

## Research Article

# Synthesis of all-*trans*-[10'-<sup>3</sup>H]-8'-apo- $\beta$ -carotenoic acid

Pulgam Veera Reddy, Monsterrat Rabago-Smith and Babak Borhan\*  
*Department of Chemistry, Michigan State University, East Lansing,  
MI 48824, USA*

## Summary

The enzyme, 15,15'- $\beta$ -carotene dioxygenase (BCDOX), facilitates the oxidation of  $\beta$ -carotene to yield retinal. This is a remarkable process in which one of 11 double bonds in  $\beta$ -carotene is selectively oxidized. To further probe the mechanistic aspects of BCDOX, the synthesis of all-*trans*-[10'-<sup>3</sup>H]-8'-apo- $\beta$ -carotenoic acid is reported. This compound will be used as a photoaffinity labeling reagent to probe the  $\beta$ -carotene binding pocket within BCDOX. The synthesis outlines a simple and efficient route for the incorporation of tritium at the 10' olefinic carbon of 8'-apo- $\beta$ -carotenoic acid. Copyright © 2002 John Wiley & Sons, Ltd.

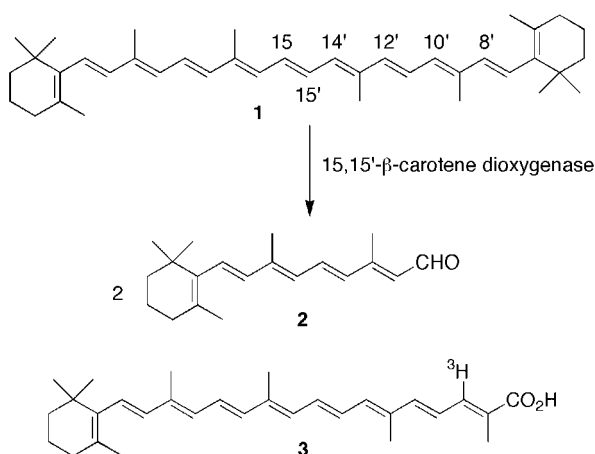
**Key Words:** 15,15'- $\beta$ -carotene dioxygenase; 8'-apo- $\beta$ -carotenoic acid; photoaffinity labeling

## Introduction

The need for carotenoids in the human diet has been well established. Either the carotenoids or their oxidation products, particularly retinoid compounds, are essential in various pathways such as the visual transduction, gene regulatory control, cancer, and other disease prevention.<sup>1–7</sup> Although animals cannot produce retinoids such as vitamin A, they can convert  $\beta$ -carotene (**1**) (a tetraterpenoid

\*Correspondence to: B. Borhan, Department of Chemistry, Michigan State University, East Lansing, MI 48824 USA. E-mail: borhan@cem.msu.edu

Contract/grant sponsor: Research Corporation; Contract/grant number RIO410

**Scheme 1.**

hydrocarbon with 11 double bonds) via a dioxygenase, which with remarkable selectivity cleaves the central olefin to yield retinal (**2**) (Scheme 1).<sup>8–10</sup> This enzyme, 15,15'- $\beta$ -carotene dioxygenase (BCDOX), was first isolated by Goodman and Huang, but has not received a great deal of attention until very recently.<sup>11</sup> The past few years has witnessed a resurgence of activity in this area, mainly as a result of the identification and isolation of the gene responsible for BCDOX in a number of organisms.<sup>12–17</sup> In view of the growing interest in the physiological implication of retinoids in human health,<sup>1,2,7,18–20</sup> and the intricate interplay of the concentration of different retinoids and their physiological role,<sup>1,18,21–24</sup> it seems prudent to understand fully the nature, function, regulation, and mechanism of BCDOX.

Oxidative cleavage of  $\beta$ -carotene is an unprecedented process for a dioxygenase enzyme. Typically, dioxygenases require a hydrophilic handle such as a hydroxyl group to proceed, such as the case with intra- and extra-diol catechol dioxygenases.<sup>25</sup> Also, the catalytic mechanism for the enzymatic cleavage of a somewhat featureless hydrocarbon such as  $\beta$ -carotene (**1**) with such high regioselectivity is not well understood. Enzyme-substrate interactions that lead to stereospecific catalytic action through hydrogen bonding and dipolar communication are common. Understanding the enzymatic action on hydrocarbon substrates can shed light onto nature's methodology for utilizing other molecular interactions for recognition and specificity. Our interest in the mechanistic aspects of BCDOX has led us to synthesize the tritiated

photoaffinity label [ $10'$ - $^3\text{H}$ ]-8'-apo- $\beta$ -carotenoic acid (**3**) to probe the binding pocket of  $\beta$ -carotene within BCDOX.

