

## AN ATLAS OF CELLULAR OSCILLATORS

BY P. E. RAPP

*Gonville and Caius College, Cambridge CB2 1TA, England*

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### SUMMARY

Rapidly accumulating evidence suggests that periodic behaviour is not confined to a limited number of cell types but is a common property of most biological systems. The argument for this proposition is presented by systematically cataloguing an atlas of biological and biochemical oscillators with periods of an hour or less. The listing consists of eight principal sections and includes oscillations in secretory cells, neural oscillators, oscillations in muscle cells and rhythmic behaviour in growth and development. Each entry states the experimental preparation, the periodic event (the observed oscillatory variable), the period and lists references to the experimental literature. Four hundred and fifty experimental papers are cited.

## OUTLINE

The purpose of this atlas is to demonstrate the variety of oscillatory biological processes by listing in one place examples of several different classes of oscillator. The coverage is restricted to systems with periods of the order of hours or less. In some of the cases the requirement of strict periodicity has been relaxed and systems are included that return to a steady state after a limited number of cycles. Besides the specific papers listed in the atlas, several recent reviews provide valuable introductions to the subject. These include Aldridge (1976), Goldbeter & Caplan (1976), Hess & Boiteux (1971) and Hess, Boiteux, Busse & Gerisch (1975).

Long-period oscillations, notably circadian rhythms, are not included. Circadian oscillations are considered in books by Bünning (1973), Conroy & Mills (1970) and Hastings & Schweiger (1975). Oscillations in non-biological chemical systems, for example the Belousov-Zhabotinskii reaction, are not included (Tyson, 1976; Winfree, 1974). Ecological rhythms (May, 1974) and oscillations of clinical interest (Glass & Mackey, 1979; MacDonald, 1978; Mackey & Glass, 1977) have not been covered.

Only experimental papers or theoretical papers that report new experimental results have been listed. For surveys of recent developments in the theoretical analysis of biological oscillations see Cronin (1977), Pavlidis (1973), Sollberger (1965) and Tyson & Othmer (1978).

The papers in this volume provided many of the references in the atlas and special thanks should be directed to these authors.

Inevitably the coverage reflects my research interests and some important papers in the field have not been included. Colleagues are invited to send suggestions for inclusion in any subsequent editions of the atlas. As it is hoped to extend the coverage to include rhythmicity in systems of clinical interest, suggestions in these areas would be particularly welcome. An abridged listing of an earlier edition has appeared in Rapp (1979).

I. *Oscillations in enzyme catalysed reactions*

Preparation	Event	Period	References
<b>(A) Miscellaneous systems</b>			
Purified horseradish peroxidase	Periodic rate of catalysed oxidation	1 min	Degn (1968, 1969, 1973) Degn & Mayer (1969) Yamazaki, Yokota & Nakajima (1965) Yamazaki & Yokota (1967, 1973 <i>a, b</i> )
Purified lactoperoxidase	Oscillatory oxidation of NADH	2 min	Degn (1973) Nakamura, Yokota & Yamazaki (1969)
Heart muscle extract	Oscillation in creatine kinase activity	3-10 min	Chetverikova (1973)
<i>Scenedesmus</i> (algae)	Oscillation in ammonium efflux	1-3 min	Pribil & Kotyk (1970)
Kidney and brain microsomes (rabbit)	Oscillation in phosphorylated protein & ATPase activity (associated with oscillatory ion transport)	1-2.5 min	Fukushima & Tonomura (1972)

Preparation	Event	Period	References
<i>Acetabularia</i>	Oscillation in lactate dehydrogenase & malate dehydrogenase activity	1-3 min	von Klitzing (1969)

