152

The bursts in successive trials are evidently within register for the first five or ten beats, thereafter the synchrony is lost.
* Time (ms) from first EMG discharge to subsequent discharges. Clonus initiated by abrupt onset of bias (square wave from slowly running wave generator). First discharge is apparently a reflex phase locked to initial motion. A.H., male, aged 45 yr (see also Fig. 6 which refers to an independent set of observations on the same patient).

FIG. 7 Wrist clonus. Beats between clonus and applied rhythmic force consisting of square waves superimposed on steady extending bias. C.E., male, aged 39 yr. Cervical spondylosis. Left wrist.

EFFECTS OF BIAS If the oscillation were dependent on self re-exciting peripheral reflexes, it would be expected that the rate of the clonus would depend strikingly on the mechanical situation in muscle. This is found in the rhythmic action which results when a normal limb is coupled to a source of negative damping (Walsh, 1970). The rate is strikingly dependent on the stiffness with which the limb is held and on its position. By contrast, in clonus varying degrees of bias, although changing the force of the clonus, do not change its rate. When the bias

is withdrawn, an electromyographic after discharge may be seen. The view that a central pacemaker exists corresponds to the terminology used by an earlier generation of French clinicians who spoke of 'épilepsie spinale' (Babinski, 1934).
INITIATION OF CLONUS The data on the initiation of clonus appear to show that the generator is switched on when dorsiflexing bias is suddenly applied. If the generator were free running, the interval between the initial swing of the foot and the first beat should vary randomly by

up to the duration of one complete cycle. A similar situation was considered in another connection elsewhere (Walsh, 1952). The wave form, however, when bias is applied may approximately repeat time and time again (Fig. 6, Table 2).

It is supposed, therefore, that the generator is switched on by a sufficiently intense abrupt proprioceptive volley. Clonus may also start when the bias is applied more gradually (Fig. 2). It seems that the generator can therefore also be switched on by a continuing and presumably asynchronous discharge. When bias is withdrawn, the rhythmicity stops, if not immediately, after some seconds. So continued activity of the generator appears also to need a proprioceptive input.

The initial movement of the foot when bias is suddenly applied is of course mechanical but is soon followed by the first electromyographic discharge which is presumably due to the operation of a stretch reflex. This may then start a clonus. It appears that when a sustained clonus is initiated a central generator is 'switched in'.

BEATS The most striking single finding of the study is that a clonus cannot be entrained at the force levels that have been used. Rather it has constantly been found that beats are set up to an applied rhythmic force. This strongly suggests that the oscillation of clonus is the result of the activity of an autonomous central pacemaker. Beats were seen not only in the cases with ankle clonus, but also in the two cases of wrist clonus.

Systems may produce beats, even though there is some weak coupling. Lord Rayleigh studied both tuning forks and organ pipes, while Appleton (1922) studied electronic oscillators. When the systems were nearly in unison it was not possible to reduce the beat frequency indefinitely, for synchronization occurred. The observations that have been made do not prove that there is no interaction but they do show that if it occurs it must be feeble and far below the level to be expected if clonus were due to the self re-excitation of hyperactive reflexes. If there were appreciable interaction between the two generators, the beat frequency should be significantly less than the predicted value and this has not been observed. The effect in physical systems is due to the tendency to synchronize and is most marked when the difference of

frequencies is small. If there is a tendency for two systems to synchronize, there is one part of the cycle when the phase relationships for this to occur are most favourable and the oscillations tend to maintain this particular phase relation longer than any other. Thus, one part of the beat cycle is prolonged. In Rayleigh's tuning fork experiments and Appleton's experiments with triode oscillators, the beats increased slowly and decreased rapidly during a beat cycle. The beats produced in the patients with clonus were usually symmetrical even when quite slow.

The materials for the apparatus were obtained with the aid of funds from the Royal Society (government grants). The apparatus was constructed by Mr G. Wright who also contributed technical expertise during the recordings. The author is indebted to Sir Ludwig Guttmann and Mr Phillip Harris for introductions to some patients, to the patients themselves, and Dr J. A. V. Bates and Dr P. W. Nathan for the information quoted in the discussion.

REFERENCES

- Appleton, E. K. (1922). The automatic synchronisation of triode oscillators. *Proceedings of the Cambridge Philosophical Society*, **21**, 231-248.
- Babinski, J. (1934). Réflexes tendineux. In *Oeuvre Scientifique*. Masson: Paris.
- Creed, R. S., Denny-Brown, D., Eccles, J. C., Liddell, E. G. T., and Sherrington, C. S. (1932). *Reflex Activity of the Spinal Cord*. Oxford University Press: London.
- Denny-Brown, D. (1929). On the nature of postural reflexes. *Proceedings of the Royal Society*, **104B**, 252-301.
- Evans, R. M. (1972). The printed circuit motor. *Electronics Today International*, **1**, No. 2, 14-18.
- Gillingham, J., Tsukamoto, Y., and Walsh, E. G. (1972). *Parkinson's Disease*, vol. I, pp. 93-114. Edited by J. Siegfried. Huber: Bern.
- Merton, P. A. (1951). The silent period in a muscle of the human hand. *Journal of Physiology*, **114**, 183-198.
- Minorsky, N. (1962). *Non-linear Oscillations*. Van Nostrand: Princeton, NJ.
- Noica (1917). Etude sur la symptomatologie et sur le mécanisme du vrai clonus et du clonus artificiel. *Revue Neurologique*, **32**, 55-61.
- Noica (1919). Phénomènes réflexes par distension tendineuse. *Revue Neurologique*, **35**, 196-200.
- Sherrington, C. S. (1939). *Selected Writings*. Edited by D. Denny-Brown. Hamish Hamilton: London.
- Walsh, E. G. (1952). Visual reaction time and the α -rhythm, an investigation of a scanning hypothesis. *Journal of Physiology*, **118**, 500-508.
- Walsh, E. G. (1970). Tremor at the wrist induced by positive velocity feedback. *Journal of Physiology*, **207**, 16-17P.
- Walsh, E. G. (1971). Ankle clonus—an autonomous central pacemaker? *Journal of Physiology*, **212**, 38-39P.
- Walsh, E. G. (1974). Pugnatron-like postural reactions in a patient with familial dystonia—torque induced motion analysis. *Journal of Neurology, Neurosurgery, and Psychiatry*, **37**, 559-565.