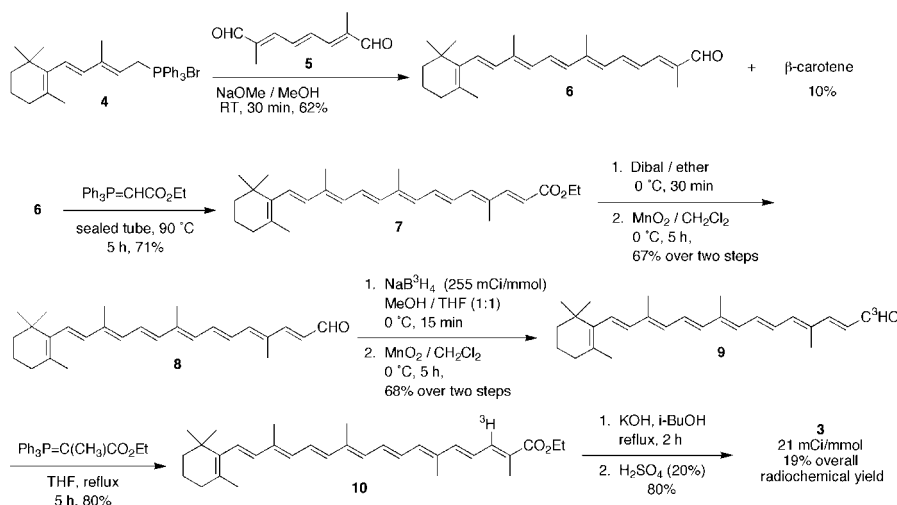
The choice of **3** as the photoaffinity probe stems from the fact that apo- $\beta$ -carotenoic acids are substrates for BCDOX, and thus will bind the enzyme.<sup>26–28</sup> On the other hand,  $\alpha,\beta$ -unsaturated polyene carboxylic acids are capable of photoactivation and can be used as photoaffinity probes. This was demonstrated by Rando and coworkers during the isolation of retinoic acid binding proteins in which radiolabeled retinoic acid was used as the photoaffinity labeling agent.<sup>29</sup> In a similar manner, our first attempt at photoaffinity labeling of BCDOX will entail the use of **3**, the synthesis of which is reported here.

## Results and discussion

Synthesis of radiolabeled carotenoids are challenging for two reasons. First, the polyolefinic nature of these compounds leads to their less than desirable stability, and thus introduction of radiolabels is generally limited to mild reactions. Although there is not a large body of literature on the synthesis of radiolabeled carotenoids (mostly biosynthesized by feeding of labeled precursors to various organisms),<sup>30,31</sup> related compounds such as retinoids have been synthesized by reduction of intermediate carbonyl groups with  $\text{Na/LiB}^3\text{H}_4$ , or semihydrogenation of intermediate acetylenes with  $^3\text{H}_2$ .<sup>32–36</sup> Secondly, their sensitivity to light forces the need to work in darkrooms with minimal red lighting and increases the technical difficulty of routine chemical manipulations.

Prudent with any radiolabeling, it is preferable to incorporate the label as close to the final step as possible. This will reduce the need for handling, and purification of radiolabeled intermediates, and increase the radioactive yield of the labeled compound. Although there are a range of positions present in 8'-apo- $\beta$ -carotenoic acid (**3**) that could be considered as appropriate to incorporate tritium, we opted to place it on the  $10'$  carbon. We chose to use of  $\text{NaB}^3\text{H}_4$  as the source of tritium, and thus required a reductive step to incorporate the label. C10' was chosen as a suitable site after several trial non-radioactive syntheses of **3** were performed, in which the last reductive step was utilized for tritiation, and the subsequent steps could be performed in high yields, without the need for extensive manipulation and purification.

