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K.S. MERESCHKOWSKY AND THE ORIGIN OF THE EUKARYOTIC CELL: 111 YEARS OF SYMBIOGENESIS THEORY

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Abstract

Theory of symbiogenesis proposed 111 years ago by K.S. Mereschkowsky, postulated the emergence of plants through the integration of phototrophic microbes into heterotrophic host cells. To date, it has become apparent that this theory can be relevant to describe an extremely wide range of evolutionary processes induced in the systems of cooperative adaptation. We have proposed a new definition of symbiogenesis as of a multi-stage process converting the symbiotic system into the entire organism (holobiont), based on the formation of an integral partners' system of heredity. This system emerges in the course of transition of partners from facultative to obligatory symbiosis and evolves from the functional integrity, based on the signaling partners' interactions (symbiogenome) to the structural integrity, based on the exchange of partners' genes (hologenome). Trade-off between the proposed approach with the symbiogenesis theory of K.S. Mereschkowsky is shown using the material of paper «The nature and origin of chromatophores in the plant kingdom» (C. Mereschkowsky 1905. Über Natur und Ursprung der Chromatophoren im Pflanzenreiche. Biologisches Centralblatt 25: 593-604). We analyzed the relationship of traditional argumentation of symbiogenesis (genetic continuity of the cellular organelles based on their transmission in the host generations) with its current argumentation, used by the Theory of Serial Endosymbioses (TSE) proposed by L. Margulis: a) the presence of rudimental organelle genomes; b) phylogenetic kinship of organelles with the free-living and symbiotic microorganisms; c) identification of the transitional cellular forms bridging the free-living bacteria and organelles. Modern versions of TSE suggest that the introduction of aerobic α-proteobacteria into anaerobic archaea gave rise to eukaryotes, which further evolved through the recruiting into their cellular structures of additional endosymbionts, including phototrophic cyanobacteria and viruses. The forms of archaea, close to the common ancestor of eukaryotes, are represented by the newly discovered chemotrophic *Lokiarchaeota* which cells are characterized by a number of eukaryotic features, including the actin cytoskeleton and the ability for endocytosis. Convincing evidence in favor of TSE was obtained in the study of cyanelles (phototrophic symbionts of protozoa, combining the properties of free-living cyanobacteria and plastids), as well as insects' endocytobionts with the deeply reduced genome (less than 200 kb), which, in contrast to mitochondria and plastids, retained the ability to implement autonomously the basic template processes — replication, transcription, translation. One of the intriguing destinations of modern TSE is the analysis of the emergence of the nucleus and chromosomes, which may be associated with the introduction of highly organized «giant» DNA-viruses into ancestral cellular forms having RNA genomes (the hypothesis of viral eukaryogenesis).

Keywords: symbiogenesis theory, evolution of bacterial genome, plastids and mitochondria, origin of eukaryotic cell, holobiont, hologenome and symbiogenome, theory of serial endosymbiosis

Development of the theory of symbiogenesis is the milestone achievement of 20th century biology. It was conceived at the turn of 19th century based on a hypothesis on symbiotic origin of chloroplasts proposed by A.S. Famintsyn and K.S. Mereschkowsky. To date, the theory of symbiogenesis has developed into a general biological concept, which ascribes evolution of major cell organization forms to their symbiotic relations, represented by the formula: bacteria + archaea = eukaryotes. At the same time, the correlation between the classical theory of

symbiogenesis and its present-day versions, considering the formation of cell organelles as further evolution of symbiotic bacteria, representing various levels of their integration with host organisms, is still poorly understood.

Our purpose was to perform a hindsight analysis of symbiogenesis concept, based on comparison of its classical version, presented by K.S. Mereschkowsky in 1905-1910, with the theory of serial endosymbiosis, developed in 1960-1980, as well as with present-day hypotheses on origin of the main components of an eukaryotic cell, including the nucleus and chromosomes, founded on this theory. This approach allows us to give a new definition of symbiogenesis, as well as to demonstrate the continuity of various stages of integrative evolution, during which genetically independent organisms form supraspecific complexes with shared systems of heredity.

