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Cardiovascular effects of low versus high-dose beta-carotene in a rat model

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Graphical abstract

ABSTRACT

β -carotene (BC), a lipid-soluble tetraterpene precursor to vitamin A, widely distributed in plants, including many used in human diet, has well-known health-enhancing properties, including reducing risk of and treatment for certain diseases. Nevertheless, BC may also act to promote disease through the activity of BC derivatives that form in the presence of external toxicants such as cigarette smoke and endogenously-produced reactive oxygen species. The present investigation evaluates the dose-dependent cardioprotective and possibly harmful properties of BC in a rat model. Adult male rats, were gavage-fed BC for 4 weeks, at dosages of either 0, 30 or 150 mg/kg/day. Then hearts excised from the animals were mounted in a “working heart” apparatus and subjected to 30 minutes of global ischemia, followed by 120 minutes of reperfusion. A panel of cardiac functional evaluations was conducted on each heart. Infarct size and total antioxidant capacity of the myocardium were assessed. Heart tissue content of heme oxygenase-1 (HO-1) by Western blot analysis; and potential direct cytotoxic effects of BC by MTT assay were evaluated. Hearts taken from rats receiving 30 mg/kg/day BC exhibited significantly improved heart function at lower reperfusion times, but lost this protection at higher BC dosage and longer reperfusion times. Myocardial HO-1 content was significantly elevated dose-responsively to both BC dosage. Finally, *in vitro* evaluation of BC on H9c2 cells showed that the agent significantly improved vitality of these cells in a dose range of 2.5-10 μ M.

Although data presented here do not allow for a comprehensive mechanistic explanation for reduced cardioprotection at high dose BC, it is speculated that since Fe^{2+} produced as a metabolite of HO-1 activity, may determine whether BC acts as an antioxidant or prooxidant agent, the strong induction of this enzyme in response to ischemia/reperfusion-induced oxidative stress may account for the high-dose BC loss of cardioprotection.

Keywords: beta-carotene, heart, ischemia/reperfusion, heme-oxygenase-1

Chemical compound studied in this article: CID: 5280489

1. INTRODUCTION

1.1 “Functional foods” in prevention of and management of chronic illness

Increasingly intensive efforts are currently being made to characterize properties of plant materials forming regular components of human diet and expand the range of their use in healthcare. Substantial ongoing increases in serious chronic diseases, particularly obesity- and lifestyle-related cardiovascular disorders and related co-morbidities, provide compelling incentive for use of natural products in healthcare – particularly in the form of “functional foods”, which are items in normal diet configured to prevent and/or mitigate disease. Such substances are increasingly attractive to healthcare providers, since they are reasonably priced compared to prescription drugs and other potentially traumatic interventions. Moreover, health-enhancing properties for many of these materials have evolved in tandem with vertebrates as mutual adaptive strategies, a process called “xenohormesis” [1]. Hence there is compelling incentive to encourage adoption of diets rich in fruits, seeds, vegetables, legumes, fish oil and other materials rich in compounds that strengthen and stabilize healthy homeostatic processes and reduce risk of cancers, cardiovascular diseases and many other chronic illnesses.

1.2 β -carotene: chemical and biological properties

The present investigation explores the capacity of the vitamin A precursor β -carotene (BC) to influence aspects of myocardial cell, tissue, and organ function that may will allow development of novel strategies for use of this compound in prevention and management of heart disease. This tetraterpene carotenoid is a 536 Da lipid-soluble plant

pigment, widely distributed in nature, including many plants regularly consumed by animals and humans [2]. It is intensely red-orange and is responsible for multi-hued coloration in many plant species; and is also used as a commercial food colorant. Many human foods contain the compound, notably yams, pumpkins and carrots. Some of its medical benefits are well established. For example, the compound has been demonstrated moderately effective as adjuvant treatment in erythropoietic protoporphyria and has additionally shown some promise also been used to reducing risk of age-related macular degeneration; and susceptibility to breast cancer risk in pre-menopausal women [3-5]. A significant cautionary note on clinical use of BC, is evidence that lung cancer risk is increased in smokers by high-dose consumption of the agent [6]. This effect is hypothesized to occur due to instability of the compound in the presence of tobacco smoke – causing its degradation to carcinogenic metabolites [7].

1.3 Ischemia-reperfusion injury to cardiovascular tissue and antioxidant defense

The present investigation, which evaluates cardiovascular effects of BC, is focused on processes underlying ischemia and reperfusion (I/R) injury to the myocardium. Heart disease and cardiac surgery frequently involve procedures that deprive heart tissue of oxygenated blood, resulting in ischemia, a disruption of normal tissue homeostasis. Further derangement of tissue function may occur as a result of re-oxygenation by restoration of blood flow (reperfusion), a process that triggers a burst expression in physiologic production of highly reactive oxygen-containing species during the first 5 minutes of blood reflow [8]. These compounds greatly increase oxidative stress on reperfused tissues and effects that typically include oxidation of myocardial membrane lipids resulting in impairment of cell membrane function. This oxidative stress increase is a primary cause of reperfusion-induced damage [9]. Adverse effects on cardiovascular function caused by

these processes may be counteracted by antioxidant compounds capable of scavenging oxygen-containing free radicals that are the primary agents of oxidative stress-mediated damage. Such cytoprotective agents of (mainly) plant origin produce carotenoids, notably BC, along with polyphenolic compounds and other phytochemicals such as flavonoids, anthocyanidins, proanthocyanidins and other carotenoids which have well documented benefits to cardiovascular health [10-14].