The synthesis of **3**, depicted in Scheme 2, followed the  $\text{C}_{15} + \text{C}_{10}$  approach used by a number of researchers for the synthesis of

**Scheme 2.**

analogous structures.<sup>37</sup> Construction of the  $\text{C}_{15}$ -ylide **4** and 2,7-dimethyl-2, 4, 6-octatrienedial (**5**) was uneventful and followed reported procedures.<sup>38,39</sup> Wittig olefination of **5** with ylide **4** was initiated with NaOMe in methanol and delivered the  $\text{C}_{25}$ -aldehyde **6** in good yields with 97% *E* stereoselectivity of the newly formed double bond. Double olefination of **5** led to the formation of  $\beta$ -carotene (**1**) in 10% yield, however, it was easily removed owing to its hydrophobic nature. Treatment of aldehyde **6** with (carbethoxymethylene)triphenylphosphorane in a sealed tube at  $95^\circ\text{C}$  for 5 h led to **7** (>97% *E*) in 71% yield. Ethyl ester **7** was reduced with DIBAL, and the resulting allylic alcohol was oxidized with  $\text{MnO}_2$  to provide  $\text{C}_{27}$ -aldehyde **8**. In our hands, commercially available oxidant did not yield any product, and led to the decomposition of starting material. However, freshly prepared activated  $\text{MnO}_2$  worked well.<sup>40</sup> Also, maintenance of the temperature at  $0^\circ\text{C}$  was critical for the success of this oxidation.

The tritium label was incorporated by reduction of aldehyde **8** with  $\text{NaB}^3\text{H}_4$  at  $0^\circ\text{C}$ , which was immediately reoxidized with  $\text{MnO}_2$  to yield the radiolabeled  $\text{C}_{27}$ -aldehyde **9**. Although past reductions of  $\alpha,\beta$ -unsaturated carbonyls have sometimes given rise to other reductive products such as 1,4-reduced compounds, none were observed in this instance. Yields reported in Scheme 2 beyond the radioactive reduction with  $\text{NaB}^3\text{H}_4$  refer to isolated and purified products from the non-radioactive reactions, which were used to optimize each step towards

the synthesis of **3**. During the radioactive synthesis, crude radioactive intermediates were carried forward without isolation to minimize the number of manipulations and avoid loss of radioactive compound. The final compound was purified and fully characterized. Wittig olefination of **9** with (carbethoxyethylidene)triphenyl-phosphorane in refluxing THF proceeded well to deliver ester **10** as the sole product (*Z* isomer was not detected by NMR spectroscopy). The resulting triphenylphosphine oxide and remaining phosphonium salts were easily removed by flushing the crude reaction mixture through a short pad of silica. Hydrolysis of ethyl ester **10** proved to be more challenging than expected and routine basic and acidic conditions did not lead to a high yielding process. However, procedures detailed by a recent report by Larsen *et al.*<sup>41</sup> for hydrolysis of such esters was used successfully (see experimental) to obtain the radiolabeled acid **3** (21 mCi/mmol) in 19% overall radiochemical yield. With **3** in hand, we are presently in the process of optimizing photoaffinity labeling conditions. In conclusion, the present procedure provides a simple and efficient route for the synthesis of all-*trans*-[10'-<sup>3</sup>H]-8'-apo- $\beta$ -carotenoic acid (**3**).

## Experimental

All reactions were carried under an atmosphere of nitrogen and removal of solvents was performed under reduced pressure with a Buchi rotary evaporator. THF and Et<sub>2</sub>O were freshly distilled from sodium/benzophenone, and CH<sub>2</sub>Cl<sub>2</sub> was distilled over CaH<sub>2</sub> under a nitrogen atmosphere. Radioactive NaB<sup>3</sup>H<sub>4</sub> was purchased from American Radiolabeled Chemicals, Inc (St. Louis, MO). Analytical TLC was carried out using Merck 250  $\mu$ m Silica gel 60 F<sub>254</sub> and spots were visualized under UV light. Column chromatography was conducted using Silicycle silica gel (230–400 mesh). 300 MHz <sup>1</sup>H-NMR and 75 MHz <sup>13</sup>C-NMR spectra were recorded on a Varian Gemini-300 instrument, and the residual protic solvent (CDCl<sub>3</sub> or DMSO-d<sub>6</sub>) was used as internal reference. UV-visible spectra were recorded on a Perkin-Elmer Lambda 40 spectrometer. A Wallac WinSpectral 1414 liquid scintillation counter was used for quantification of radioactivity. In a typical measurement 1–10  $\mu$ l of sample was added to 3 ml of Optiphase 'HiSafe' 3 liquid scintillation cocktail (Wallac) and the solution was counted for 1 min. All the reactions were carried out in a darkroom under minimal photographic safety red lights.