In the authorized Russian translation of the first work of K.S. Mereschkowsky, which focused on symbiogenesis concept justification [1] and was published in German, several out-of-date taxonomic names are replaced by modern equivalents (doi: 10.15389/agrobiology.2016.5.746rus). The addendum published by K.S. Mereschkowsky two months after the main paper had its own reference list, and we took the liberty of combining it with the main reference list; the annotated strict English translation may be recommended for clarifications (2).

Notes in the text will be useful for comparison of out-of-date and modern terms and definitions.

Symbiogenesis as a key strategy of evolutionary process (*notes to translation*). The theory of symbiogenesis proposed by K.S. Mereschkowsky 111 years ago [1] currently represents one of the best developed divisions of evolutionary biology. Development of this theory was preceded by works of A.S. Famintsyn and O.V. Baranetsky [3], who isolated the free-living green algae *Trebuoxia* apart from lichens which were previously considered as unitary organisms. Based on these results, A.S. Famintsyn [4] attempted to prove that phototrophic components (chromatophores) extracted from another lower plant, i.e. algae *Vaucheria*, are able to exist independently; however, these attempts were fruitless.

Nevertheless, the works of A.S. Famintsyn formed the basis for development of symbiology [5], which was closely related to evolutionism from the very start. Anton de Bary [6] defined symbiosis as «the living together of differently named organisms», where mutualistic and antagonistic (parasitic) interactions are connected by frequent evolutionary transitions [7]. Considering symbiosis as an analog of hybridization (in Greek symbiosis — living together, irregular marriage), A. de Bary preempted the development of symbiogenetics, analyzing supraspecific systems of heredity, which control the development of deeply integrated superorganismic complexes (symbiotic, biocenotic, etc.) [8].

Properties of two plasmas — major cellular forms recognized by K.S. Mereschkowsky [9, 10]

Mycoplasma (bacteria, cyanophyceae[a], fungi)	Amoeboplasma (animals, protozoa)
Has the ability of protein formation from inorganic substances	Has no ability of protein formation from inorganic substances
Tolerates the temperatures up to 90 °C and higher	Does not tolerate the temperatures above 50 °C
Consume hydrocyanic acid, strychnine, morphine. High tolerance	Hydrocyanic acid, strychnine, morphine are strong poisons. Low tolerance
No amoeboid movement, no formation of pulsating vacuoles	Amoeboid movement, formation of pulsating vacuoles
Rich in nuclein	Does not contain nuclein
Can exist without oxygen	Can not exist without oxygen

Note. a — cyanobacteria.

The symbiogenesis concept was formulated by K.S. Mereschkowsky in the context of the theory of two plasmas [9, 10], providing for existence of cell

organization forms with independent origin, which, however, are able to combine into novel organisms (see table). According to K.S. Mereschkowsky, the plant living form appeared as a result of invasion of phototrophic representatives of mycoplasma (cyanobacteria) into heterotrophic amoeboplasma; the former give birth to cell organelles (chromatophores). K.S. Mereschkowsky considered genetic continuity of these cell components (binary fission and inability to differentiate from unstructured protoplasm), related to vertical transmission of organelles during reproduction of hosts, as the main criterion of symbiogenic origin of these cell components [1, 9].

Creation of the theory of symbiogenesis by K.S. Mereschkowsky became the culminating point of a 40-year long development of concepts of close cooperation between phototrophic and heterotrophic organisms. Based on the data on binary fission of chloroplasts provided by C. Nageli [11], as well as on the data on their development from colorless proplastids provided by A.F.W. Schimper [12, 13], K.S. Mereschkowsky [1, 9] came to a conclusion that chloroplasts are independent organisms, rather than plant cell organs, developing during its protoplasm differentiation. The author's reference to genetic concepts, which was quite novel in the early 19th century, played an important role in substantiation of symbiotic origin of chloroplasts.