1.4 β -carotene: a double-edged sword in health maintenance

The effects of BC have been intensively studied and both beneficial and potentially harmful effects of the compound have been noted [6,7]. In addition to its ability to affect risk and pathogenesis of cancer, BC has been considered for use in management of heart disease based on its free radical scavenging capacities, with the cautionary note that it may also act as a tissue-damaging prooxidant – depending on the physiologic environment [15,16]. Several clinical studies can be found having investigated the cardiovascular effects of BC, but all these results are rather controversial. Most of these studies found that BC had no any benefit and may have had adverse effects on the risk of death from cardiovascular diseases mainly among smokers [17-19]. The cardioprotective value of beta carotene also appears to vary among individuals based on genetic factors. This effect is illustrated by an intriguing April 2015 report demonstrating that healthy Korean women bearing single nucleotide polymorphisms that correlate with arterial stiffening, were differentially protected by dietary supplementation with BC, along with folate and vitamin E [20]. A primary mechanism by which BC counteracts pathogenesis of cardiovascular disease, has recently been shown to result from the compound's ability to abate atherogenic processes by inhibition of peroxidation of cardiac-associated lipids [21].

The investigation described in the present report was undertaken to evaluate the effects of BC administration in a rat model, segregated into groups administered two different BC dosages during a 4-week period. One test group, defined as “low dose” (LD) was fed 30 mg/kg/day; and a second, “high dose” (HD) group received 150 mg/kg/day, with a cohort of control (C) rats given hydroxyethyl cellulose-water vehicle. Following sacrifice at the end of the 4-week dosing period, hearts surgically excised and mounted in a “working-heart” apparatus were evaluated for cardiac function parameters and tissue biomarker correlates of physiological regulation of heart activity. Potentially toxic effects of BC on cardiomyocyte function was conducted by *in vitro* studies of BC dosage effect on H9c2 cells. The comparison of outcomes in hearts from animals treated with low-dose, high-dose BC and vehicle, provided a clear perspective into how this compound affected features of heart function relevant to maintenance of healthy heart activity and treatment of disease.

2. MATERIALS AND METHODS

2.1 Animals

The experiments were accomplished using adult male rats (Charles River Laboratories), with a body weight range of 350-400 grams. All animals received humane care in compliance with the “Principles of Laboratory Animal Care” (formulated by the U.S. National Society for Medical Research, as described in U.S. National Institutes of Health publication No. 86-23, revised 1996) and the “Guide for the Care and Use of Laboratory Animals”. Maintenance and treatment of animals used in the present study was additionally approved by the Institutional Animal Care and Use Committee of the University of Debrecen, Debrecen, Hungary. The animals were housed in wire-bottomed

cages (three rats per cage) throughout the study and were maintained on a 12:12-h light-dark cycle; and provided with laboratory rodent chow pellets, and water *ad libitum*.

2.2 Groups and administration of β -carotene

Rats used in the present study were segregated into 3 groups and gavage-administered the following agents: hydroxyethyl cellulose-water (1:4) vehicle control (C); LD-BC (30 mg/kg/day) and HD-BC (150 mg/kg/day) suspended in hydroxyethyl cellulose-water, respectively. BC was obtained from Sigma-Aldrich Kft. (Budapest, Hungary).

2.3 Ischemia-reperfusion and isolated working hearts

Following 4-week treatment with vehicle or BC, the rats were anesthetized with intraperitoneal injections of ketamine-xylazine (75/10 mg/kg), with heparin anticoagulant administered intraperitoneally (1000 IU/kg). After thoracotomy, the hearts were excised and placed in ice-cold modified Krebs-Henseleit bicarbonate buffer (118.5 NaCl, 4.7 KCl, 2.5 $\text{CaCl}_2 \times \text{H}_2\text{O}$, 25 NaHCO_3 , 1.2 KH_2PO_4 , 1.2 MgSO_4 , and 10.0 glucose (in mM)), then cannulated through the aorta and perfused in a Langendorff apparatus in “non-working” mode (100 cm of water) for 5 minutes to flush blood out from the hearts. Subsequently, Langendorff perfusion was conducted using a cannulated pulmonary vein, during which the isolated heart preparatum was switched to working mode (at a filling pressure of 17 cm of the buffer). After 10 minutes of working perfusion, 30 minutes of global ischemia (ISA) was initiated for each procedure, by clamping the pulmonary inflow and the aortic outflow. At the end of the ischemic period, 120 minutes of reperfusion (REP) was initiated by unclamping the inflow and outflow lines. The first 10

minutes of REP was conducted in Langendorff mode to avoid the fatal ventricular arrhythmias as described [22].

2.4 Cardiac function measurements

Baseline assessment of cardiac function for each isolated heart was made following 10 minutes of working perfusion. To examine the recovery of the left ventricle, these parameters were measured after 30, 60, and 120 minutes of REP. Cardiac function evaluation for each experiment was conducted as previously described [22]. Briefly, heart rate (HR) was measured using a computer acquisition system (ADInstruments, PowerLab, Castle Hill, Australia); coronary flow (CF) values were obtained by timed collection of effluent draining from each heart; aortic flow (AF) measurements were made using a calibrated flow meter; cardiac output (CO) was generated as the sum of AF and CF. Stroke volume (SV) was calculated as the quotient of CO/HR [23]; and alteration in SV values, as a function of treatments, were calculated as the ratio of SV at reperfusion divided by baseline SV and multiplied by 100.