*2,7,11-Trimethyl-13-(2,6,6-trimethyl-cyclohex-1-enyl)-trideca-2,4,6,8,10,12-hexaenal (6)*

Sodium methoxide (121.0 mg, 2.250 mmol, 1.5 eq.) was added to a solution of **4**<sup>39</sup> (817.0 mg, 1.5 mmol) in dry methanol (8 ml) at 0°C, and stirred until the phosphonium salt was completely converted to the deep red phosphorane. A solution of 7-dimethyl-2,4,6-trienedial **5**<sup>38</sup> (164.0 mg, 1 mmol) in dry methanol (1 ml) was added and the mixture was stirred for 30 min. The reaction mixture was diluted with water (10 ml) and extracted with diethyl ether (3 × 5 ml). The organic layer was dried over Na<sub>2</sub>SO<sub>4</sub> and the solvent was removed in *vacuo* to give the C<sub>25</sub>-aldehyde **6** (217.0 mg, 62%, 97:3 *E:Z*), and β-carotene **1** (57.0 mg, 10%), which was purified by flash silica chromatography (2% ethyl acetate in hexane).

UV: λ<sub>max</sub> (hexanes) 414 nm; <sup>1</sup>H NMR (300 MHz, CDCl<sub>3</sub>) δ 9.40 (1H, s), 7.03 (1H, d, *J* = 12 Hz), 6.96 (1H, dd, *J* = 14.4, 12.3 Hz), 6.77 (1H, dd, *J* = 14.4, 11.4 Hz), 6.41 (1H, dd, *J* = 14.4, 11.7 Hz), 6.5 (1H, d, *J* = 11.7 Hz), 6.7 (1H, d, *J* = 12.3 Hz), 6.12 (3H, m), 2.00 (3H, s, CH<sub>3</sub>), 1.97 (3H, s, CH<sub>3</sub>), 1.86 (3H, s, CH<sub>3</sub>), 1.67 (3H, s, CH<sub>3</sub>), 1.97–1.40 (6H, m, 3 × CH<sub>2</sub>), 1.00 (6H, s, 2 × CH<sub>3</sub>); <sup>13</sup>C NMR (75 MHz, CDCl<sub>3</sub>) δ 194.38, 148.94, 141.72, 137.88, 137.71, 137.42, 136.66, 136.22, 130.73, 130.30, 129.74, 127.74, 127.63, 127.16, 39.51, 34.17, 33.03, 28.89, 26.81, 21.70, 19.13, 12.97, 12.77, 9.51.

*4,9,13-Trimethyl-15-(2,6,6-trimethyl-cyclohex-1-enyl)-pentadeca-2,4,6,8,10,12,14-heptaenoic acid ethyl ester (7)*

A solution of **6** (110.0 mg, 0.310 mmol) and (carbethoxymethylene)-triphenylphosphorane (323.0 mg, 0.930 mmol) in dry THF (4 ml) was heated at 95°C for 5 h in a sealed tube. The reaction mixture was cooled to room temperature and diluted with water (10 ml) and Et<sub>2</sub>O (10 ml). Phases were separated and the aqueous phase was extracted with Et<sub>2</sub>O (2 × 10 ml). The combined organics were dried over Na<sub>2</sub>SO<sub>4</sub>, filtered and concentrated under reduced pressure. Crude product was purified by flash silica chromatography (5% ethyl acetate in hexane) to yield **7** (93.0 mg, 71%, >97% *E*). The coupling constant for the newly formed double bond confirms the *E* stereochemistry. The *Z* isomer was not detected by NMR spectroscopy.