Novelty of K.S. Mereschkowsky's approach was not associated with the hypothesis on symbiotic origin of chloroplasts proposed by him, as it was earlier formulated by A. Schimper [12, 13] and F. Schmidt (14); it was attributable to identification of possible ancestors of chloroplasts, i.e. cyanobacteria and zoochlorellas (unicellular algae, photobionts of invertebrates). This opened up the possibility of verification of the theory of symbiogenesis. The conclusions on symbiogenic origin of differences between plant and animal living forms, observed at the cellular, organismic and ecological levels, were also a breakthrough. The assumption that the presence of photosynthesizing symbionts can make an aggressive lion behave like a peaceful palm tree is a good example of the power of K.S. Mereschkowsky's scientific foresight. The hypothesis on direct origination of plants from animals by obtaining chloroplasts was not confirmed, but several cases of the presence of chloroplasts were revealed in animals, changing over to phototrophy. A shellfish named *Elysia*, which is capable of long-term preservation of chloroplasts obtained with vegetable food (kleptoplasts), is a well-known example. At that, *Elysia* not only assimilates the products of photosynthesis taking place in chloroplasts and completely refuses from heterotrophic nutrition, but also obtains some chloroplast genes: the animal transforms into a functional and genetic equivalent of plants [15].

Numerous provisions of K.S. Mereschkowsky's theory [1, 9, 10] which was well in advance of the experimental biology level of the early 20th century were subjected to severe criticism. For example, A.S. Famintsyn, whose works had formed the basis for development of the theory of symbiogenesis, did not accept the origin of chloroplasts from both cyanobacteria and zoochlorellas [as per 16]. Later both objections turned out to be inadequate: both primary plastids (originating from cyanobacteria), surrounded by 2 membranes, and secondary plastids (originating from green or red algae), surrounded by 3-4 membranes, were discovered [17]. However, the heuristic potential of the symbiogenesis concept was highly appreciated by some contemporaries of K.S. Mereschkowsky. Based on it, I.E. Wallin [18] proposed the hypothesis on symbiotic origin of mitochondria, which later proved to be relevant. E.B. Wilson [19], referred to by K.S. Mereschkowsky as his major opponent, admitted that the symbiogenesis concept, despite its speculative nature, may «require detailed consideration» in future.

In 1920-1950 the theory of symbiogenesis was hardly ever mentioned in

literature; however, accumulation of facts intended to prove it took place. Among them, the key role belonged to identification of fundamental differences in cell organization of prokaryotes and eukaryotes [20], as well as cytoplasmatic genes of eukaryotes, which turned out to be functionally related to plastids and mitochondria [21]. These works have set the background for rebirth of the symbiogenesis concept, strongly associated with the works of L. Margulis-Sagan [22, 23]. She was guided by the data obtained in 1950-1960 on the presence of nucleus-independent genomes and translation systems in plastids and mitochondrias, similar to those of bacteria (genome in the form of a circular DNA molecule, protein synthesis on 70S ribosomes).

The new version of the symbiogenesis concept is known as the theory of serial endosymbiosis; this name reflected the multiple stages of symbiogenic evolution in eukaryotes. Introduction of aerobic α-proteobacteria, which gave birth to mitochondria, into anaerobic archaea cells, which used endosymbionts as sources of ATP, forming during oxidative phosphorylation, is usually considered as its first stage [23]. When justifying the theory of serial endosymbiosis, L. Margulis referred to the theory of symbiogenesis, developed by K.S. Mereschkowsky [9, 10], as well as to the concepts of symbiogenesis as a universal evolutionary strategy, supported by natural selection, proposed by B.M. Kozo-Polyanski [24]. According to L. Margulis, most, if not all, eukaryotic cell components are of symbiotic origin irrespective of presence of their own genomes.

In fact, it is currently evident that identification of semi-independent genomes is not a mandatory criterion for symbiotic origin of organelles: genome-free mitochondria (mitosomes, hydrogenosomes) and plastids have been discovered, which have preserved their cell structure and ability of binary fission, as well as the significant part of ancestor microorganisms proteome, coded by nuclear genes, which were obtained by the hosts from their endosymbionts [17, 25]. At the same time, attempts to apply the symbiogenesis concept to ciliums and flagellums of eukaryotes (locomotive structures, which are the most ancient cell organelles, according to L. Margulis), as well as to peroxisomes, have found no confirmation: neither own genomes, nor proteins of bacterial origin were discovered in these organelles [26, 27].