2.5 Infarct size determination

Estimations of infarct size (IS) were conducted using the triphenyl tetrazolium chloride (TTC) staining method as previously described [22]. Briefly, following each 30-minute ISA/120-minute REP period, hearts were perfused with 50 ml 1 % (w/v) solution of TTC in phosphate buffer (pH 7.4), and the samples were stored at -70 °C for subsequent analysis. The frozen samples were sectioned, weighted, and blotted dry. The dried sections were scanned on an Epson J232D flat-bed scanner. The infarcted area (white coloration) and the risk area (entire scanned section) were measured using

planimetry software (Image J, National Institute of Health, Bethesda, Maryland, USA). Estimates of infarcted zone magnitude were subsequently obtained by multiplying infarcted areas by weight of each slice. The resulting numbers represent weight of the risk zone and the infarcted zone. Infarct size was expressed as percentage of the weight of infarcted tissue and the weight of risk zone (whole heart) [13].

2.6 Western blot analysis of heart tissue

Content of HO-1 protein in the myocardium were obtained by Western blot as previously described [22]. Briefly, approximately 300 mg of left ventricular myocardial tissue were homogenized on ice using a tissue homogenizer (IKA T10 basic ULTRA-TURRAX®) in isolating buffer (25 mM Tris-HCl, 25 mM NaCl, 1 mM orthovanadate, 10 mM NaF, 10 mM pyrophosphate, 10 mM okadaic acid, 0.5 mM EDTA, 1 mM PMSF, and 1x protease inhibitor cocktail) and centrifuged at 2000 rpm at 4 °C for 10 minutes. The supernatants were transferred to fresh tubes and centrifuged at 10,000 rpm at 4 °C for 20 minutes, after which the resulting supernatant was used as cytosolic fraction. The protein concentration was measured by ND-1000 Nano drop spectrophotometer with BCA Protein Assay Kit (Thermo Scientific, Rockford, IL). Thirty µg of protein in each sample were loaded in 10 % polyacrylamide gel and resolved using SDS-PAGE electrophoresis and then transferred to 0.45 µm pore size nitrocellulose membrane to concentrate the samples. After blocking the membranes with 7 % nonfat dry milk in TBST, membranes were incubated overnight with primary antibody solution in 1 % of nonfat dry milk in TBST (GAPDH 1/40000, antibody was obtained from Cell Signaling Technology, Boston, MA; and HO-1 1/50 was ordered from Sigma-Aldrich Kft. Budapest, Hungary) at 4 °C. Then, the membranes were washed 3 times, each for 10 minutes, in TBST and incubated with horseradish peroxidase-conjugated secondary

antibody solution (Cell Signaling Technology) containing 1 % of nonfat dry milk in TBST, for two hours at room temperature. The membranes were treated with Western blot Enhanced Chemiluminescent HRP substrate (Millipore, Billerica, MA) to visualize the bands. After the Enhanced Chemiluminescent treatment, the membranes were exposed on x-ray films (Agfa, Mortsel, Belgium). The films were then digitalized by flat-bed scanner (Epson J232D) and analyzed using ImageJ program and normalized the HO-1 band intensities to GAPDH.

2.7 MTT cell viability assays for β -carotene cytotoxicity

Evaluation of BC cytotoxicity on cellular survival was accomplished using the 3-(4,5-dimethylthiazol-2-yl)-2,5-diphenyltetrazolium bromide (MTT) assay as previously described [24]. Briefly, H9c2 cells (ATCC, CRL-1446, LGC Standards GmbH, Wesel Germany) dissociated by trituration in medium (Dulbecco's modified eagle's medium from Sigma with 10% FBS, 1% penicillin-streptomycin), were seeded into 96 well plates at a density of 3000 cells/well and cultured for 1 day to establish adhesion of the wells. BC containing medium was prepared as described by Wertz et al. for keratinocyte cultures with some modifications [25]. Cells were treated with 0, 2.5, 5, 10 and 20 μ M BC for 4 hours, respectively. Next, following a 30-minute incubation period, half of the wells were treated with 125 μ M H₂O₂. Four hours later addition of 20 μ l MTT solution (5 mg/ml in PBS) to each well and an additional 3 hours incubation at 37 °C to allow mitochondrial uptake, the medium were removed and cells were lysed by addition of 150 μ l of isopropanol, incubated for 15 minutes followed by measurement of absorbance at 570 and 690 nm using a plate reader (FLUOstar OPTIMA, BMG Labtech). Within each experiment, absorbance values were averaged across 4 replicate wells and repeated 3 times. BC cytotoxic effect assessments were estimated based on linear correlation of

absorbance values with MTT-associated H9c2 viability and reported as percentage of cells surviving 4 hours of BC exposure relative to control cells not exposed to BC.

2.8 Tissue antioxidant capacity (TAC)

TAC of heart tissue was measured using the CS0790-1KT antioxidant assay kit (Sigma-Aldrich Kft., BP., Hungary). Briefly, at the end of reperfusion, the hearts were frozen and stored at -70 °C until analysis. Approximately 100 mg of left ventricular myocardial tissue from each heart were homogenized in 0.5 ml of 1x Assay buffer, centrifuged at 12000 rpm, for 15 min at 4 °C and the supernatants collected for assay. Following sample preparation according to manufacturer's instructions, the absorbance was measured at 405 nm using a plate reader (FLUOstar OPTIMA, BMG Labtech). TAC values for each heart was derived from absorbance values and expressed as Trolox equivalent (μ M).