(B) The glycolytic oscillator

<i>Saccharomyces carlsbergensis</i> (intact cells or cell-free extract)	Oscillation in glycolytic intermediates	2 s to 3 h	Aldridge & Pye (1976) Becker & Betz (1972) Betz (1973) Betz & Chance (1965 <i>a, b</i> ) Betz & Moore (1967) Betz & Sel'kov (1969) Boiteux & Hess (1973) Boiteux, Goldbeter & Hess (1975) Chance, Estabrook & Ghosh (1964) Chance, Ghosh <i>et al.</i> (1964) Chance, Hess & Betz (1964) Chance, Schoener & Elsaesser (1964) Chance, Schoener & Elsaesser (1965) Ghosh & Chance (1964) Ghosh, Chance & Pye (1971) Hess & Boiteux (1968 <i>a, b</i> , 1973) Hess, Boiteux & Krüger (1969) Hess & Brand (1966) Hess, Kleinhans & Kuschmitz (1973) Hommes (1964 <i>a, b</i> ) Mochan & Pye (1973) Pye (1969, 1971, 1973) Pye & Chance (1966) Richter, Betz & Giersch (1975) von Klitzing & Betz (1970) Winfree (1972)
<i>Saccharomyces carlsbergensis</i> single cell	Same	5 min	Chance, Pye & Higgins (1967)
<i>S. cerevisiae</i>	Same	30 s.	Hess & Boiteux (1968 <i>b</i> )
<i>Photobacterium phosphoreum</i>	Same	1 min	Duysens & Ames (1957)
Beef-heart cell-free extract	Same	4-26 min	Frenkel (1965, 1966, 1968 <i>a, b, c</i> )
Rat leg muscle extract	Same	20 min	Tornheim & Lowenstein (1974, 1975)
Cell suspension Ehrlich ascites tumour cells	Same	2 min	Ibsen & Schiller (1967, 1971)
Cultured mouse fibroblast (L-cell)	Oscillation in respiratory activity	1-3 min	Werrlein & Glinos (1974)
<i>Klebsiella aerogenes</i>	Same	2-7 min	Degn & Harrison (1971) Harrison (1970)

(C) Oscillatory ion movements in mitochondria

Rat liver mitochondria	Oscillatory ion movement, organelle volume and respiration rate	1-5 min	Carafoli, Gamble & Lehninger (1965, 1966) Falcone & Hadler (1968) Gooch & Packer (1971, 1974 <i>a, b</i> ) Graven, Lardy & Estrada-O. (1967) Graven, Lardy & Rutter (1966) Höfer & Pressman (1966) Lardy & Graven (1965) Mustafa, Utsumi & Packer (1966) Packer, Utsumi & Mustafa (1966)
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Preparation	Event	Period	References
			Pressman (1965) Utsumi & Packer (1967) Wrigglesworth & Packer (1968)
Pigeon heart mitochondria	Same	1 min	Chance & Yoshioka (1966) Deamer, Utsumi & Packer (1967) Gooch & Packer (1974 <i>a, b</i> )
Rat liver mitochondria	Slow oscillation in organelle volume	30 min	Cristea (1966)

#### (D) Oscillations in photosynthesis

Algae	Oscillation in dark cycle photosynthesis	80 min	Wilson & Calvin (1955)
<i>Chorella pyrenoidosa</i>	Oscillation of oxygen evolution	4-6 s	Bannister (1965)

### II. Oscillations in protein synthesis

<i>Bacillus subtilis</i>	Periodic synthesis OCT-ase, ACT-ase, DHQ-ase and histidase	1 h	Masters & Donachie (1966)
<i>Pseudomonas aeruginosa</i>	Periodic synthesis creatine dehydrogenase	2 h	Kleber & Aurich (1967)
<i>P. aeruginosa</i>	Oscillation in amidase activity	40 min	Boddy, Clarke <i>et al.</i> (1967)
<i>Saccaromyces cerevisia</i>	Periodic synthesis glutamate dehydrogenase	6.5 h	Bernhardt, Panten & Holzer (1965)
<i>S. cerevisia</i>	Periodic synthesis alpha-glucosidase	1.5 h	Halvorson <i>et al.</i> (1966)
<i>E. coli</i>	Periodic synthesis beta-galactosidase	50 min	Donachie & Masters (1969) Goodwin (1969) Knorre (1968, 1973)
<i>E. coli</i>	Periodic synthesis pyruvate synthesizing enzymes	1 h	Sikyta & Slezack (1965)
Chinese hamster cells	Periodic activity lactate dehydrogenase, aldolase and G6P dehydrogenase	3-4 h	Gilbert (1969) Klevecz (1969) Klevecz & Ruddle (1968)
<i>Klebsiella aerogenes</i>	Long-period oscillation in respiration	4 h	Harrison & Pirt (1967)
Rat, <i>in vivo</i>	Oscillation in haem biosynthesis	10 h	Waxman, Collins & Tschudy (1966)
Sea-urchin embryo	Cyclic protein synthesis	0.5-1 h	Mano (1970, 1975)