Identification of transitional forms, connecting nonsymbiotic bacteria with cell organelles, provided a convincing proof of the theory of symbiogenesis. They include cyanellas of protozoa *Paulinella chromatophora* (amoeba) and *Cyanophora paradoxa* (Glaucophyta). Cyanellas of *P. chromatophora* have preserved a genome of significant size (about 1,000 kbp, which amounts to 30 % of the genome of *Synechococcus* — nonsymbiotic equivalents of these cyanellas), containing a complete set of genes for basic template processes, i.e. replication, transcription and translation [28]. Cyanellas of *C. paradoxa* are characterized with the size of genome similar to that of green algae plastids (less than 200 kbp); however, these cyanellas have preserved cytological traits of nonsymbiotic ancestors, i.e. murein cell wall and intracellular thylakoids with phycobilisomes [29]. It is important to note the absence of nitrogen fixation genes in both types of cyanellas, which are present in their nonsymbiotic relatives, presumably due to incompatibility of nitrogenase reaction with metabolic processes taking place in the host cell cytoplasm.

Intracellular symbionts (endocytobionts) of insects can also be considered as an example of transitional forms between nonsymbiotic bacteria and organelles [30]. They provide their hosts with essential nutrients (amino acids, cofactors), and the size of their genome is similar to that of permanent cell organelles: 140 kbp for *Tremblaya* (endocytobiont of scale insects), 160 kbp for *Car-*

sonella (endocytobiont of psyllids). Interestingly, these bacteria are taxonomically unrelated to plastids and mitochondrias (*Tremblaya* is a β-proteobacterium, *Carsonella*is a γ-proteobacterium) which demonstrates the ability of representatives of all main bacteria groups to transform to cell organelles.

Discovery of *Lokiarchaeota*, a group of anaerobic chemotrophic archaea with cytological organization similar to that of eukaryotes, was a triumph of the theory of symbiogenesis [31]. Unlike the other prokaryotes, *Lokiarchaeota* have actin cytoskeleton, are capable of intracellular membrane components formation and endocytosis, which probably ensured obtaining of symbiotic bacteria - ancestors of organelles. Genome of *Lokiarchaeota* contains more than 5300 protein-coding genes; only 26 % and 29 % of them show homology to known genes of archaea and bacteria, respectively, while more than 30 % code previously unknown proteins. According to molecular phylogeny methods, *Lokiarchaeota* and eukaryotes had a common ancestor, which confirms the hypothesis on origin of eukaryotes from anaerobic organisms, which obtained mitochondrias as a result of endosymbiosis with aerobic α-proteobacteria [32].

L. Margulis emphasized in one of final studies that symbiogenesis does not come down to exchange of trophic or signal factors, but the combination is based on assimilation of microsymbiont genomes by a host, leading to formation of a supraspecific system of heredity [33]. Later it was called hologenome and was considered as a set of genes of closely interacting symbiotic partners [34]. Developing this approach we have proposed the term “symbiogenome” [8], defining it as a product of initial stages of partners coevolution, i.e. functional integration of their inherited material as a result of development of inter-organismic signal interaction systems [35].

Thus, based on the present-day data, symbiogenesis can be defined as a multiple stage process of formation of a new functionally integrated individual with a fused system of heredity formed by the interacting partners. The partners become more dependent on symbiosis in the course of evolution (facultative→ecologically obligate→genetically obligate→absolute) and integrity of their genetic material (functional→structural) [35].

Summarizing the brief review of the symbiogenesis concept, it should be highlighted that its classical version, proposed by K.S. Mereschkowsky 111 years ago [1], has still preserved the huge heuristic potential. For example, the assumption on symbiotic origin of the nucleus and chromosomes was recently developed within the theory of viral eukariogenesis [36, 37]. The classification of cell forms by mycoplasma and amoeboplasma, proposed by K.S. Mereschkowsky [10, 11], was not confirmed, but the presence of two different prokaryote types, i.e. bacteria and archaea, combination of which gave birth to eukaryotes, can be considered proved [23]. The hypothesis on independent origin of various cell organization forms, proposed by K.S. Mereschkowsky, was not confirmed as well: multiple data indicate that bacteria and archaea had a common ancestor, presumably an anaerobic organism [38] with RNA genome [36]. However, the basic idea of K.S. Mereschkowsky with regard to symbiogenic origin of eukaryotic cell organelles have stood the test of time and determined the main direction of development in biology for decades to come.

It should be noted that the first work of K.S. Mereschkowsky, which focused on symbiogenesis concept justification, evoke wide response among biologists of various specializations. This work can be rightly considered as a masterpiece of scientific literature: it combines in-depth theoretical analysis with an easily accessible form, and novel approach to the problems of evolutionary biology with extremely correct references to works of predecessors and opponents.