UV: λ<sub>max</sub> (hexanes) 423 nm; <sup>1</sup>H NMR (300 MHz, CDCl<sub>3</sub>) δ 7.35 (1H, d, *J* = 15.6 Hz), 6.78 (1H, d, *J* = 12.9 Hz), 6.79 (1H, dd, *J* = 14.7, 11.4 Hz), 6.65 (1H, dd, *J* = 13.5, 11.7 Hz), 6.45 (1H, d, *J* = 11.1 Hz),

6.33 (1H, d,  $J = 14.7$  Hz), 6.23 (1H, d,  $J = 11.7$  Hz), 5.96 (3H, m), 5.84 (1H, d,  $J = 15.6$  Hz), 4.20 (2H, q,  $J = 7.2$  Hz), 2.01, (2H, m, CH<sub>2</sub>), 1.97 (3H, s, CH<sub>3</sub>), 1.96 (3H, s, CH<sub>3</sub>), 1.89 (3H, s, CH<sub>3</sub>), 1.69 (3H, s, CH<sub>3</sub>), 1.60 (2H, m, CH<sub>2</sub>), 1.45 (2H, m, CH<sub>2</sub>), 1.28 (3H, t,  $J = 7.2$  Hz, OCH<sub>2</sub> CH<sub>3</sub>), 1.00 (6H, s,  $2 \times$  CH<sub>3</sub>); <sup>13</sup>C NMR (75 MHz, CDCl<sub>3</sub>)  $\delta$  167.51, 148.72, 139.25, 138.93, 137.79, 137.58, 136.91, 136.73, 133.74, 133.36, 131.57, 130.56, 129.54, 128.60, 127.16, 126.28, 116.23, 60.17, 39.55, 34.20, 33.07, 28.92, 21.75, 19.18, 14.31, 12.90, 12.76, 12.53.

*4,9,13-Trimethyl-15-(2,6,6-trimethyl-cyclohex-1-enyl)-pentadeca-2,4,6,8,10,12,14-heptaenal (8)*

To a cold (0°C) solution of **7** (90.0 mg, 0.215 mmol) in dry Et<sub>2</sub>O (6 ml) was added 1 M solution of DIBAL in cyclohexane (0.43 ml, 0.430 mmol) and stirred for 30 min. Saturated sodium–potassium tartrate solution (3 ml) and glycerol (5 drops) were added. The reaction mixture was stirred over night at room temperature; phases were separated and the aqueous phase was extracted with Et<sub>2</sub>O ( $3 \times 10$  ml). The combined organic layers were washed with brine (3 mL), dried over Na<sub>2</sub>SO<sub>4</sub>, filtered and concentrated in *vacuo* to give the corresponding allylic alcohol, which was pure enough to be used without further purification (80.0 mg, 99%).

UV:  $\lambda_{\max}$  (hexanes) 400, 422 nm; <sup>1</sup>H NMR (300 MHz, CDCl<sub>3</sub>)  $\delta$  6.67 (3H, m), 6.22 (7H, m), 5.84 (1H, dt,  $J = 12$ , 6 Hz), 4.22 (2H, t,  $J = 6.0$  Hz), 2.00 (2H, m, CH<sub>2</sub>), 1.94 (6H, s,  $2 \times$  CH<sub>3</sub>), 1.89 (3H, s, CH<sub>3</sub>), 1.70 (3H, s, CH<sub>3</sub>), 1.60 (2H, m, CH<sub>2</sub>), 1.45 (2H, m, CH<sub>2</sub>), 1.00 (6H, s,  $2 \times$  CH<sub>3</sub>); <sup>13</sup>C NMR (75 MHz, CDCl<sub>3</sub>)  $\delta$  137.82, 137.68, 137.06, 136.68, 136.27, 136.09, 134.62, 132.32, 131.96, 130.68, 130.35, 129.35, 127.28, 126.66, 125.14, 63.91, 39.55, 34.21, 33.05, 28.92, 21.73, 19.20, 12.82, 12.78, 12.71.

MnO<sub>2</sub><sup>40</sup> (100.0 mg, 1.160 mmol, 20 eq.) was added to a stirred solution of the aforementioned allylic alcohol (22.0 mg, 0.058 mmol) in CH<sub>2</sub>Cl<sub>2</sub> (3 ml) at 0°C and stirred for 5 h. The reaction mixture was filtered through a pad of celite and washed with CH<sub>2</sub>Cl<sub>2</sub> ( $4 \times 0.5$  ml). Solvent was removed under reduced pressure and the crude aldehyde was purified by flash silica column chromatography (5% ethyl acetate in hexane) to yield **8** (15.0 mg, 68%).