2.9 Statistical analysis

Statistical analyses were performed using GraphPad Prism 5 software. The data are expressed as mean \pm SEM. One-way ANOVA followed by Bonferroni post-test was carried out for heart function data analysis. MTT data were compared by t-test. For Western blot and TAC data outcomes, repeated measures of one-way ANOVA followed by Tukey's post-test was conducted. Differences were considered significant at values of $P < 0.05$.

3. RESULTS

3.1 β -carotene dose effects on cardiac function in isolated hearts subjected to I/R

Figure 1 shows the dose-responsive influence of 0, 30 or 150 mg/kg/day BC gavage-administered to rats during a 4-week period on cardiac function in hearts isolated from the animals and subjected to 30 minutes of global ISA and 120 minutes of REP in a “working-heart” apparatus. No BC-mediated effects on AF were observed in hearts not subjected to REP, however, relative to hearts from vehicle-treated control animals, hearts from animals subjected to 30 min of ISA followed by 30 and 60 min of REP exhibited significantly increased AF when taken from rats treated with LD-BC; but interestingly, not which were subjected to 120 min of REP or from those fed with HD-BC (Figure 1A). No significant BC dosage effects on CF were observed in non-reperfused hearts, or in hearts from animals subjected to 30 min of I/R (Figure 1B). Furthermore, HD-BC treatment resulted in a significant increase on CF values after 60 and 120 min of REP relative to organs from non-BC-treated controls ($P<0.05$). Likewise CO in non-ISA/REP hearts and those subjected to 120 minutes of REP did not vary significantly as a result of BC treatment, whereas significant CO increases in these hearts relative to organs from non-BC-treated controls were observed in those sustaining reperfusion periods of 30 minutes ($P<0.05$) and 60 minutes ($P<0.05$) from rats receiving 30 mg/kg/day BC, but not 150 mg/kg/day of the agent (Figure 1C). Treatment of animals with 150 mg/kg/day BC resulted in significant increase in HR for I/R hearts ($P<0.05$) (Figure 1D). Evaluation of the effects of BC on heart SV, revealed no significant BC effect on this variable in non-I/R hearts, or organs subjected to I/R. It was further noted that SV values in hearts receiving 30 and 60 minutes of REP from animals treated with 150 mg/kg/day BC were reduced, however it was not significant, relative to those from rats receiving low BC dose (Figure 1E). This apparent loss of cardioprotection at elevated BC dosage was further confirmed by measurement of stroke volume decline (dSV). These results demonstrated that relative to non-I/R hearts, hearts subjected to 30 and 60, but not 120 minutes of REP

exhibited lesser declines in stroke volume when taken from animals treated with 30 mg/kg/day BC than from rats receiving 0 or 150 mg/kg/day BC, however it did not reach the significant level. (Figure 1F).

Hearts were isolated from 3 groups of rats (n = 6 per group). Rats in each test group received hydroxyethyl cellulose-water (1:4) vehicle control (white bars); BC 30 mg/kg/day (black-shaded bars); and BC 150 mg/kg/day (gray-shaded bars) and sacrificed following a 4-week time period of BC treatment. Hearts isolated from each rat were subjected to 30 minutes of global ISA followed by either 120 minutes of REP in an isolated “working-heart” apparatus to induce I/R-induced injury and evaluated for selected cardiac functions. Results are shown as average values from each group of animals \pm SEM of AF (1A); CF (1B); CO (1C); HR (1D); SV (1E); and dSV (1F).

*P<0.05 for comparison of the magnitude of each cardiac function measured in each test group receiving BC, relative to hearts from vehicle-treated control animals. #P<0.05 for comparison of the magnitude of cardiac function measured in LD-BC relative to hearts from HD-BC treated animals.

3.2 β -carotene dose effects on I/R-induced infarct zone extent and tissue antioxidant capacity

The influence of BC on the extent of I/R injury-associated infarct zones is shown in Figure 2A. Macroscopic analysis of TTC solution-perfused heart sections from rats subjected to 30 minutes of global ISA followed by 120 minutes of REP in a “working-heart” apparatus revealed that LD-BC treatment, correlated with significant reduction of the extent of infarcted myocardium relative to the control values (*P<0.05). This protective effect is abolished in hearts taken from animals treated with high-dose BC

([#]P<0.05), moreover, the average extent of I/R-induced infarcted zones of hearts of these animals was non-significantly increased relative to hearts from rats administered vehicle only.

The phenomenon of diminished BC-mediated protective effect on cardiac physiology was also dramatically illustrated in outcomes of experiments to assess contribution of the agent to tissue antioxidant capacity (TAC), a process that has evolved as a homeostatic countermeasure to oxidative stress. As shown in Figure 2B, isolated, I/R-injured working hearts taken from rats administered LD-BC, exhibited TAC values significantly in excess of vehicle-treated controls (*P<0.05) and hearts isolated from HD-BC treated animals ([#]P<0.05). Nevertheless, TAC values measured in hearts from animals received HD-BC were not significantly higher than hearts from control rats received vehicle.

Infarct size was measured in hearts (n=4) following 120 min of REP by perfusion with triphenyl tetrazolium (TTC) solution, followed by macroscopic analysis of transverse sections of each heart. Average sizes of infarct zone for hearts in each group \pm SEM are shown for each treatment group. TAC values for each tissue sample is expressed as Trolox equivalent (μ M) \pm SEM are shown for each treatment group. *P<0.05 for comparison relative to values for hearts from vehicle-treated control (C) animals. [#]P<0.05 for comparison relative to values for hearts from HD-BC treated animals.

