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Electron uptake by classical electron donators: astaxanthin and carotenoid aldehydes

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ABSTRACT

Carotenoids are prime examples for antioxidants: they donate electrons to noxious radicals. Density functional calculations anticipate the possibility of electron uptake by carotenoids. This prediction has been confirmed experimentally: carbonyl carotenoids, including the super-antioxidant astaxanthin, easily take up electrons and react as antireductants.

The electron rich polyenic carotenoids (Car) are eminent electron donators to reactive radicals. This specific property of providing electrons to noxious radicals and converting them into benign homologs made carotenoids legendary as antioxidants.[1] The antioxidant qualities of carotenoids culminate in astaxanthin (Ast), the excellent class 1 super-antioxidant.[2–4] The uptake of electrons by Car has not yet been observed in nature, although the scavenging of superoxide anion radicals $O_2^{\bullet -}$ occurs by electron release to Car.[5,6] Cyclic polyenes such as annulenes and benzenoids straightforwardly attract electrons (Birch reduction).[7,8] Contrastingly, oblong polyenes defy capturing electrons. Procedures with alkali metals are quite elaborated,[9] producing $Car^{\bullet -}$ and Car^{2-} electrochemically, with laser or nuclear radiation, requires specific instruments.[10–12] Nevertheless, it has been predicted theoretically that Car could favorably act as electron acceptors.[13] It was then found in a simple bench-top experiment that a specific carotenoid dialdehyde accepted electrons from the electron donator alkaline DMSO = $DMSO^-$ = $H_3C(S{=}O)CH_2^-$.[14] In this trial, the electron uptake reaction

$$\text{crocetindial (C20:7)} \rightarrow \text{crocetin dienolate } (\text{C20:8}^{2-})$$

was confirmed spectroscopically and by analyzing secondary products. We have now synthesized several homologous carotenoid dialdehydes C*n* (*n* = number of carbon atoms) with N C═C bonds: Cn:N (Fig. 1). The electron transfer reactions of these aldehydes and diketone Ast were systematically investigated experimentally and by molecular modeling. The dialdehydes were synthesized with Wittig salt C5P [Scheme 1, Figs. 2, and 1S in the Supplementary data]:[15]

$$\text{Cn:N} + \text{C5AldP} \rightarrow \text{Cn} + 5\text{:N} + 2$$

The dialdehydes were dissolved in DMSO and filled in a quartz cuvette; under nitrogen a minute amount of $DMSO^-$ was injected resulting in an immediate bathochromic color change indicating the formation of dienolates with an additional double bond (Scheme 2, Figs. 3, and 2S):

$$\text{Cn:N} + \text{DMSO}^- \rightarrow \text{Cn:N} + 1^{2-}$$

The limiting solvation in DMSO was reached for the elongation reaction with C45:17 and with C50:19 for spectra recording. The observed color conversion of Ast:11 represents an analogous reaction to Ast:12^{2-} (Table 1S Supplementary data). Despite extensive investigations the role of $DMSO^-$ in the electron transfer reaction remains ambiguous, especially concerning structure and fate of the electron donator species.[16] Since the reaction occurs in the presence of N_2O ($Car^{\bullet -}$ scavenger)[17] a direct two-electron uptake (one electron to each of the C═O groups) is probable (Scheme 2) precluding a consecutive one-electron uptake via $Cn^{\bullet -}$. There was no obvious difference in the reaction of Cn and Ast; an exception is C10:3, which showed a retarded color change. The $DMSO^-$ reaction reminds of electron transfer from sodium to C═O groups (Bouveault-Blanc reduction).