UV:  $\lambda_{\max}$  (hexanes) 436 nm; <sup>1</sup>H NMR (300 MHz, CDCl<sub>3</sub>)  $\delta$  9.57 (1H, d,  $J = 7.8$  Hz), 7.13 (1H, d,  $J = 15.3$  Hz), 6.82 (1H, dd,  $J = 13.8$ , 11.7 Hz), 6.73 (1H, dd,  $J = 14.7$ , 11.4 Hz), 6.53 (2H, m), 6.35 (1H, d,

$J = 15$  Hz), 6.25 (1H, d,  $J = 12$  Hz), 6.14 (4H, m), 2.01(2H, m, CH<sub>2</sub>), 2.00 (3H, s, CH<sub>3</sub>), 1.96 (3H, s, CH<sub>3</sub>), 1.94 (3H, s, CH<sub>3</sub>), 1.70 (3H, s, CH<sub>3</sub>), 1.60 (2H, m, CH<sub>2</sub>), 1.45 (2H, m, CH<sub>2</sub>), 1.01(6H, s, 2 × CH<sub>3</sub>); <sup>13</sup>C NMR (75 MHz, CDCl<sub>3</sub>)  $\delta$  193.74, 156.62, 141.21, 140.06, 137.81, 137.56, 137.44, 136.57, 135.36, 133.61, 131.43, 130.50, 129.73, 128.36, 127.53, 127.08, 126.93, 39.61, 34.25, 33.11, 28.95, 21.76, 19.21, 12.99, 12.82, 12.70.

#### *NaB<sup>3</sup>H<sub>4</sub> reduction of 8 and synthesis of 9*

Aldehyde **8** (15.0 mg, 0.039 mmol) was added to a cold (0°C) solution of NaB<sup>3</sup>H<sub>4</sub> (1.8 mCi, 255 mCi/mmol) in THF/MeOH (4 ml, 1:1). The reaction mixture was stirred for 20 min at which time unlabeled NaBH<sub>4</sub> (1.5 mg, 0.040 mmol) was added to the reaction mixture (stirred for 15 min). The reaction was quenched by addition of saturated NH<sub>4</sub>Cl and extracted with Et<sub>2</sub>O (3 × 2 ml). Phases were separated and the organic layer was washed with sat. NaCl, and dried over Na<sub>2</sub>SO<sub>4</sub>. Removal of solvent under reduced pressure gave the corresponding allylic alcohol (13.0 mg, 93%) which was used without further purification. After removal of solvent under reduced pressure, the crude residue was dissolved in CH<sub>2</sub>Cl<sub>2</sub> (2 ml), freshly prepared MnO<sub>2</sub><sup>40</sup> (58.0 mg, 20 eq., 0.680 mmol) was added at 0°C, and the reaction was stirred for 5 h. The suspension was filtered through a pad of celite, washed with CH<sub>2</sub>Cl<sub>2</sub> (1 × 2 ml), and concentrated under reduced pressure followed by chromatographic purification over silica gel (5% ethyl acetate in hexanes) to yield pure aldehyde **9** (9.6 mg, 73%). The latter yield refers to product obtained from non-radioactive syntheses. The radioactive material was used without purification following extraction and removal of CH<sub>2</sub>Cl<sub>2</sub> in the next step and the amount isolated was assumed to be the same as for the non-radioactive reaction.

#### *2,6,11,15-Tetramethyl-17-(2,6,6-trimethyl-cyclohex-1-enyl)-heptadeca-2,4,6,8,10,12,14,16-octaenoic acid ethyl ester (10)*

(Carbethoxyethylidene)triphenylphosphorane (18.0 mg, 0.050 mmol) was added to a solution of **9** (9.6 mg, 0.025 mmol) in THF (3.5 ml) and the reaction was refluxed for 5 h. The reaction mixture was diluted with water (4 ml) and extracted with Et<sub>2</sub>O (3 × 2 ml). The combined ether extracts were dried over Na<sub>2</sub>SO<sub>4</sub>. The solvent was removed under reduced pressure and the crude product was purified by flushing it



through a small pad of silica in a Pasteur pipet (5% ethyl acetate in hexane) to yield ethyl ester **10** (9.4 mg, 80%). During the preparation of the radioactive material, the crude product was also flushed through a small pad of silica, however, it was not isolated and characterized, but was used directly in the next step.