### III. Oscillations in cell membrane potential (see also subsequent sections)

L cells (mouse fibroblast origin)	Oscillation in membrane potential	6-15 s	Nelson & Henkart (1979) Nelson, Peacock & Minna (1972) Okada <i>et al.</i> (1977 <i>a, b</i> , 1978)
<i>Neurospora crassa</i>	Same	1 min	Gradman & Slayman (1975)
<i>Nitella mucronata</i>	Oscillation in cell wall & vacuole potential after electrode insertion	1 min	Radenović & Vúčinić (1976) Radenović, Vúčinić & Damjanović (1977)
<i>Hydrodictyon reticulatum</i> (algae)	Membrane potential oscillation	2 min	Metlicka & Rybova (1967)

Preparation	Event	Period	References
Mammalian macrophage	Oscillation in spontaneous hyperpolarization	1 s	Gallin & Gallin (1977) Gallin <i>et al</i> (1975)
Guinea-pig megakaryocytes	Periodic depolarization	0.25 s	Miller, Sheridan & White (1978)

IV. Oscillations in secretory cells

Clonal line isolated from rat anterior pituitary	Membrane potential oscillation	1 s	Kidokoro (1975)
Rat adenohypophysis	Same	1 s	Poulsen & Williams (1976)
Rabbit adrenal glands	Same	5 s	Matthews & Saffran (1968)
Mouse pancreatic islet cells	Same	0.5-10 s	Atwater, Ribalet & Rojas (1978) Atwater & Beigelman (1976) Beigelman, Ribalet & Atwater (1977) Dean & Matthews (1968, 1970a, b) Dean, Matthews & Sakamoto (1975) Matthews (1975, 1977) Matthews & O'Connor (1979) Matthews & Sakamoto (1975a, b) Meissner (1976a, b) Meissner & Schmelz (1974) Meissner & Schmidt (1976) Pace & Price (1972, 1974)
Fleshfly neuro-secretory cells	Periodic discharge	0.5 s	Bruce & Wilkens (1976)
Blowfly ( <i>Calliphora erythrocephala</i> ) salivary gland	Oscillation in transepithelial and membrane potential	0.5-5 min	Rapp & Berridge (1977)

V. Neural oscillators

(A) Oscillations in neurotransmitter content and release

Electric organ of <i>Torpedo marmorata</i>	Slow and fast oscillations in acetylcholine concentration	4-5 s 1-5 min	Dunant <i>et al.</i> (1974, 1975, 1977) Israel <i>et al.</i> (1975, 1977, 1978, 1979)
Frog neuromuscular junction	Oscillation in transmitter release	2-14 s	Erulkar & Rahamimoff (1976) Meiri & Rahamimoff (1978)

(B) Membrane potential oscillations in single neurones

Blowfly ( <i>Calliphora vomitoria</i> )	Neural firing to flight motor system	0.1 s	Wyman (1966)
<i>Aplysia</i> (marine snail) abdominal ganglion	Periodic discharge and slow wave depolarizations	1-20 s	Alving (1968) Barker & Gainer (1975a, b) Chaplain (1976, 1979) Chaplain & Kramer (1976) Chen, von Baumgarten & Harth (1973) Chen, von Baumgarten & Takeda (1971) Connor & Stevens (1971a, b, c) Fraizer <i>et al.</i> (1967) Gola (1974 b) Gulrajani & Roberge (1978) Ifshin, Gainer & Barker (1975) Levitan, Harmer & Adams (1979) Lickey (1969) Meech (1972, 1974a, b, 1979) Meech & Strumwasser (1970) Parnas <i>et al.</i> (1974)