3.3 β -carotene effects on heme oxygenase-1 (HO-1) protein expression

Myocardial tissue levels of HO-1, which is a major mediator of cardiac homeostasis, were determined by Western blot analysis. As shown in Figure 3., the presence of HO-1 protein was evaluated in isolated working hearts taken from control rats administered hydroxyethyl cellulose-water vehicle (C), over 4 weeks; a second test group given LD-

BC; and a third group, fed with HD-BC. Hearts excised from these animals were either sham-treated (BL-baseline) (Figure 3. panel A), or I/R-injured (I/R) (Figure 3. panel B) by 30 minutes of global ISA and 120 minutes of REP. The results show that in control hearts which were not subjected to I/R (C-BL) HO-1 expression was not significantly different from non-injured hearts removed from rats receiving LD-BC (LD-BL), while high dose treatment (HD-BL) resulted in significantly increased HO-1 level (* $P < 0.05$) (Figure 3.A). Furthermore, in hearts from non-treated animals and subjected to I/R (C-I/R) we detected mild but non-significant increase of HO-1 compared to non-ischemic baseline hearts (C-BL) (Figure 3.B) while, production of HO-1 protein in I/R injured hearts from rats fed with either low-dose (LD-I/R) or high-dose BC (HD-I/R), was significantly higher compared to non-treated non-injured (C-BL) group (* $P < 0.05$) (Figure 3.B). Moreover, HO-1 expression in hearts removed from vehicle treated animals and subjected to I/R (C-I/R) was not significantly different from hearts excised from rats receiving LD-BC and subjected to I/R (LD-I/R), however, hearts from high-dose treated animals expressed significantly elevated levels of HO-1 protein relative to corresponding levels measured in vehicle-treated controls (C-I/R) ($^{\#}P < 0.05$) (Figure 3.B).

Expression of HO-1 protein in rat myocardium was measured in homogenized cardiac tissue samples from vehicle or BC treated hearts, with or without I/R injury. Western blot analyses were conducted on each tissue homogenate in triplicate and the signal intensity of resulting bands corresponding to HO-1 protein was measured using the Scion for Windows Densitometry Image program. Tissue content of each protein is shown as a ratio of arbitrary units for HO-1 protein to GAPDH signal. Data are expressed as mean \pm SEM of 6 different blots. * $P < 0.05$ for comparison of average levels of HO-1 in ventricular myocardium from BC-treated animals, versus non-ischemic control (C-BL)

hearts. [#] P<0.05 for comparison of average levels of HO-1 in ventricular myocardium from BC-treated animals subjected to I/R, versus I/R-injured control (C-I/R) hearts.

3.4 MTT assay-based evaluation of β -carotene cytotoxicity

To determine if the significant loss of cardioprotective capacity of BC when administered at the levels defined as “high-dose” in the present study, experiments were carried out to evaluate cytotoxicity of the agent in rat H9c2 cardiomyoblasts, an *in vitro* model, which along with the MTT cell viability assay, has proven to be a highly versatile tool for use in cardiovascular pharmacology [26]. As shown in Figure 4., significant increases in H9c2 cell viability was observed in cultures of these cells grown 24 hours in Dulbecco’s medium supplemented with 2.5, 5 and 10 μ M BC, relative to cells grown with no BC added (*P<0.05). Furthermore, this protective effect was not observed in cells treated with 20 μ M of BC.

Evaluation of BC cytotoxicity on cellular survival was accomplished using the MTT assay. H9c2 cells grown 24 hours in Dulbecco’s modified eagle’s medium and treated with 0, 2.5, 5, 10 and 20 μ M BC, were followed by 4-hour treatments with 125 μ M H₂O₂ and 5 mg/ml MTT reagent, lysis of cells and measurement of absorbance was at 570- and 690 nm. Absorbance values were averaged across 4 replicate wells, and repeated 3 times. Outcomes are shown as average percentage of cell viability for each BC dosage level, relative to control cultures not BC-treated. *P<0.05 for comparison of average % viability versus non BC-treated cultures.

4. DISCUSSION

Outcomes of the present study contribute to emerging insight into how widely available plant materials may be used to enhance strategies for maintenance of cardiovascular health and develop novel therapeutic approaches. Here, the capacity of β -carotene is evaluated for its ability to alter processes resulting in reduced tissue oxygenation, leading to ischemic injury to the heart and with strong relevance to the kidneys, brain and many other organs [27]. A major finding reported here, is that increasing BC dosage of may not add to any cardiovascular benefits. Moreover, the agent may mediate – and indeed, may exacerbate existing pathological mechanisms.

The efficiency and vigor with which a heart is able to maintain healthy circulation may be quantitatively described by cardiac functional measurements, in particular, AF, CF, CO, SV and dSV [28] and the ability of agents that enhance antioxidant signaling to improve these functions in isolated ischemic/reperfused rat hearts has previously been demonstrated [29]. Accordingly, the significant LD-BC-mediated improvement in AF (Figure 1A), CO (Figure 1C), were not unexpected. Nevertheless, the apparent abolition or mitigation of these protective effects against I/R injury in rats treated with BC at the higher dose is intriguing.