UV:  $\lambda_{\max}$  (hexanes) 440 nm;  $^1\text{H}$  NMR (300 MHz,  $\text{CDCl}_3$ )  $\delta$  7.25 (1H, d,  $J = 11.6$  Hz), 6.59 (4H, m), 6.4 (2H, m), 6.25 (1H, d,  $J = 11.1$  Hz), 6.4 (4H, m), 4.21 (2H, q,  $J = 7.2$  Hz), 2.00 (2H, m,  $\text{CH}_2$ ), 1.97 (3H, s,  $\text{CH}_3$ ), 1.95 (3H, s,  $\text{CH}_3$ ), 1.69 (6H, s,  $2 \times \text{CH}_3$ ), 1.60 (2H, m,  $\text{CH}_2$ ), 1.54 (3H, s,  $\text{CH}_3$ ), 1.45 (2H, m,  $\text{CH}_2$ ), 1.29 (3H, t,  $J = 7.2$  Hz,  $\text{OCH}_2 \text{CH}_3$ ), 1.00 (6H, s,  $2 \times \text{CH}_3$ );  $^{13}\text{C}$  NMR (75 MHz,  $\text{CDCl}_3$ )  $\delta$  168.52, 143.84, 138.74, 137.83, 137.80, 137.65, 136.94, 136.53, 135.71, 135.39, 131.99, 131.91, 130.67, 129.48, 129.32, 126.95, 126.15, 125.72, 123.14, 60.46, 39.58, 34.22, 33.07, 29.65, 28.92, 21.73, 19.19, 14.32, 12.86, 12.81, 12.75, 12.68.

*[10'- $^3\text{H}$ ]-8'-apo- $\beta$ -carotenoic acid (**3**)*

KOH (25%, 2 ml) was added to a solution of **10** (9.4 mg, 0.020 mmol), in iso-butyl alcohol (3 ml). The resulting mixture was heated at 95°C for 2 h and cooled to room temperature.  $\text{H}_2\text{SO}_4$  (20%, 2 ml) was added and the reaction mixture was again heated to 70°C for 30 min. The organic layer was separated and washed with hot water ( $3 \times 1$  ml). Dichloromethane (5 ml) was added to the extracted iso-butyl alcohol resulting in two layers; the desired acid was extracted into  $\text{CH}_2\text{Cl}_2$ . The  $\text{CH}_2\text{Cl}_2$  layer was separated, dried over  $\text{Na}_2\text{SO}_4$ , and concentrated under reduced pressure. The crude product was purified through a small pad of silica in a Pasteur pipet (5–15% ethyl acetate in hexane) to yield pure acid **3** (7.0 mg, 80%, 21 mCi/mmol, 0.34 mCi, 19% of total radionuclei incorporated) based on comparative TLC, and UV with authentic cold material, and all spectroscopic data were consistent with reported values.<sup>41</sup>

UV:  $\lambda_{\max}$  (acetone) 440 nm;  $^1\text{H}$  NMR (300 MHz,  $\text{CDCl}_3$ )  $\delta$  12.20 (1H, bs,  $-\text{CO}_2\text{H}$ ), 7.20 (1H, d,  $J = 10.8$  Hz), 6.80–6.16 (11H, m, olefinic), 2.00 (2H, m,  $\text{CH}_2$ ), 1.96 (6H, s,  $2 \times \text{CH}_3$ ), 1.95 (3H, s,  $\text{CH}_3$ ), 1.92 (3H, s,  $\text{CH}_3$ ), 1.69 (3H, s,  $\text{CH}_3$ ), 1.58 (2H, m,  $\text{CH}_2$ ), 1.44 (2H, m,  $\text{CH}_2$ ), 1.02 (6H, s,  $2 \times \text{CH}_3$ ).

## Acknowledgements

We are grateful to the Research Corporation (RI0410) for financial support of this research.