Preparation	Event	Period	References
			Parnas & Strumwasser (1974) Perkel, Schulzman <i>et al.</i> (1964) Pinsker (1975, 1977 <i>a, b</i> ) Schlapfer <i>et al.</i> (1974) Smith, Barker & Gainer (1975) Stinnakre & Tauc (1969) Strumwasser (1965) Treistman & Levitan (1976) von Baumgarten (1970)
<i>Aplysia burster</i> treated with TTX	Slow membrane potential oscillation persisting after abolition of action potentials	15 s	Barker & Gainer (1975 <i>a</i> ) Junge (1967) Junge & Stephens (1973) Mathieu & Roberge (1971) Strumwasser (1967, 1968, 1971) Strumwasser & Kim (1969)
<i>Aplysia burster</i> with Arsenazo III	Oscillation in absorbance correlated with periodic bursting	20 s	Gorman & Thomas (1978) Thomas & Gorman (1977)
<i>Procambrus</i> (stretch receptor)	Periodic discharge	1 s	Calvin (1978) Perkel <i>et al.</i> (1964)
<i>Helix</i> (land snail)	Slow-wave depolarization	2-20 s	Connor & Stevens (1971 <i>a, b, c</i> ) Eckurt & Lux (1976) Gola (1974 <i>a</i> ) Kerkut & Meech (1966) Lambert (1975) Levitan, Harmar & Adams (1979) Levitan & Treistman (1977) Meech & Standen (1975) Standen (1975) Treistman & Levitan (1976)
<i>Octala lactea</i> (mollusc)	Periodic discharge	0.25-1 s	Barker & Gainer (1974, 1975 <i>a, b</i> ) Barker, Ifshin & Gainer (1975) Gainer (1972 <i>a, b, c</i> ) Smith, Barker, & Gainer (1975)
<i>Archidoris</i> (mollusc) <i>Callinectes</i> (crustacean)	Same	0.1-1 s	Connor (1978)
<i>Homarus</i> (lobster)	Same	10 ms	Cooke & Hartline (1975)
<i>Squilla</i> (shrimp)	Slow-wave neurogenic cardiac oscillation	1-3 s	Watanabe, Obara & Akiyama (1976)
Hermit crab and Lobster	Oscillating nonspiking mem- brane depolarizations	0.5 s	Mendelson (1971)
Coelenterates (including jellyfish)	Periodic pulsations	1 s	Bullock & Horridge (1965)
<i>Onchidium</i> (mollusc)	Periodic discharge	0.2 s	Oomura, Ozaki & Maeno (1961)
<i>Hirudo medicinalis</i> (leech)	Periodic discharge of interneurons	1 s	Friesen, Poon & Stent (1976)
<i>Rana catesbiana</i> (bullfrog)	Rhythmic hyperpolarization of a sympathetic ganglion	2 s	Kuba & Nishi (1976)

## (C) Central nervous system oscillations (EEG)

Review: crickets to mammals	Oscillations in electro- corticogram	1-30 s	Aladjalova (1964)
Mammalian cerebral cortex	EEG	0.1-0.5 s	Bremer (1958) Calvin (1978) Elul (1972) Mountcastle (1968)

Preparation	Event	Period	References
Cat prepyriform cortex	Oscillatory average evoked potentials	20 ms	Freeman (1968)
Cat olfactory bulb	Oscillatory response to stimulus	20 ms	Freeman (1972) von Baumgarten (1975)
Monkey	Oscillatory thalamic discharge sensory neurone	30 ms	Poggio & Viernstein (1964)
Cat: awake or light anesthesia	Slow oscillation in available oxygen	6-48 s	Clark & Mishrahy (1957) Clark & Sachs (1968) Davies & Bronk (1957) Gijbers & Melzack (1967) Travis & Clark (1965)
Cat light anesthesia	Slow oscillation in CNS temperature	7-20 s	Melzack & Casey (1967)
Cat light anesthesia	Slow oscillation in electrocorticogram	4-30 s	Norton & Jewett (1965)
Rabbit hippocampus	Slow potential waves in localized regions near granule cells	0.2 s	Green, Maxwell & Petsche (1961)
Chick embryo	Pacemaker potential in cultured cerebellar explants	5 s	Cunningham & Rylander (1961)

VI. *Muscle oscillations*

(A) **Skeletal muscle**

Frog and rabbit	Oscillatory contraction of a fibre bundle	0.1-0.2 s	Rüegg, Steiger & Schädler (1970)
Skinned muscle fibres	Oscillatory contractions stimulated by caffeine	70 s	Endo, Tanaka & Ogawa (1970)
Cultured chick skeletal muscle	Periodic contractions	1 s	Königsberg (1963)
Giant water bug	Tension oscillation in dorsal longitudinal muscle	0.05 s	Jewell & Rüegg (1966) Pringle (1967) Rüegg (1973)
Locust	Intrinsic rhythm in jumping muscle	20-30 s	Evans & O'Shea (1978) Hoyle (1978)