REFERENCES

1. Mereschkowsky C. Uber Natur und Ursprung der Chromatophoren im Pflanzenreiche. *Biol. Centralbl.*, 1905, 25: 593-604 (addendum in 25: 689-691).
2. Martin W., Kowallik K.V. Annotated English translation of Mereschkowsky's 1905 paper «Uber Natur und Ursprung der Chromatophoren im Pflanzenreiche». *Eur. J. Phycol.*, 1999, 34: 287-295.
3. Famintzin A.S., Baranetzky O.V. Zur Entwickelungsgeschichte der Gonidien und Zoosporenbildung der Flechten. *Mémoires de l'Académie imp. des sciences de St.-Pétersbourg*, 7 serié, 1867, 11: 1-35.
4. Famintsyn A.S. *Zapiski Imperatorskoi akademii nauk, fiz.-mat. otd.*, seriya 8, 1907, 20: 1-14 (in Russ.).
5. Read C.R. *Parasitism and symbiology. 1st edition.* NY, 1970.
6. de Bary A. Uber Symbiose. *Versammlung deutscher Naturforscher und Aerzte in Cassel*, 1878, 51: 121-126.
7. Provorov N.A. *Sel'skokhozyaistvennaya biologiya* [*Agricultural Biology*], 2014, 3: 113-126 (doi: 10.15389/agrobiology.2014.3.113rus) (in Russ.).
8. Tikhonovich I.A., Provorov N.A. *Genetika*, 2012, 48: 437-450 (in Russ.).
9. Merezhkovskii K.S. *Teoriya dvukh plazm kak osnova simbiogenezisa, novogo ucheniya o proiskhozhdenii organizmov* [The theory of two plasmas as a basis of symbiogenesis, the new doctrine of the origin of organisms]. Kazan', 1909 (in Russ.).
10. Mereschkowsky C. Theorie der zwei Plasmaarten als Grundlage der Symbiogenesis, einer neuen Lehre von der Entstehung der Organismen. *Biol. Centralbl.*, 1910, 30: 278-288.
11. Nageli C. Blaschenformige Gebilde im Inhalte der Pflanzenzelle. *Z. Wiss. Bot.*, 1846, 3/4: 94-128.
12. Schimper A.F.W. Uber die Entwickelung der Chlorophyllkorner und Farbkorper. *Bot. Zeit.*, 1883, 41: 105-113.
13. Schimper A.F.W. Untersuchungen uber die Chlorophyllkorner und die ihnen homologen Gebilde. *Jahrb. Wiss. Bot.*, 1885, 16: 1-247.
14. Schmitz F. Die Chromatophoren der Algen. Vergleichende Untersuchungen uber Bau und Entwicklung der Chlorophyllkorper und analogen Farbstoffkorper der Algen. *Verhandlungen des Naturwissenschaftlichen Vereins der Preussischen Rheinlande und Westfalen*, 1883, 40: 1-180.
15. Rumpho M.E., Worful J.M., Lee J. Horizontal gene transfer of the algal nuclear gene *psbO* to the photosynthetic sea slug *Elysia chlorotica*. *PNAS USA*, 2008, 105: 17867-17871 (doi: 10.1073/pnas.0804968105).
16. Hoxtermann E. Konstantin S. Merezkovskij und die Symbiogenesetheorie der Zellevolution. In: *Bakterienlicht und Wurzelpilz.* A. Geus (ed.). Marburg, 1998: 11-29.
17. Gross J., Bhattacharya D. Mitochondrial and plastid evolution in eukaryotes: an outsiders' perspective. *Nat. Rev. Genet.*, 2009, 10: 495-505 (doi: 10.1038/nrg2610).
18. Wallin I.E. *Symbionticism and the origin of species.* London, 1927.
19. Wilson E.B. *The cell in development and heredity. 3d edition.* NY, 1928.
20. Chatton E. *Pansporella perplexa.* Réflexions sur la biologie et la phylogenie des protozoaires. *Ann. Sci. Nat. Zool. 10è serie*, 1923, 7: 1-84.
21. Zakharov-Gezekhus I.A. *Vavilovskii zhurnal genetiki i selektsii*, 2014, 18: 93-102 (in Russ.).
22. Sagan L. On the origin of mitosing cells. *J. Theor. Biol.*, 1967, 14: 225-274.
23. Margulis L. *Rol' simbioza v evolyutsii kletki* [The role of symbiosis in cell evolution]. Moscow, 1983 (in Russ.).
24. Kozo-Polyanskii B.M. *Novyi printsip biologii. Ocherk teorii simbiogeneza* [A new principle of biology. Essay on symbiogenesis theory]. Leningrad-Moscow, 1924 (in Russ.).
25. Smith D.R., Lee R.W. A plastid without a genome: evidence from the nonphotosynthetic green algal genus *Polytomella. Plant Physiol.*, 2014, 164: 1812-1819 (doi: 10.1104/pp.113.233718).
26. Rizotti M. Non-symbiotic origin of locomotory organelles. In: *Symbiosis: mechanisms and model systems.* J. Seckbach (ed.). Dordrecht, Boston, London, 2002: 99-110.
27. Gabaldyn T., Snel B., van Zimmeren F., Hemrika W., Tabak H., Huynen M.A. Origin and evolution of the peroxisomal proteome. *Biol. Direct.*, 2006, 1: 8 (doi: 10.1186/1745-6150-1-8).
28. Rogers M.B., Patron N.J., Keeling P.J. Horizontal transfer of a eukaryotic plastid-targeted protein gene to cyanobacteria. *BMC Biol.*, 2007, 5: 26 (doi: 10.1186/1741-7007-5-26).
29. Price D.C., Chan C.X., Yoon H.S., Yang E.C., Qiu H., Weber A.P., Schwacke R., Gross J., Blouin N.A., Lane C., Reyes-Prieto A., Durnford D.G., Neilson J.A., Lang B.F., Burger G., Steiner J.M., Luffelhardt W., Meuser J.E., Posewitz M.C., Ball S., Arias M.C., Henrissat B., Coutinho P.M., Rensing S.A., Symeonidi A., Doddapaneni H., Green B.R., Rajah V.D., Boore J., Bhattacharya D. *Cyanophora paradoxa* genome elucidates origin of photosynthesis in algae and plants. *Science*, 2012, 335: 843-847 (doi: 10.1126/science.1213561).

