Consumption of high ω-3 fatty acid diet suppressed prostate tumorigenesis in C3(1) Tag mice

Juliana A.Akinsete, Gabriela Ion, Theodore R.Witte and W.Elaine Hardman

Department of Biochemistry and Microbiology, Marshall University School of Medicine, Huntington, WV 25755, USA

*To whom correspondence should be addressed. Tel: +1 304 696 7339; Fax: +1 304 696 7207; E-mail: hardmanw@marshall.edu

Prostate cancer incidence and mortality are high in the Western world and high ω-6/ω-3 PUFA in the Western diet may be a contributing factor. We investigated whether changing from a diet that approximates ω-6 fat content of the Western diet to a high ω-3 fat diet at adulthood might reduce prostate cancer risk. Female SV 129 mice that had consumed a high ω-6 diet containing corn oil for 2 weeks were bred with homozygous C3(1)/Tag transgenic male mice. All male offspring were weaned to the corn oil diet (CO) until puberty when half of the male offspring were transferred to a high ω-3 diet containing canola oil and fish oil concentrate (FS). High ω-3 diet increased ω-3 and decreased ω-6 fat content of mice tissues. Average weights of prostate and genitourinary block were significantly lower in mice consuming high ω-3 diet at adulthood (CO-FS) than mice fed a lifetime high ω-6 diet (CO-CO). There was slower progression of tumorigenesis in dorsolateral prostate of CO-FS than in CO–CO mice. CO-FS mice had slightly lower plasma testosterone level at 24 and 40 weeks, significantly lower estradiol level at 40 weeks and significantly less expressed androgen receptor (AR) in the dorsolateral prostate at 40 weeks than CO–CO mice. Consumption of high ω-3 diet lowered the expression of genes expected to increase proliferation and decrease apoptosis in dorsolateral prostate. Our results suggest that consumption of high ω-3 diet slows down prostate tumorigenesis by lowering estradiol, testosterone and AR levels, promoting apoptosis and suppressing cell proliferation in C3(1)Tag mice.

Introduction

Prostate cancer has remained the most frequently diagnosed cancer and the second leading cause of cancer related death among men in the USA, accounting for 28% of total expected cancer incidence in men of USA in 2010 (1). In general, the incidence and mortality of prostate cancer are high in North America and Northern Europe but much lower in Japan and other Asian countries (2). Migration studies show that Asian men living in the USA have a lower risk of prostate cancer than the Caucasians but have a higher risk than their counterparts living in Asia (3). Japanese men that immigrate to the USA die of prostate cancer with increasing frequency as a function of the number of years of their residency (4). The major factor for this increased frequency in prostate cancer death is thought to be the Western diet.

Polyunsaturated fatty acids (PUFA) are a component of dietary fat reported from several investigations to influence the development of prostate cancer (5). In the past 100 years, the fatty acid composition of Western diets has witnessed a dramatic change, largely due to a high increase in the consumption of omega-6 (ω-6) PUFA from vegetable oils and red meat and less consumption of omega-3 (ω-3) PUFA (6). This has resulted in an ω-6/ω-3 ratio of 25:1 to 40:1 rather than near the ideal 1:1 in the US diets. Asian diets are lower in ω-6 and higher in ω-3 than the Western diet due to more consumption of fish and other sea products and low consumption of plant oils and red meat.

Several studies have investigated the effects of ω-3 and ω-6 fat on prostate tumor cells. Omega-3 PUFA [eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA)] inhibit tumor cell growth in animal models and human prostate cell lines (7,8), whereas ω-6 PUFA [linoleic acid (LA) and arachidonic acid (AA)] increase growth of human prostate tumor cell lines (7,9). Epidemiologic studies also reported a decrease of metastatic prostate cancer risk and prostate cancer death in men who consume the most fish (10–13), a good source of EPA and DHA. LA is the most abundant ω-6 PUFA in the human diet. It is abundant in many plant oils such as corn oil, safflower oil and sunflower oil. LA is the precursor for the synthesis of AA, which is abundant in red meat and meat fat.