(B) **Cardiac muscle**

*Cultured cells*

Cultured rat heart	Periodic mechanical and electrical activity	0.1-1 s	Goshima (1973, 1974, 1975, 1976 a, b) Harary, Renaud, Sato & Wallace (1976) Krause <i>et al.</i> (1970) Krause, Halle & Wollenberger (1972) Lawrence, Beers & Gilula (1978)
Cultured chick heart	Same	0.1-1 s	deHaan (1967 a, b, 1968, 1970) deHaan & deFelice (1978) deHaan & Sachs (1972) Lehmkuhl & Sperelakis (1967) Pappano & Sperelakis (1969)
Cultured chick heart cells	Continuing pacemaker depolarizations after suppression of action potentials by TTX	2 s	McDonald & Sachs (1975)

Preparation	Event	Period	References
Cultured chick heart cells	Transient extinction of action potentials at time of electrode insertion	1 s	Fange, Persson & Thesleff (1956)
<i>Purkinje fibres</i>			
Sheep Purkinje fibres	Periodic mechanical and electrical activity	1 s	Cohen, Eisner & Noble (1978) Hauswirth, Noble & Tsien (1969) McAllister, Noble & Tsien (1975) Reuter (1974)
Calf Purkinje fibres	Same	1 s	*Kass <i>et al.</i> (1978) Lederer & Tsien (1976) Reuter (1974) Tsien (1973) Tsien & Carpenter (1978) Tsien, Giles & Greengard (1972) Tsien, Kass & Weingart (1979)
Dog Purkinje fibres	Same	0.4 s	Ferrier (1976)
<i>Atrial muscle</i>			
Rabbit s-a node	Periodic mechanical and electrical activity	0.5-1 s	Brown, Giles & Noble (1977) Noma & Irisawa (1976) Noma, Yanagihara & Irisawa (1977) Pues de Carvalho, <i>et al.</i> (1969) Seifen, Schaer & Marshall (1964) Yamasaki, Fujimara & Toda (1974) Yamasaki, Toda & Fujiwara (1973)
Rabbit s-a node	Oscillation continues in presence of TTX	0.5-1 s	Brown, diFrancesca & Noble (1979) Kreitner (1975)
Guinea-pig atrial muscle	Periodic mechanical and electrical activity	1 s	Jensen & Katzung (1968) Kaufmann, Fleckenstein & Antoni (1963)
Frog atrial muscle	Same	1 s	Brown, Clark & Noble (1972, 1976 <i>a, b</i> ) Brown & Noble (1974)
Carp atrial muscle	Same	0.3 s	Askelrod <i>et al.</i> (1977)
<i>Ventricular muscle</i>			
Dog ventricular muscle	Periodic mechanical and electrical activity	0.3-1 s	Beeler & Reuter (1970) Ferrier (1976)
Turtle ventricular muscle	Same	1-2 s	Bolzer (1943) Bolzer & Delahayes (1973)
Frog ventricular muscle	Oscillation in intracellular cyclic AMP and/or cyclic GMP	1 s	Brooker (1973 <i>a, b</i> , 1975) Wollenberger <i>et al.</i> (1973)
Cat papillary muscle	Periodic mechanical and electrical activity	0.3 s	Mascher (1971)
Guinea-pig papillary muscle	Same	1 s	Kaufmann, Fleckenstein & Antoni (1963) Reiter (1962, 1963)
<b>(C) Smooth muscle</b>			
<i>Digestive tract smooth muscle</i>			
Human stomach smooth muscle	Periodic mechanical and electrical activity	10-30 s	Davenport (1966) El-Sharkawy <i>et al.</i> (1978)
Human and dog stomach smooth muscle	Very slow rhythms in mechanical activity	1.5-2.5 h	Weitz & Vollers (1925)
Dog stomach smooth muscle	Periodic mechanical and electrical activity	10-30 s	Daniel (1965 <i>b</i> ) El-Sharkawy <i>et al.</i> (1978)