30. Douglas A.E. The molecular basis of bacterial—insect symbiosis. *J. Mol. Biol.*, 2014, 426: 3830-3837 (doi: 10.1016/j.jmb.2014.04.005).
31. Spang A., Saw J.H., Jшrgensen S.L., Zaremba-Niedzwiedzka K., Martijn J., Lind A.E., van Eijk R., Schleper C., Guy L., Ettema T.J. Complex archaea that bridge the gap between prokaryotes and eukaryotes. *Nature*, 2015, 521: 173-179 (doi: 10.1038/nature14447).
32. Guy L., Ettema T.J. The archaeal TACK superphylum and the origin of eukaryotes. *Trends in Microbiol.*, 2011, 19: 580-587 (doi: 10.1016/j.tim.2011.09.002).
33. Margulis L., Sagan D. *Acquiring genomes. A theory of the origins of species.* NY, 2002.
34. Zilber-Rosenberg I., Rosenberg E. Role of microorganisms in the evolution of animals and plants: the hologenome theory of evolution. *FEMS Microbiol. Rev.*, 2008, 32: 723-735 (doi: 10.1111/j.1574-6976.2008.00123.x).
35. Provorov N.A., Tikhonovich I.A. *Zhurnal obshchei biologii*, 2014, 75: 247-260 (in Russ.).
36. Forterre P. Three RNA cells for ribosomal lineages and three DNA viruses to replicate their genomes: a hypothesis for the origin of cellular domain. *PNAS USA*, 2006, 103: 3669-3674 (doi: 10.1073/pnas.0510333103).
37. Witzany G. The viral origins of telomeres and telomerases and their important role in eukaryogenesis and genome maintenance. *Biosemiotics*, 2008, 1: 191-206 (doi: 10.1007/s12304-008-9018-0).
38. Di Giulio M. The universal ancestor and the ancestors of Archaea and Bacteria were anaerobes whereas the ancestor of the Eukarya domain was an aerobe. *J. Evol. Biol.*, 2007, 20: 543-548 (doi: 10.1111/j.1420-9101.2006.01259.x).