Prostate cancer burden continues to increase because of the aging and growing population as well as nutritional patterns that tend to increase the risk for the disease. There is the need to identify and establish factors that might prevent or slow the progression of prostate cancer. If beneficial, a dietary change that includes the reduction in the intake of ω-6 PUFA and increase the proportion of dietary ω-3 PUFA may therefore be a powerful tool for prevention of mortality from prostate cancer.

In this study, we tested the hypothesis that compared with a diet that approximates the ω-6 fatty acid content of the Western diet exposure to a diet with more ω-3 fatty acids during adulthood will slow the progression of prostate cancer and to identify the underlying molecular factors. The C3(1)Tag mouse was used for the study because it develops prostate cancer slowly and has a well-characterized disease progression making it suitable for prevention studies (14). We show that compared with a diet that is high in ω-6/ω-3 fat, consumption of low ω-6/ω-3 diet slows prostate carcinogenesis.

Materials and methods

Mice

Twenty female SV 129 mice, at 6 weeks of age, were obtained from Charles River Laboratories (Wilmington, MA), quarantined for 2 weeks and transferred to a study room. Mice that bear a transgene for the SV40 large T antigen with a C3(1) rat prostatic steroid-binding protein promoter were obtained from Dr Jeffrey Green of the National Cancer Institute. The male transgenic mice develop prostatic intraepithelial neoplasia (PIN) that progresses to prostate carcinoma due to expression of the large T antigen in the prostate (14). All mice were genotyped to confirm the presence of the transgene.

Abbreviations: AA, arachidonic acid; ADC, adenocarcinoma; AR, androgen receptor; EPA, eicosapentaenoic acid; DHA, docosahexaenoic acid; DL, dorsolateral prostate; HGPIN, high-grade prostatic intraepithelial lesion; GU, genitourinary; LA, linoleic acid; LGPIN, low-grade prostatic intraepithelial neoplasia; NOS, nitric oxide synthase; PCR, polymerase chain reaction; PIN, prostatic intraepithelial neoplasia; PCNA, proliferating cell nuclear antigen; PUFA, polyunsaturated fatty acid.

© The Author 2011. Published by Oxford University Press.
Study design and feeding
All female SV 129 mice were placed on a diet containing 10% wt/wt corn oil (high o-6, control diet, ratio of o-6/o-3 was 50). After 2 weeks, they were bred with homozygous C3(1) Tag transgenic male mice. All male hemizygous off-spring were weaned to the corn oil diet (CO) and consumed this diet until the postpuberty age of 7 weeks. Half of the offspring were retained on the corn oil diet to generate the high o-6 CO-CO (mother—pup diet) group, whereas the remaining half were transferred to a higher o-3 diet ([F0, test diet] to generate the CO-FS (mother—pup diet) group. The high o-3 diet contained 5% canola oil (to provide adequate essential o-6 fatty acid) and 5% fish oil concentrate (ratio of o-6/o-3 in the diet was 0.3). The offspring were housed not more than four in a cage, numbered for individual identification and weighed weekly. All animals were maintained in an isolated environment in barrier cages and fed the specified diet. Mice were fed ad libitum with fresh food 6 days per week and any leftover food in the cages was discarded.

The animal protocol was approved by the Marshall University school of Medicine Institutional Animal Care and Use Committee.

Diet
Diets were prepared in the animal diet prep room of Marshall University School of Medicine, using an AIN-76-A rodent diet modified to contain 10% total fat (Supplementary Table I is available at Carcinogenesis Online). The AIN-76-A diet is adequate for the supply of nutrition and growth of the mice (15). The control and test diets were isocaloric and isonitritent and are relevant to human consumption. Casein, corn starch and other dry ingredients for the diets (except sugar) were obtained from MP Biomedicals (Solon, Ohio), fish oil concentrate (containing 60% EPA + DHA) (Supplementary Table II is available at Carcinogenesis Online) were obtained from Zone Labs (Danvers, MA), whereas sugar and oil (100% canola oil or 100% corn oil) were obtained locally. Diets were prepared in batches as needed and stored in sealed contain- ers at −20°C to prevent bacterial growth and fat oxidation in the food.