## References

1. Gudas LJ. Cellular biology and biochemistry of the retinoids. In *The Retinoids: Biology, Chemistry, and Medicine* Sporn MB, Roberts AB, Goodman DS, (eds). Raven Press: New York, 1994; 443–520.
2. Krinsky NI. *Ann NY Acad Sci* 1998; **854**: 443–447.
3. Mangelsdorf DJ, Evans RM. *Cell* 1995; **85**: 841–850.
4. Peto R, Doll R, Buckley JD, Sporn MB. *Nature* 1981; **290**: 201–208.
5. Rando RR. *Angew Chem Int Ed Engl* 1990; **29**: 461–480.
6. Rando RR. *Chem Biol* 1996; **3**: 255–262.
7. Ross AC. *FASEB J* 1993; **7**: 317–327.
8. Goodman DS, Olson JA. *Methods Enzymol* 1969; **15**: 462–475.
9. Lakshman MR, Mychkovsky I, Attlesey M. *Proc Natl Acad Sci USA* 1989; **86**: 9124–9128.
10. Olson JA. *J Nutr* 1989; **119**: 105–108.
11. Goodman DS, Huang HS. *Science* 1965; **149**: 879–880.
12. Kiefer C, Hessel S, Lampert JM, Vogt K, Lederer MO, Breithaupt DE, von Lintig J. *J Biol Chem* 2001; **276**: 14110–14116.
13. Redmond TM, Gentleman S, Duncan T, Yu S, Wiggert B, Gantt E, Cunningham FX. *J Biol Chem* 2001; **276**: 6560–6565.
14. von Lintig J, Dreher A, Kiefer C, Wernet MF, Vogt K. *Proc Natl Acad Sci USA* 2001; **98**: 1130–1135.
15. von Lintig J, Wyss A. *Arch Biochem Biophys* 2001; **385**: 47–52.
16. Wyss A, Wirtz G, Woggon WD, et al. *Biochem Biophys Res Commun* 2000; **271**: 334–336.
17. von Lintig J, Vogt K. *J Biol Chem* 2000; **275**: 11915–11920.
18. Evans TR, Kaye SB. *Br J Cancer* 1999; **80**: 1–8.
19. Merlet-Benichou C, Vilar J, Lelievre-Pegorier M, Gilbert T. *Curr Opin Nephrol Hypertens* 1999; **8**: 39–43.
20. Ulukaya E, Wood EJ. *Cancer Treat Rev* 1999; **25**: 229–235.
21. Collins MD, Mao GE. *Ann Rev Pharmacol Toxicol* 1999; **39**: 399–430.
22. Goodman AB. *Proc Natl Acad Sci, USA* 1998; **95**: 7240–7244.
23. Kliewer SA, Lehmann JM, Willson TM. *Science* 1999; **284**: 757–760.
24. Morriss-Kay GM, Ward SJ. *Int Rev Cytol* 1999; **188**: 73–131.
25. Funabiki T. Dioxygenases. In *Oxygenases and Model Systems* Funabiki T (ed). Kluwer Academic Publishers: Dordrecht, 1997; 19–104.
26. Lakshman MR, Pope JL, Olson JA. *Biochem Biophys Res Commun* 1968; **33**: 347–352.
27. Mordt RC, Walton JC, Burton GW, et al. *Tetrahedron* 1993; **49**: 911–928.
28. Singh M, Cama HR. *Biochim Biophys Acta* 1974; **370**: 49–61.
29. Bernstein PS, Choi S-Y, Ho Y-C, Rando RR. *Proc Natl Acad Sci, USA* 1995; **92**: 654–658.
30. Purcell AE, Walter J, W. M. *Method Enzymol* 1971; **18**: 701–706.

31. Liebman AA, Burger W, Choudhry SC, Cupano J. *Method Enzymol* 1992; **213**: 42–49.
32. Lin Y, Burri BJ, Ducker SR, Clifford AJ. *Faseb J* 1998; **12**: 3022.
33. Tosukhowong P, Supasiri T. *J Label Compound Radiopharm* 1985; **22**: 925–930.
34. Rhee SW, Degraw JI, Kaegi HH. *J Label Compound Radiopharm* 1985; **22**: 843–850.
35. Kaegi HH, Bupp JE, Degraw JI. *J Label Compound Radiopharm* 1982; **19**: 745–752.
36. Chien PL, Sung MS, Bailey DB. *J Label Compound Radiopharm* 1979; **16**: 791–797.
37. Britton G, Liaaen-Jensen S, Pfander H. *Carotenoids: Synthesis*, vol. 2. Verlag: Boston, 1995.
38. Babler JH. *US Patent* 5,107,030, 1992.
39. Horst P. *Angew Chem* 1960; **72**: 811–819.
40. Goldman IM. *J Org Chem* 1969; **34**: 1979–1981.
41. Larsen E, Abendroth J, Partali V, Schulz B, Sliwka HR, Quartey EGK. *Chem Eur J* 1998; **4**: 113–117.