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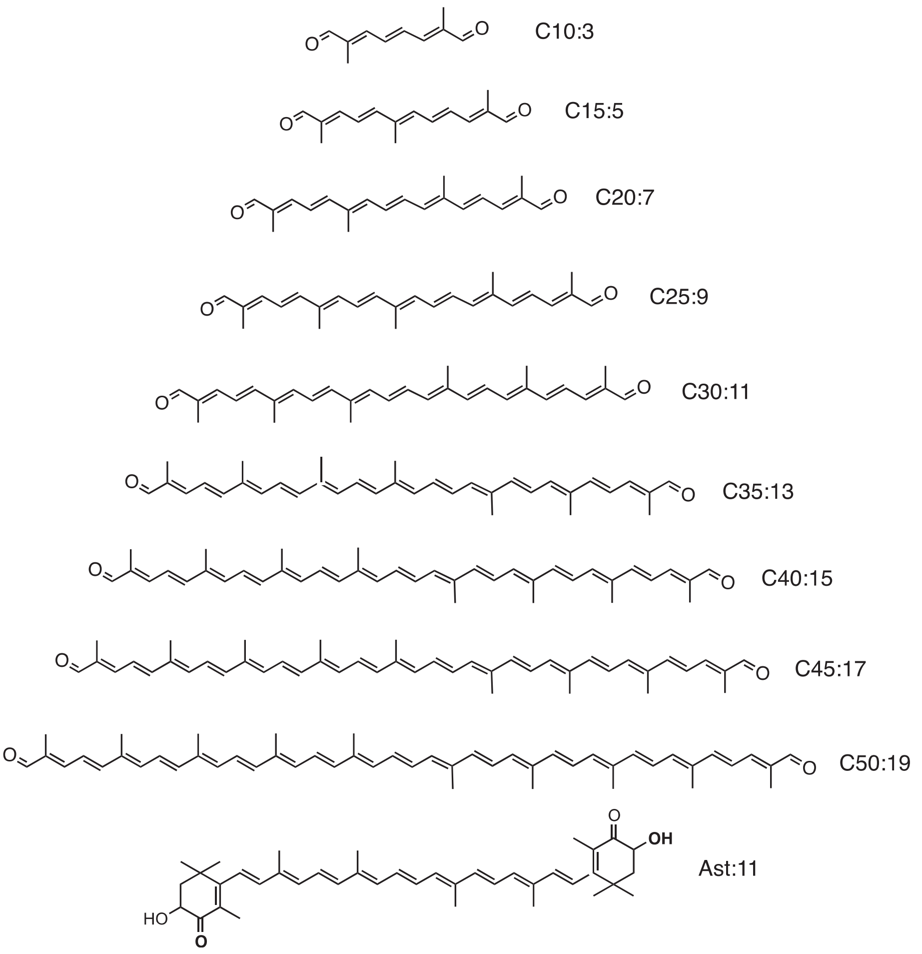
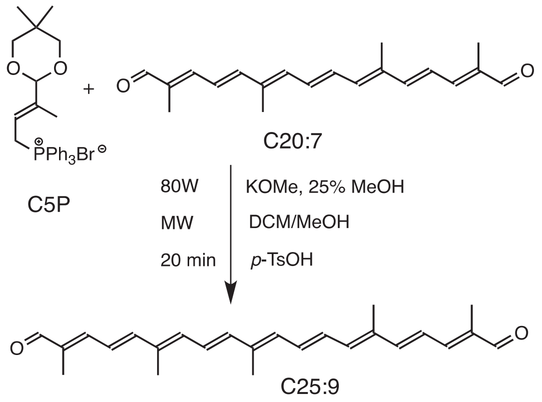


Figure 1. Schematic representation of the investigated carotenoids.



Scheme 1. Representative dialdehyde synthesis.

The electron transfer from and to Cn and Ast in relation to N was validated by quantum chemical calculations, which correspondingly established the molecular structure, simulated the absorption spectra, and determined the reaction energy. C10:3, C15:5, and C20:7 are straight polyenes; the other molecules become increasingly bended with extended N (Fig. 3S). The shape of Cn^{2-} and Ast^{2-} was similar to the neutral molecules showing the characteristic alteration of bonding character: the formal C═C bonds (central C═C in C50:19 $l = 0.138$ nm) convert into formal C–C bonds (central C–C in $C50:20^{2-}$ $l = 0.144$ nm), the equalized bond lengths express conjugation and charge delocalization. The

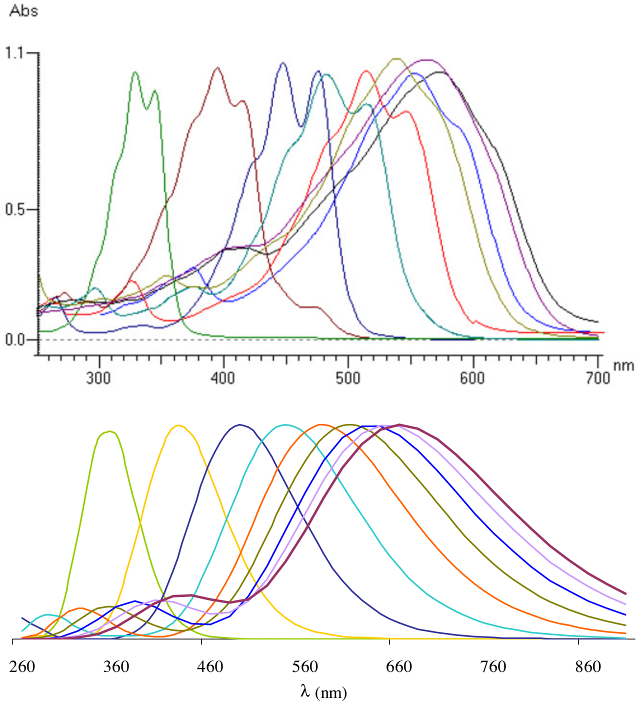


Figure 2. Experimental and theoretical (arbitrary units for absorption) spectra of dialdehydes Cn in DMSO: C10:3 (—), C15:5 (—), C20:7 (—), C25:9 (—), C30:11 (—), C35:13 (—), C40:15 (—), C45:17 (—), C50:19 (—) (See Fig. 1S).