AN ATLAS OF CELLULAR OSCILLATORS

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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.
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

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<th>Preparation</th>
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<tbody>
<tr>
<td>Purified horseradish peroxidase</td>
<td>Periodic rate of catalysed oxidation</td>
<td>1 min</td>
<td>Degrn (1968, 1969, 1973)</td>
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<td></td>
<td></td>
<td></td>
<td>Degrn &amp; Mayer (1969)</td>
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<td></td>
<td>Yamazaki, Yokota &amp; Nakajima (1965)</td>
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<td></td>
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<td></td>
<td>Yamazaki &amp; Yokota (1967, 1973a, b)</td>
</tr>
<tr>
<td>Purified lactoperoxidase</td>
<td>Oscillatory oxidation of NADH</td>
<td>2 min</td>
<td>Degrn (1973)</td>
</tr>
<tr>
<td>Heart muscle extract</td>
<td>Oscillation in creatine kinase activity</td>
<td>3–10 min</td>
<td>Nakamura, Yokota &amp; Yamazaki (1969)</td>
</tr>
<tr>
<td>Scenedesmus (algae)</td>
<td>Oscillation in ammonium efflux</td>
<td>1–3 min</td>
<td>Chetverikova (1973)</td>
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<tr>
<td>Kidney and brain microsomes (rabbit)</td>
<td>Oscillation in phosphorylated protein &amp; ATPase activity (associated with oscillatory ion transport)</td>
<td>1–2.5 min</td>
<td>Fukushima &amp; Tonomura (1972)</td>
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### (B) The glycolytic oscillator

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

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<tr>
<td>Rat liver mitochondria</td>
<td>Oscillatory ion movement, organelle volume and respiration rate</td>
<td>1-5 min</td>
<td>Carafoli, Gamble &amp; Lehninger (1965, 1966)</td>
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<td>Falcone &amp; Hadler (1968)</td>
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<td>Gooch &amp; Packer (1971, 1974 a, b)</td>
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<td>Graven, Lardy &amp; Estrada-O. (1967)</td>
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<td>Graven, Lardy &amp; Rutter (1966)</td>
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<td>Höfer &amp; Pressman (1966)</td>
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<td>Lardy &amp; Graven (1965)</td>
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<td>Mustafa, Utsumi &amp; Packer (1966)</td>
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<td>Packer, Utsumi &amp; Mustafa (1966)</td>
</tr>
</tbody>
</table>
### Oscillations in photosynthesis

#### Algae

- **Chorella pyrenoidosa**
  - Oscillation in dark cycle photosynthesis
  - Period: 80 min
  - Reference: Wilson & Calvin (1955)

### Oscillations in protein synthesis

- **Bacillus subtilis**
  - Periodic synthesis of OCT-ase, ACT-ase, DHQ-ase and histidase
  - Period: 1 h
  - Reference: Masters & Donachie (1966)

- **Pseudomonas aeruginosa**
  - Periodic synthesis of creatine dehydrogenase
  - Period: 2 h
  - Reference: Kleber & Aurich (1967)

- **P. aeruginosa**
  - Oscillation in amidase activity
  - Period: 40 min
  - Reference: Boddy, Clarke et al. (1967)

- **Saccharomyces cerevisia**
  - Periodic synthesis of glutamate dehydrogenase
  - Period: 6.5 h
  - Reference: Bernhardt, Panten & Holzer (1965)

- **S. cerevisia**
  - Periodic synthesis of alpha-glucosidase
  - Period: 1.5 h
  - Reference: Halvorson et al. (1966)

- **E. coli**
  - Periodic synthesis of beta-galactosidase
  - Period: 50 min

- **E. coli**
  - Periodic synthesis of pyruvate synthesizing enzymes
  - Period: 1 h
  - Reference: Sikyta & Slezack (1965)

- **Chinese hamster cells**
  - Periodic activity of lactate dehydrogenase, aldolase and G6P dehydrogenase
  - Period: 3–4 h

- **Klebsiella aerogenes**
  - Long-period oscillation in respiration
  - Period: 4 h
  - Reference: Harrison & Pirt (1967)

- **Rat, in vivo**
  - Oscillation in haem biosynthesis
  - Period: 10 h
  - Reference: Waxman, Collins & Tschudy (1966)