The rat model was selected for the present investigation based on the well-known features of this animal's physiology its widespread use in cardiovascular research [30], and extensive use of these animals in previous cardiac-related drug discovery and basic scientific work by authors of this report [10,11,13,22,31,32]. The experiments described here, were nevertheless undertaken in the context of known limitations on the translational value of carotenoid research using rat data. A significant consideration in studies such as the present one, is that although rats and mice readily convert BC to vitamin A, bioavailability of carotenoids through gut absorption is very low, requiring administration of supraphysiologic BC dosages – greatly in excess of levels from any

natural source [33]. The experiments were designed to partly offset this limitation by administration of BC in a high dose range for all conditions. Accordingly, use of these outcomes and findings in design of improved human healthcare strategies must be made conservatively, taking into account experimental versus normal dietary or therapeutic dose ranges. In the present study, even the lowest dose of BC administered to rats is very high, equivalent to more than 2 g/day/70 kg man. On a daily basis, a normal human diet may contain 3 orders of magnitude less BC [34]. The degree of translational value that these findings have for managing cardiovascular disease, will require human nutritional studies – for which the present study provides a guide to major outcomes that might be evaluated. Here it is important to emphasize the value of human, versus extended animal studies. No single animal model completely replicates BC absorption and metabolism of humans [33]. Moreover, since the present study was designed to obtain mostly qualitative evaluations of low-, versus high-dose BC effects on major cardiac parameters, no attempt was made to determine precise rat-to-human dose equivalents. Thus, human clinical evaluations of the effects described here, constitute appropriate and easily accomplished follow-on studies.

Although data presented here do not allow a comprehensive mechanistic analysis, the observation that low-dose-mediated improvement of AF and CO observed at 30 and 60, but not 120 minutes of post-ischemic REP suggest that BC at the lower dosage is effectively quenching oxidative stress-promoting prooxidant compounds produced by cardiac tissue as a consequence of inflammatory reactions triggered by I/R-induced damage and/or otherwise counteracting adverse effect of these metabolites. If this is the case, then it is reasonable to predict that the higher levels of oxidative stress present with longer reperfusion periods, might overwhelm the quenching ability of BC, significantly diminishing the beneficial effects of the 150 mg/kg/day treatments. The relative ability of

BC to quench prooxidant molecules may also account for differences in magnitudes of myocardial infarct zones and tissue antioxidant capacity shown in Figure 2. The significantly reduced average infarct size observed in I/R-injured hearts of animals treated with LD-BC, relative those not administered the agent, is consistent with previous work by authors of the present report, demonstrating that the extent of myocardial infarct zones in I/R-injured hearts may be diminished with agents that reduce oxidative stress [13,22,35]. Accordingly, the significant LD-BC-mediated reduction of infarct size (Figure 2A) and increased TAC (Figure 2B), were not surprising. Moreover, abolition of these effects in hearts of animals treated with 150 mg/kg/day BC, would be expected if the quenching ability of the molecule were suppressed at a higher dose, allowing a more prooxidant cardiac tissue environment at the higher dosage. The dose-responsively increased expression of HO-1 by myocardial tissue observed for both BC and duration of REP shown in Figure 3., further supports the possibility that BC loses quenching potential and may become prooxidant as dosage increases. HO-1 is an ubiquitous antioxidant response to a wide variety of oxidative stressors, hence it is expected that its expression would increase as a result of I/R injury [27].

It is further expected that BC acting as a protective antioxidant would not be diminished by BC also acting as a quenching agent and contributor to TAC, as shown in Figure 2B. However, if this model is accurate, BC at the elevated dose, acting to promote prooxidant tissue environments is expected to stimulate HO-1 production – which is what was observed (Figure 3.). The possibility of such a mechanism is additionally validated, by the observation that HO-1 expression in I/R-injured hearts of rats treated with high-dose BC (HD-I/R) was elevated relative to production of the enzyme by hearts from rats treated with high dose BC, but not subjected to I/R injury (HD-BL) (Figure 3.), since

elevated HO-1 expression would be an expected consequence of significantly higher levels of oxidative stress present in I/R-injured tissue.

This analysis is supported, albeit to a minor extent by outcomes of the *in vitro* assays for BC cytotoxicity on H9c2 rat myocardial cells. Outcomes of these experiments (Fig. 4.) show that viability of these cells is significantly enhanced in comparison to unstimulated control cultures, by addition of BC at 2.5, 5 and 10 μ M, with a loss of this effect at 20 μ M. Although these data are insufficient on which to base definitive conclusions, the results suggest that as BC dosage is increased, the protective effect of the compound is diminished and may include deleterious properties.

An explanation for apparent cardioprotective effect of BC at one selected dosage and mitigation or elimination of that protection at a higher dose is speculative based on the outcomes presented here. This notwithstanding, previous studies provide some clues as to the mechanisms that may underlie the observations in this report. It is known that free radical species of the kind responsible for oxidative stress in vertebrate tissues, react with BC to produce prooxidant degradation products, such as apo-8'-beta-carotenal, that are particularly damaging to subcellular organelles, particularly mitochondria, resulting in further disruption of the redox balance of myocardial cells, oxidation of critical proteins and exacerbation of damage caused by ischemia-reperfusion injury [15,16]. Ironically, the HO-1 expression response to oxidative stressors may also contribute to loss of cardioprotection at elevated BC dosage. This is a possibility because heme oxygenases, including HO-1, reduce oxidative stress by degrading heme produced in the tissue by red blood cell turnover to produce metabolites with cytoprotective qualities, principally biliverdin (converted rapidly into bilirubin) and subtoxic levels of carbon monoxide, which promotes antioxidant signaling. Interestingly, although ferrous iron (Fe^{2+}) also produced by normal HO-1 activity is a benign metabolite and readily cleared, its presence