Assessment of transgene expression
Ear punches stored at −20°C were digested as described previously (16) and assessed for the presence of SV40 Tag transgene by real time polymerase chain reaction (PCR) method, using an ABI Prism 7000 instrument (Applied Biosystems, Foster City, CA).

Body weights
To assess the effect of diet on body weight, mice body weights were recorded weekly and terminally during dissection.

Dissection and tissue collection
Mice were euthanized at 24 and 40 weeks of age. A 24-week time point was chosen as adequate time for early-stage disease progression in our heterozygote mice since previous studies indicated that C3(1)Tag male mice develop high-grade prostatic intraepithelial lesion (HPGIN) at 20 weeks (14). PIN is the primary precursor of prostate cancer. The HPGIN in C3(1)Tag male mice pro- gresses to prostate carcinoma by 28 weeks (14). The 40-week time point therefore ensures advanced disease progression and provides for adequate time for inter- vention in our prevention study. After macroscopic evaluation during necropsy, the genitourinary (GU) apparatus [consisting of the anterior prostate, dorsolateral prostate (DL), ventral prostate, seminal vesicle, bladder, proximal ductal defer- ence and proximal urethra] was dissected and weighed to assess the effect of diet on GU weight. The anterior prostate, ventral prostate and DL prostate lobes were dissected from the GU apparatus with the aid of a dissecting microscope and weighed to assess the effect of diet on prostate weight. GU apparatus was fixed in phosphate-buffered 10% paraformaldehyde for 4 h and transferred to 70% ethanol until ready for histopathological analyses. Mouse inguinal fat, liver and prostate were collected and stored at −80°C for other analyses.

Blood collection
Blood (~600 µl) was collected from each animal into ethylenediaminetetra- acetate acid vials by cardiac puncture at necropsy to assess testosterone and estrogen levels. Plasma was separated from blood samples by centrifugation and stored at −80°C until assayed.

Plasma measures
Total testosterone and estrogen were measured from plasma obtained from individual mice from CO-CO and CO-FS groups at 24 and 40 weeks, using the Testosterone EIA Kit or Estradiol EIA Kit respectively (Cayman Chemical Company, Ann Arbor, MI). Measurements were done in triplicate following the protocol provided in the kit.

Histopathological assessment
To assess cancer progression due to diet, GU apparatus previously fixed in paraformaldehyde and thereafter in ethanol were sent to the Rodent Histopa-
Unmasking solution (Vector Laboratories, Burlingame, CA). This was followed by blocking endogenous peroxidase activity using 3% hydrogen peroxide and Avidin/Biotin activity using Vector Avidin/Biotin blocking kit (Vector Laboratories) following the manufacturers protocols. After blocking, sections were treated with rabbit anti-AR (PG21; (Millipore, Temecula, CA) or mouse anti-PCNA (Biogenex, San Ramon, CA) and thereafter with secondary antibodies and vectastain Elite ABC kit (Vector Laboratories) for rabbit antibody or Vector M.O.M kit (Vector Laboratories) for mouse primary antibodies. Sections were incubated with 3, 3'-diaminobenzidine (Vector Laboratories) and counterstained using hematoxylin. The levels of proliferation or AR expression were compared between the two diet groups by counting the number of cells with PCNA or AR positively stained nucleus, respectively, per 1000 cells within viable areas of lesions. Apoptosis was assayed by morphological identification (nuclear and cellular condensation, fragmentation of nuclei and/or membrane blebbing and fragmentation of the cell into apoptotic bodies) of apoptotic cells (18). The numbers of cells undergoing apoptosis based on morphological indicators in 1000 epithelial cells of viable areas of lesions were counted to estimate an apoptotic index.

Statistics
Western blot protein expression levels, apoptosis, AR and PCNA levels, fatty acid composition, mean body weight gain, prostate and GU weight between diet groups and across time, were statistically analyzed by t-test. Testosterone and estradiol levels between diet groups and across time were analyzed by Mann-Whitney test. The differences in prostate lesion incidence between diet groups were assessed by Fisher’s exact test. All statistical tests were performed using Prism software.