- **Sea-urchin embryo**
  - Cyclic protein synthesis
  - Period: 0.5–1 h

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

- **L cells (mouse fibroblast origin)**
  - Oscillation in membrane potential
  - Period: 6–15 s
  - References: Nelson & Henkart (1979), Nelson, Peacock & Minna (1972), Okada et al. (1977, a, b, 1978)

- **Neurospora crassa**
  - Same
  - Period: 1 min
  - Reference: Gradman & Slayman (1975)

- **Nitella mucronata**
  - Oscillation in cell wall & vacuole potential after electrode insertion
  - Period: 1 min
  - References: Radenovič & Vučinić (1976), Radenovič, Vučinić & Damjanović (1977)

- **Hydrodictyon reticulatum (algae)**
  - Membrane potential oscillation
  - Period: 2 min
  - Reference: Metlicka & Rybova (1967)
### IV. Oscillations in secretory cells

<table>
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<th>Preparation</th>
<th>Event</th>
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<tr>
<td>Clonal line isolated from rat anterior pituitary</td>
<td>Membrane potential oscillation</td>
<td>1 s</td>
<td>Kidokoro (1975)</td>
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<td>Rat adenohypophysis</td>
<td>Same</td>
<td>1 s</td>
<td>Poulsen &amp; Williams (1976)</td>
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<td>Rabbit adrenal glands</td>
<td>Same</td>
<td>5 s</td>
<td>Matthews &amp; Saffran (1968)</td>
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<td>Mouse pancreatic islet cells</td>
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<tr>
<td>Fleshfly neuro-secretory cells</td>
<td>Periodic discharge</td>
<td>0.5 s</td>
<td>Bruce &amp; Wilkens (1976)</td>
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<tr>
<td>Blowfly (Calliphora erythrocephala) salivary gland</td>
<td>Oscillation in transepithelial and membrane potential</td>
<td>0.5–5 min</td>
<td>Rapp &amp; Berridge (1977)</td>
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### V. Neural oscillators

#### (A) Oscillations in neurotransmitter content and release

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<td>Electric organ of <em>Torpedo marmorata</em></td>
<td>Slow and fast oscillations in acetylcholine concentration</td>
<td>4–5 s</td>
<td>Dunant et al. (1974, 1975, 1977)</td>
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<td></td>
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<td>1–5 min</td>
<td>Israel et al. (1975, 1977, 1978, 1979)</td>
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<td>Frog neuromuscular junction</td>
<td>Oscillation in transmitter release</td>
<td>2–14 s</td>
<td>Erulkar &amp; Rahamimoff (1976)</td>
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<td>Meiri &amp; Rahamimoff (1978)</td>
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#### (B) Membrane potential oscillations in single neurones