under some physical settings determines whether BC acts as an antioxidant or prooxidant compound [36]. This property has potential consequences that are paradoxical in the context of the putative role of HO-1. Normally, increased activity of this enzyme reduces oxidative stress and protects tissues from toxic insult. In the present study, I/R injury to cardiac tissue, strongly activated HO-1, resulting in elevated levels of its metabolic products, including Fe^{2+} . Since, as described by Andersen et al., Fe^{2+} enhances the prooxidant properties of BC, influences that elevate HO-1 in the presence of high BC levels, potentially overwhelm the cytoprotective effects of HO-1 and increase oxidative stress on a tissue. This conclusion is speculative and will require further analysis of BC cardiovascular effects. Such a mechanism is nevertheless consistent with the known behavior of BC in the presence of Fe^{2+} - and if valid, accounts for the results shown in Figure 4. Potential relevance of this finding to management of cardiovascular disease is provided by an observation that an inducer of HO-1 administered orally to human patients significantly altered serum levels of transferrin, which is the physiologic transport molecule for Fe^{2+} [37] indicating that aspects of iron metabolism that may also impact BC utilization may be modulated by drugs that affect HO-1 activity and possibly selective chelators of Fe^{2+} .

CONCLUSIONS: The findings described above, suggest that the level of HO-1 activity in response to I/R injury may be a critical determinant for the role of BC as either a protective agent against I/R-induced heart damage, or as a contributor to I/R-related syndromes through activation of its prooxidant properties. Validity of this model depends on the degree to which redox activities of BC may be influenced in either direction by presence of Fe^{2+} - which has been identified as a primary factor. Ongoing characterization of these processes is continuing by this laboratory. A particularly valuable outcome anticipated for this ongoing research initiative, is the potential for combining use of BC

with HO-1 inducers, such as the sour cherry seed extracts described by Csiki et al [37], in modulation of the clinical effects of BC.

FUTURE DIRECTIONS: Current efforts by authors of this report to mitigate the cardiotoxic effects of β -carotene, while retaining the cardioprotective value of this compound and also HO-1 activity, are focused on development of a novel functional food class containing whole leaf extract of *Tamarindus indica* L. (tamarind), which in March 2015 was reported to chelate ferrous iron, with a binding constant of 1.085 mol L^{-1} [38]. It is predicted that Fe^{2+} chelation in this potency range will augment transferrin activity to the extent that the capacity of endogenous HO-1 to reduce oxidative stress will be retained, while simultaneously counteracting BC toxicity by removal of Fe^{2+} . This conclusion is currently speculative and await outcome of ongoing studies.

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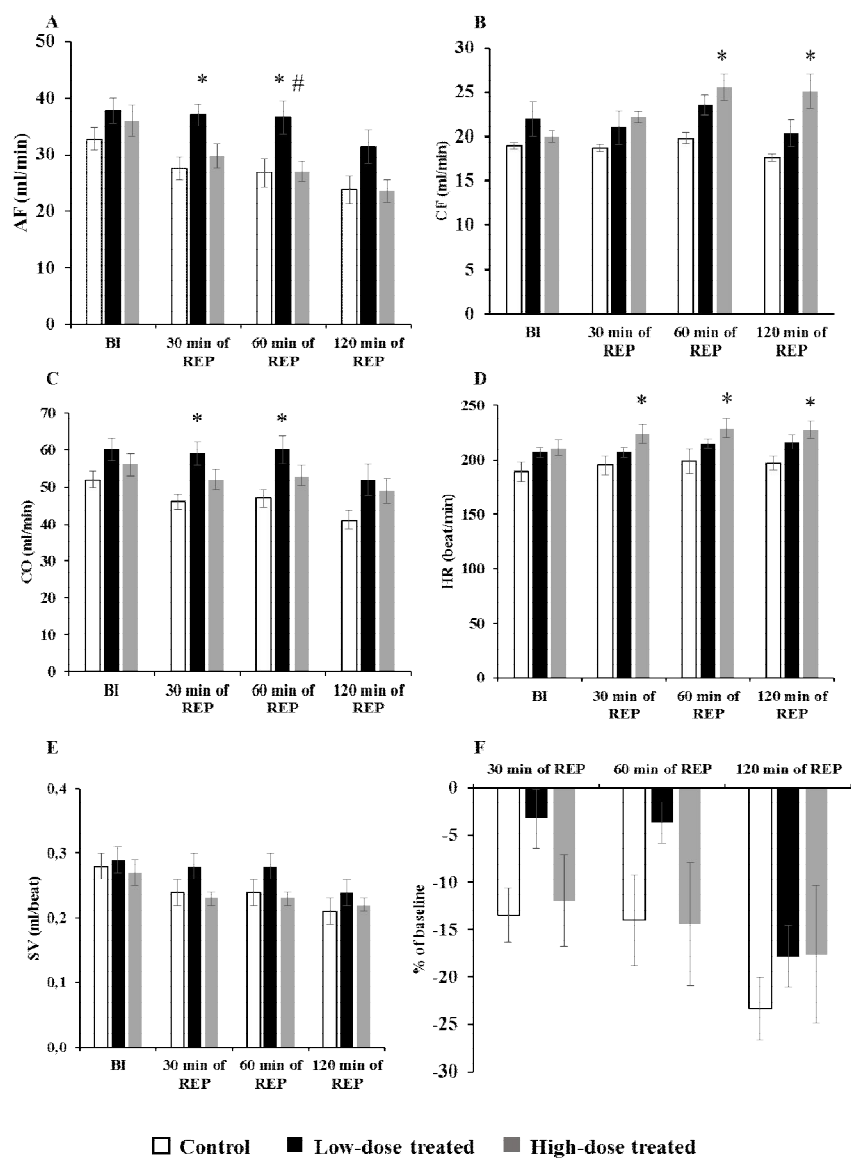


Figure 1.: β -carotene effects on cardiac function in isolated working hearts.