Preparation	Event	Period	References
■ Dog stomach smooth muscle	Rhythm continues in presence of TTX	20 s	Szurszewski (1975)
Cat stomach smooth muscle	Rhythm continues in presence of TTX	20 s	Papasova, Nagai & Prosser (1968)
Guinea-pig stomach smooth muscle	Periodic mechanical and electrical activity	10-25 s	Golenhofen & Lammel (1972) Ito, Kuriyama & Sakamoto (1970) Kuriyama, Osa & Tasaki (1970) Ohba, Sakamoto & Tomita (1975, 1977) Ohkawa & Watanabe (1976)
Skate stomach smooth muscle	Same	20 s	Prosser <i>et al.</i> (1977)
<i>Small intestine</i>			
Human small intestine	Periodic mechanical and electrical activity	5 s	Davenport (1966)
Monkey small intestine	Same	5 s	Diamant & Bortoff (1969) Ohkawa & Watanabe (1975)
Dog small intestine	Same	3-12 s	Armstrong, Milton & Smith (1956) Bass, Code & Lambert (1961) Carlson, Bedi & Code (1972) Daniel (1965 <i>a</i> ) Daniel, Honour & Bogoch (1960) Diamant & Bortoff (1969) Szurszewski (1969)
Dog small intestine	Very slow rhythms in mechanical activity	Hours	Templeton & Lawson (1931)
Cat small intestine	Periodic mechanical and electrical activity	3-10 s	Bortoff (1961 <i>a, b</i> , 1965) Connor (1979) Connor, Kreulen & Prosser (1976) Connor, Kreulen, Prosser & Weigel (1977) Connor & Prosser (1974) Connor, Prosser & Weems (1974) Diamant & Bortoff (1969) Kobayashi, Nagai & Prosser (1966) Kobayashi, Prosser & Nagai (1967) Liu, Prosser & Job (1969) Ohkawa (1975, 1976) Ohkawa & Watanabe (1975) Prosser (1978) Prosser <i>et al.</i> (1977) Tamai & Prosser (1966)
Rabbit small intestine	Same	5 s	Bortoff (1961 <i>a, b</i> ) El-Sharkawy & Daniel (1975 <i>a, b, c</i> )
Guinea-pig small intestine	Same	2-5 s	Bolton (1971, 1975) Golenhofen & Lammel (1972) Hidaka & Kuriyama (1969) Kuriyama, Osa & Toida (1967 <i>b</i> )
<i>Large intestine</i>			
Human colon	Periodic mechanical and electrical activity	5-30 s	Ritchie, Ardran & Truelove (1962)
Dog large intestine	Same	5 s	Code & Szurszewski (1970)
Guinea-pig large intestine	Same	10 s	Kuriyama, Osa & Toida (1967 <i>b</i> )
<i>Urogenital tract</i>			
■ Human uterus, urinary bladder, scrotum and penis	Periodic mechanical and electrical activity	1 min	Weitz & Vollers (1926)

Preparation	Event	Period	References
Rabbit uterus	Same	1-2 min	Csapo (1962) Mitznegg, Schubert & Heim (1974) Takeda & Csapo (1961)
Guinea-pig ureter	Same	5-20 s	Golenhofen & Lammel (1972) Kuriyama, Osa & Toida (1967a)
Guinea-pig oviduct	Same	5 s	Tomita & Watanabe (1973)
<i>Circulatory system smooth muscle</i>			
Human peripheral circulation	Blood pressure wave (distinct from pulse wave and respiratory wave)	10-12 s	Golenhofen & Hildebrandt (1958)
Cat spleen	Rhythmic contraction of the spleen	8 s	Barcroft & Nisimaru (1932a, b)

## VII. Oscillations in cell movement, growth and development

### (A) Periodic cell movement in *Physarum polycephalum*

<i>P. polycephalum</i>	Periodic contractions of protoplasmic strands and periodic protoplasmic flow	1-3 min	Fleischer & Wohlfarth-Bottermann (1975) Grebecki & Cieslowska (1978) Hülsmann & Wohlfarth-Bottermann (1978a, Isenberg & Wohlfarth-Bottermann (1976) Kamiya (1959, 1968, 1970) Kishimoto (1958a, b) Krüger & Wohlfarth-Bottermann (1978) Matthews (1977) Sachsenmaier & Hanson (1973) Samans <i>et al.</i> (1978) Takeuchi & Yoneda (1977) Ueda <i>et al.</i> (1978) Wohlfarth-Bottermann (1962, 1965, 1975, 1978) Wohlfarth-Bottermann & Isenberg (1976) Wohlfarth-Bottermann <i>et al.</i> (1977) Yoshimoto & Kamiya (1978a-d)
<i>P. polycephalum</i>	Periodic light emission by aequorin	2 min	Durham & Ridgway (1976) Ridgway & Durham (1976)