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<tr>
<td>Blowfly (Calliphora vomitoria) abdominal ganglion</td>
<td>Neural firing to flight motor system</td>
<td>0.1 s</td>
<td>Wyman (1966)</td>
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<td><em>Aplysia</em> (marine snail) abdominal ganglion</td>
<td>Periodic discharge and slow wave depolarizations</td>
<td>1–20 s</td>
<td>Alving (1968)</td>
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<td>Barker &amp; Gainer (1975a, b)</td>
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<td>Chaplain (1976, 1979)</td>
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<td>Chaplain &amp; Kramer (1976)</td>
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<td>Chen, von Baumgarten &amp; Harth (1973)</td>
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<td>Chen, von Baumgarten &amp; Takeda (1971)</td>
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<td>Connor &amp; Stevens (1971a, b, c)</td>
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<td>Fraizer et al. (1967)</td>
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<td>Gola (1974 b)</td>
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<td>Gulrajani &amp; Roberge (1978)</td>
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<td>Ifshin, Gainer &amp; Barker (1973)</td>
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<td>Levitan, Harmer &amp; Adams (1979)</td>
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<td>Lickey (1969)</td>
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<td>Meech (1972, 1974a, b, 1979)</td>
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<td>Meech &amp; Strumwasser (1970)</td>
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<td>Parnas et al. (1974)</td>
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<td><em>Aplysia burster</em></td>
<td>Slow membrane potential oscillation persisting after abolition of action potentials</td>
<td>15 s</td>
<td>Barker &amp; Gainer (1975a)</td>
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<tr>
<td>treated with TTX</td>
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<td>Junge (1967)</td>
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<td><em>Aplysia burster</em></td>
<td>Oscillation in absorbance correlated with periodic bursting</td>
<td>20 s</td>
<td>Junge &amp; Stephens (1973)</td>
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<td>with Arsenazo III</td>
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<td>Mathieu &amp; Roberge (1971)</td>
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<td>Periodic discharge</td>
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<td>Strumwasser (1967, 1968, 1971)</td>
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<td>Strumwasser &amp; Kim (1969)</td>
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<td><em>Helix</em> (land snail)</td>
<td>Slow-wave depolarization</td>
<td>2–20 s</td>
<td>Calvin (1978)</td>
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<td><em>Octala lactea</em></td>
<td>Periodic discharge</td>
<td>0.25–1 s</td>
<td>Perkel et al. (1964)</td>
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<td>(mollusc)</td>
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<td>Gola (1974a)</td>
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<td><em>Archidoris</em> (mollusc)</td>
<td>Same</td>
<td>0.1–1 s</td>
<td>Kerkut &amp; Meech (1966)</td>
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<td><em>Callinectes</em></td>
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<td>0.1–1 s</td>
<td>Lambert (1975)</td>
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<td>(crustacean)</td>
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<td>Levitan, Harmar &amp; Adams (1979)</td>
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<td><em>Homarus</em> (lobster)</td>
<td>Same</td>
<td>10 ms</td>
<td>Levitan &amp; Treistman (1977)</td>
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<td><em>Squilla</em> (shrimp)</td>
<td>Slow-wave neurogenic cardiac oscillation</td>
<td>1–3 s</td>
<td>Meech &amp; Standen (1975)</td>
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<td><em>Hermit crab and</em></td>
<td>Oscillating nonspiking membrane depolarizations</td>
<td>0.5 s</td>
<td>Standen (1975)</td>
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<td>Lobster</td>
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<td>Treistman &amp; Levitan (1976)</td>
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<td><em>Octopus</em></td>
<td>Periodic discharge</td>
<td>0.2 s</td>
<td>Barker &amp; Gainer (1974, 1975a, b)</td>
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<td>(including jellyfish)</td>
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<td>Barker, Ifshin &amp; Gainer (1975)</td>
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<td><em>Onchidium</em> (mollusc)</td>
<td>Periodic discharge</td>
<td>0.2 s</td>
<td>Gainer (1972a, b, c)</td>
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<td><em>Hirudo medicinales</em></td>
<td>Periodic discharge of interneurones</td>
<td>1 s</td>
<td>Smith, Barker, &amp; Gainer (1975)</td>
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<td>(leech)</td>
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<td><em>Rana catesbiana</em></td>
<td>Rhythmic hyperpolarization of a sympathetic ganglion</td>
<td>2 s</td>
<td>Kuba &amp; Nishi (1976)</td>
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<td>(bullfrog)</td>
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<td><strong>(C) Central nervous system oscillations (EEG)</strong></td>
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<td>Review: crickets to mammals</td>
<td>Oscillations in electro- corticogram</td>
<td>1–30 s</td>
<td>Aladjalova (1964)</td>
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<td>Mammalian cerebral cortex</td>
<td>EEG</td>
<td>0.1–0.5 s</td>
<td>Bremer (1958)</td>
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<tr>
<td>Cat prepyriform cortex</td>
<td>Oscillatory average evoked potentials</td>
<td>20 ms</td>
<td>Freeman (1968)</td>
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<td>Cat olfactory bulb</td>
<td>Oscillatory response to stimulus</td>
<td>20 ms</td>
<td>Freeman (1972)</td>
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<td>von Baumgarten (1975)</td>
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<td>Monkey</td>
<td>Oscillatory thalamic discharge</td>
<td>30 ms</td>
<td>Poggio &amp; Viernstein (1964)</td>
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<td>sensory neurone</td>
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<td>Cat: awake or light anesthesia</td>
<td>Slow oscillation in available oxygen</td>
<td>6–48 s</td>
<td>Clark &amp; Mishrahy (1957)</td>
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<td>Clark &amp; Sachs (1968)</td>
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<td>Davies &amp; Bronk (1957)</td>
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<td>Gijsbers &amp; Melzack (1967)</td>
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<td>Travis &amp; Clark (1965)</td>
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<td>Cat light anesthesia</td>
<td>Slow oscillation in CNS temperature</td>
<td>7–20 s</td>
<td>Melzack &amp; Casey (1967)</td>
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<tr>
<td>Cat light anesthesia</td>
<td>Slow oscillation in electrocorticogram</td>
<td>4–30 s</td>
<td>Norton &amp; Jewett (1965)</td>
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<tr>
<td>Rabbit hypocampus</td>
<td>Slow potential waves in localized regions near granule cells</td>
<td>0.2 s</td>
<td>Green, Maxwell &amp; Petsche (1961)</td>
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<tr>
<td>Chick embryo</td>
<td>Pacemaker potential in cultured cerebellar explants</td>
<td>5 s</td>
<td>Cunningham &amp; Rylander (1961)</td>
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</table>