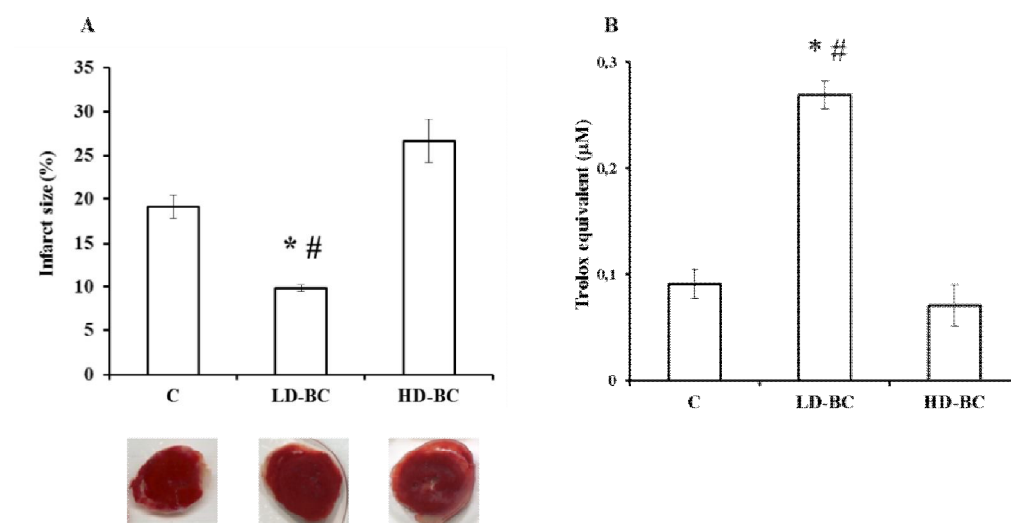


Figure 2.: Effect of β -carotene on infarcted zone magnitude (A) and tissue antioxidant capacity (B).

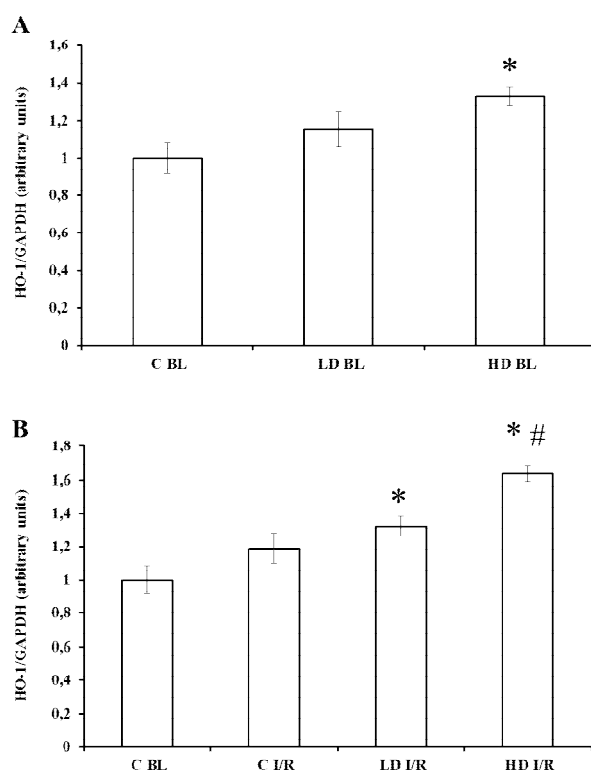
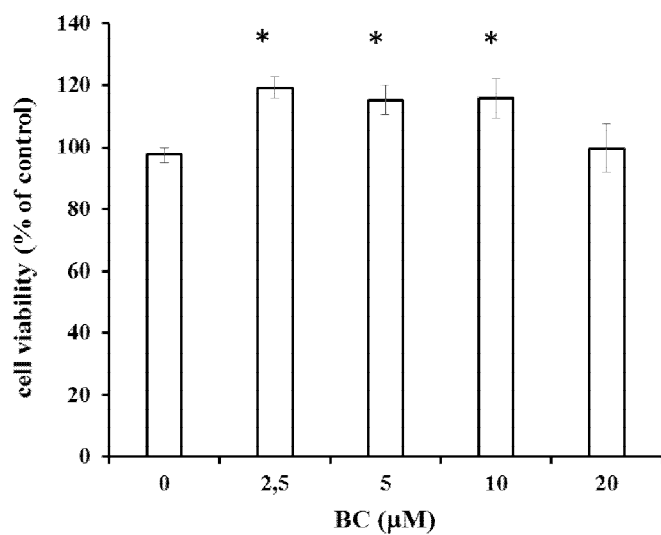


Figure 3.: Western blot analysis for cardiac expression of heme oxygenase-1 (HO-1) protein.



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Figure 4.: *In vitro* (MTT) assays for β -carotene cytotoxicity on H9c2 cells.

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