### (B) Periodic movement during aggregation in *Dictyostelium* and *Polyspondylium*

<i>D. mucoroides</i>	Periodic movement	5 min	Arndt (1937)
<i>D. discoideum</i>	Periodic movement	5-10 min	Alcantara & Monk (1974) Durstion (1974a, b) Gerisch (1968, 1971) Robertson & Drage (1975) Robertson, Drage & Cohen (1972) Shaffer (1957, 1962)
<i>D. discoideum</i>	Periodic synthesis of cyclic AMP	10 min	Shaffer (1975)
<i>D. discoideum</i>	Oscillatory light scattering, internal cyclic AMP, adenylate cyclase activity and redox state of cytochrome b	10 min	Gerisch & Hess (1974) Gerisch & Malchow (1976) Gerisch, Malchow <i>et al.</i> (1975) Gerisch & Wick (1975) Malchow, Nanjundiah & Gerisch (1978) Roos & Gerisch (1976) Roos, Scheidegger & Gerisch (1977)
<i>D. discoideum</i>	Periodic synthesis cyclic GMP	10 min	Wurster <i>et al.</i> (1977)

Preparation	Event	Period	References
<i>P. violaceum</i>	Periodic movement	1.5 min	Cohen & Robertson (1971)

**(C) Periodic mitosis in *Physarum polycephalum***

<i>P. polycephalum</i>	Periodic mitosis	8-12 h	Kauffman & Willie (1975) Rusch, Sachsenmaier, Berens & Gruter (1966) Sachsenmaier & Hansen (1973) Sachsenmaier, Remy & Plattner-Schobel (1972)
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**(D) Periodic spore release and growth in Ascomycetes**

<i>Asobolus immersus</i>	Branching pattern rhythm	26 h	Berliner & Neurath (1965)
<i>Nectria cinnabarina</i>	Periodic spore release	6-16 h	Bourret, Lincoln & Carpenter (1969)
<i>Penicillium diversum</i>	Same	24 h	Bourret <i>et al.</i> (1969)
<i>Nectria cinnabarina</i>	Same	16 h	Winfree (1970, 1973)

**(E) Periodic events in development**

<i>Hydra</i>	Rhythmic contractions and potential spikes	0.1 min	Passano & McCullough (1964, 1965)
<i>Dynamena pumila</i>	Periodic movement	14 min	Belousov <i>et al.</i> (1972)
<i>Obelia loveni</i>	Same	5-8 min	Belousov <i>et al.</i> (1972)
<i>Acetabularia mediterranea</i>	Action potential during regeneration	10-25 min	Novák & Bentrup (1972)
<i>Pelvetia</i> (seaweed)	Current pulses in developing eggs	0.2-1 h	Nuccitelli & Jaffe (1974)
<i>Triturus alpestris</i>	Oscillations during closure of the neural fold	5 min	Selman (1958)
<i>Ambystoma mexicanum</i>	Same	30 min	Selman (1958)
Chick embryo	Periodicity in wing and leg motility	35-75 s	Hamburger & Balaban (1963)
<i>Tubularia</i>	Periodic contractions during hydranth regeneration	4-10 min	Goodwin (1974)
Sea-urchin embryo	Periodic variation in 5-HT associated with contractile activity	10-20 h	Gustafson & Toneby (1971)

**VIII. Miscellaneous**

<i>Avena</i> (oat plant)	Oscillation in transpiration and water uptake	30 min	Brogårdh & Johnsson (1973, 1974) Johnsson (1973)
Fireflies	Periodic flashing	0.5-1 s	Buck & Buck (1966) Hanson (1978)
<i>Chlorella fusca</i>	Damped oscillation in ATP	40 s	Lewenstein & Bachofen (1972)

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