VI. Muscle oscillations

(A) Skeletal muscle

Frog and rabbit Oscillatory contraction of a fibre bundle 0.1–0.2 s Ruegg, 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 & Ruegg (1966)
Pringle (1967)
Ruegg (1973)
Locust Intrinsic rhythm in jumping 20–30 s muscle 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 et al. (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
- **Preparation**: Transient extinction of action potentials at time of electrode insertion
- **Period**: 1 s
- **References**: Fange, Persson & Thesleff (1956)

### Sheep Purkinje fibres
- **Preparation**: Periodic mechanical and electrical activity
- **Period**: 1 s

### Calf Purkinje fibres
- **Preparation**: Same
- **Period**: 1 s

### Dog Purkinje fibres
- **Preparation**: Same
- **Period**: 0.4 s
- **References**: Ferrier (1976)

## Atrial muscle

### Rabbit s-a node
- **Preparation**: Periodic mechanical and electrical activity
- **Period**: 0.5-1 s

### Guinea-pig atrial muscle
- **Preparation**: Periodic mechanical and electrical activity
- **Period**: 1 s
- **References**: Jensen & Katzung (1968), Kaufmann, Fleckenstein & Antoni (1963)

### Frog atrial muscle
- **Preparation**: Same
- **Period**: 1 s

### Carp atrial muscle
- **Preparation**: Same
- **Period**: 0.3 s
- **References**: Askelrod *et al.* (1977)

## Ventricular muscle

### Dog ventricular muscle
- **Preparation**: Periodic mechanical and electrical activity
- **Period**: 0.3-1 s

### Turtle ventricular muscle
- **Preparation**: Same
- **Period**: 1-2 s
- **References**: Bolzer (1943), Bolzer & Delahayes (1973)

### Frog ventricular muscle
- **Preparation**: Oscillation in intracellular cyclic AMP and/or cyclic GMP
- **Period**: 1 s
- **References**: Brooker (1973a, b, 1975), Wollenberger *et al.* (1973)

### Cat papillary muscle
- **Preparation**: Periodic mechanical and electrical activity
- **Period**: 0.3 s
- **References**: Mascher (1971)

### Guinea-pig papillary muscle
- **Preparation**: Same
- **Period**: 1 s
- **References**: Kaufmann, Fleckenstein & Antoni (1963), Reiter (1962, 1963)

## (C) Smooth muscle

### Digestive tract smooth muscle

### Human stomach smooth muscle
- **Preparation**: Periodic mechanical and electrical activity
- **Period**: 10-30 s
- **References**: Davenport (1966), El-Sharkawy *et al.* (1978)

### Human and dog stomach smooth muscle
- **Preparation**: Very slow rhythms in mechanical activity
- **Period**: 1.5-2.5 h
- **References**: Weitz & Vollers (1925)

### Dog stomach smooth muscle
- **Preparation**: Periodic mechanical and electrical activity
- **Period**: 10-30 s
- **References**: Daniel (1965b), El-Sharkawy *et al.* (1978)
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<th>Preparation</th>
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<th>Period</th>
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<tr>
<td>Dog stomach smooth muscle</td>
<td>Rhythm continues in presence of TTX</td>
<td>20 s</td>
<td>Szurszewski (1975)</td>
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<tr>
<td>Cat stomach smooth muscle</td>
<td>Rhythm continues in presence of TTX</td>
<td>20 s</td>
<td>Papasova, Nagai &amp; Prosser (1968)</td>
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<tr>
<td>Skate stomach smooth muscle</td>
<td>Same</td>
<td>20 s</td>
<td>Prosser et al. (1977)</td>
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<tr>
<td>Human small intestine</td>
<td>Periodic mechanical and electrical activity</td>
<td>5 s</td>
<td>Davenport (1966)</td>
</tr>
<tr>
<td>Monkey small intestine</td>
<td>Same</td>
<td>5 s</td>
<td>Diamant &amp; Bortoff (1969) Ohkawa &amp; Watanabe (1975)</td>
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<tr>
<td>Dog small intestine</td>
<td>Very slow rhythms in mechanical activity</td>
<td>Hours</td>
<td>Templeton &amp; Lawson (1931)</td>
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<tr>
<td>Rabbit small intestine</td>
<td>Same</td>
<td>5 s</td>
<td>Bortoff (1961a, b) El-Sharkawy &amp; Daniel (1975a, b, c)</td>
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<tr>
<td>Human colon</td>
<td>Periodic mechanical and electrical activity</td>
<td>5–30 s</td>
<td>Ritchie, Ardran &amp; Truelove (1962)</td>
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<tr>
<td>Dog large intestine</td>
<td>Same</td>
<td>5 s</td>
<td>Code &amp; Szurszewski (1970)</td>
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<tr>
<td>Guinea-pig large intestine</td>
<td>Same</td>
<td>10 s</td>
<td>Kuriyama, Osa &amp; Toida (1967b)</td>
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<tr>
<td>Human uterus, urinary bladder, scrotum and penis</td>
<td>Periodic mechanical and electrical activity</td>
<td>1 min</td>
<td>Weitz &amp; Vollers (1926)</td>
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**Small intestine**
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<th>Period</th>
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<tr>
<td>Rabbit uterus</td>
<td>Same</td>
<td>1–2 min</td>
<td>Csapo (1962)</td>
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<td></td>
<td></td>
<td></td>
<td>Mitznegg, Schubert &amp; Heim (1974)</td>
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<td></td>
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<td>Takeda &amp; Csapo (1961)</td>
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<tr>
<td>Guinea-pig ureter</td>
<td>Same</td>
<td>5–20 s</td>
<td>Golenhofen &amp; Lammel (1972)</td>
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<td></td>
<td></td>
<td></td>
<td>Kuriyama, Osa &amp; Toida (1967a)</td>
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<tr>
<td>Guinea-pig oviduct</td>
<td>Same</td>
<td>5 s</td>
<td>Tomita &amp; Watanabe (1973)</td>
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<tr>
<td>Human peripheral circulation</td>
<td>Blood pressure wave</td>
<td>10–12 s</td>
<td>Golenhofen &amp; Hildebrandt (1958)</td>
</tr>
<tr>
<td></td>
<td>(distinct from pulse wave</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>and respiratory wave)</td>
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<tr>
<td>Cat spleen</td>
<td>Rhythmic contraction of the</td>
<td>8 s</td>
<td>Barcroft &amp; Nisimaru (1932a, b)</td>
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<tr>
<td></td>
<td>spleen</td>
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**Circulatory system smooth muscle**

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

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

*P. polycephalum*  Periodic contractions of protoplasmic strands and periodic protoplasmic flow 1–3 min

- Fleischer & Wohlfarth-Bottermann (1975)
- Grebecki & Cieslawska (1978)
- Kishimoto (1958a, b)
- Krüger & Wohlfarth-Bottermann (1978)
- Matthews (1977)
- Sachsenmaier & Hanson (1973)
- Samans et al. (1978)
- Takeuchi & Yoneda (1977)
- Ueda et al. (1978)
- Wohlfarth-Bottermann & Isenberg (1976)
- Wohlfarth-Bottermann & I. (1977)
- Yoshimoto & Kamiya (1978a-d)

*P. polycephalum*  Periodic light emission by aequorin 2 min

- Durham & Ridgway (1976)
- Ridgway & Durham (1976)

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

*D. mucoroides*  Periodic movement 5 min

- Arndt (1937)
- Alcantara & Monk (1974)
- Durston (1974a, b)
- Gerisch (1968, 1971)
- Robertson & Drage (1975)
- Robertson, Drage & Cohen (1972)
- Shaffer (1957, 1962)

*D. discoideum*  Periodic movement 5–10 min

- Shaffer (1975)
- Gerisch & Malchow (1976)
- Gerisch, Malchow et al. (1975)
- Gerisch & Wick (1975)
- Malchow, Nanjundiah & Gerisch (1978)
- Roos & Gerisch (1976)
- Roos, Scheidegger & Gerisch (1977)

*D. discoideum*  Periodic synthesis of cyclic AMP 10 min

- Wurster et al. (1977)

*D. discoideum*  Oscillatory light scattering, internal cyclic AMP, adenylate cyclase activity and redox state of cytochrome b 10 min

- Gerisch & Malchow (1976)
- Gerisch, Malchow et al. (1975)
- Gerisch & Wick (1975)
- Malchow, Nanjundiah & Gerisch (1978)
- Roos & Gerisch (1976)
- Roos, Scheidegger & Gerisch (1977)

*D. discoideum*  Periodic synthesis of cyclic GMP 10 min
### Preparation

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<tr>
<td><em>P. violaceum</em></td>
<td>Periodic movement</td>
<td>1.5 min</td>
<td>Cohen &amp; Robertson (1971)</td>
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<tr>
<td><em>P. polycephalum</em></td>
<td>Periodic mitosis</td>
<td>8-12 h</td>
<td>Kauffman &amp; Willie (1973)</td>
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<td></td>
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<td>Rusch, Sachsenmaier, Berens &amp; Gruter (1966)</td>
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<td>Sachsenmaier &amp; Hansen (1973)</td>
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<td></td>
<td>Sachsenmaier, Remy &amp; Plattner-Schobel (1972)</td>
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### (C) Periodic mitosis in *Physarum polycephalum*

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<td><em>P. polycephalum</em></td>
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<td>Kauffman &amp; Willie (1973)</td>
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<td>Rusch, Sachsenmaier, Berens &amp; Gruter (1966)</td>
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<td>Sachsenmaier, Remy &amp; Plattner-Schobel (1972)</td>
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### (D) Periodic spore release and growth in Ascomycetes

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<tr>
<td><em>Asobolus immersus</em></td>
<td>Branching pattern rhythm</td>
<td>26 h</td>
<td>Berliner &amp; Neurath (1965)</td>
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<td><em>Nectria cinnabarina</em></td>
<td>Periodic spore release</td>
<td>6-16 h</td>
<td>Bourret, Lincoln &amp; Carpenter (1969)</td>
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<td><em>Penicillium diversum</em></td>
<td>Same</td>
<td>24 h</td>
<td>Bourret et al. (1969)</td>
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<tr>
<td><em>Nectria cinnabarina</em></td>
<td>Same</td>
<td>16 h</td>
<td>Winfree (1970, 1973)</td>
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### (E) Periodic events in development

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

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<td><em>Avena</em> (oat plant)</td>
<td>Oscillation in transpiration and water uptake</td>
<td>30 min</td>
<td>Brogårdh &amp; Johnsson (1973, 1974)</td>
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<td>Johnsson (1973)</td>
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<td>Fireflies</td>
<td>Periodic flashing</td>
<td>0.5-1 s</td>
<td>Buck &amp; Buck (1966)</td>
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<td>Hanson (1978)</td>
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<td><em>Chlorella fusca</em></td>
<td>Damped oscillation in ATP</td>
<td>40 s</td>
<td>Lewenstein &amp; Bachofen (1972)</td>
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BREBECI, A. & CIESLAWSKA, M. (1978). Plasmodium of


GREBECKI, A. & CIESLAWSKA, M. (1978). Plasmodium of...


Kobayashi, M., Nagai, T. & Prosser, C. L. (1966). Electrical interaction between muscle layers of
Kuba, K. & Koketsu, K. (1976). Decrease of Na conductance during desensitisation of the frog end-
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muscle of the guinea pig. J. Physiol., Lond. 191, 239-255.
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