Results
Effect of diets on tissue lipid composition
The lipid composition of the prostate, liver and fat at 24 weeks of age were analyzed. Mice at this age consumed either high ω-3 diet or high ω-6 diet. As expected, the lipid composition of tissues reflected the lipid content of the diet (Supplementary Figure 1 is available at Carcinogenesis Online). The prostate, liver and fat of mice that consumed high ω-6 diet contained significantly more (by t-test at P < 0.05) LA than the prostate, liver and fat of mice that consumed high ω-3 diet. AA was significantly more (by t-test at P < 0.05) in the liver and prostate but not in the fat of mice that consumed the high ω-6 diet than mice that consumed high ω-3 diet. The liver, prostate and fat of mice that consumed the high ω-6 diet contained significantly more (by t-test at P < 0.05) ALA, EPA and DHA than the liver, fat and prostate of mice that consumed high ω-6 diet.

Effect of diets on body weight gain
To assess the effect of diet on body weight of mice, we weighed the mice weekly from the time of weaning to time of killing (40 weeks).
Control and test diets were designed to be nutritionally balanced and with the same percentage of energy from fat. There was no significant difference in body weight gain between mice consuming high \( \omega-6 \) control diet (CO–CO group) and mice consuming high \( \omega-3 \) test diet (CO-FS group) (Figure 1A).

**Effect of diets on prostate weight and GU weight**

We assessed the effect of diet on prostate and GU weights as an indicator of progression of prostate tumorigenesis. Two time points, 24 and 40 weeks, were considered for assessment of disease progression. The prostate of mice consuming the high \( \omega-3 \) diet weighed significantly less than prostate of mice consuming the high \( \omega-6 \) diet at 24 and 40 weeks (by \( t \)-test at \( P < 0.05 \)) (Figure 1B). Mice that consumed high \( \omega-3 \) diet had an increase of 10.21 mg in prostate weight between 24 and 40 weeks, whereas mice that consumed high \( \omega-6 \) diet had an increase of 22.49 mg. Diet did not affect the GU weight significantly at 24 weeks (Figure 1C and D). The gross appearance of the GU apparatus (Figure 1C) was similar between the two diet groups at 24 weeks. In contrast, the gross appearance of the GU apparatus of mice that consumed high \( \omega-3 \) diet appeared smaller and the average weight was significantly lower than GU apparatus of mice consuming high \( \omega-6 \) diet at 40 weeks (Figure 1D).

**Figure 2.** Effect of diets on the incidence of PIN and ADC lesions in the DL prostate. (A–D) Representative hematoxylin- and eosin-stained sections from 24 to 40 weeks old mice. A and C illustrate the presence of LGPIN and HGPIN and ADC lesions as demonstrated by epithelial cells proliferation, hyperchromasia, nuclear enlargement and membrane irregularity. (B and D) Consumption of high \( \omega-3 \) diet resulted in marked reduction of epithelial cells proliferation, hyperchromasia, nuclear enlargement and membrane irregularity. (E) Incidence of PIN lesions and ADC in CO–CO and CO-FS groups at 24 and 40 weeks of age. Prostate specimens were histologically examined for lesions by two independent evaluators and scores were averaged (\( n = 11–12 \)/group). Pictures were taken at ×40 magnification (Star indicates LGPIN; arrow indicates HGPIN; arrow head indicates ADC. * \( P < 0.05 \), † \( P < 0.01 \), ‡ represent significant difference in LGPIN, HGPIN and ADC, respectively, between CO–CO and CO-FS group at \( P < 0.05 \).)

**Effect of diets on prostate histopathology**

The histology of the prostate in C3(1) Tag mice of various ages has previously been documented, and it is known that on a usual diet, mice develop HGPIN in the prostate beginning \( \approx 20 \) weeks of age, which subsequently progresses to adenocarcinoma (ADC) with advancing age (14). DLs of C3(1) Tag mice were evaluated in CO–CO and CO-FS groups at 24 and 40 weeks of age. The degree and progression of epithelial hyperplasia and atypia were compared between the two diet groups (Figure 2). There was a slower progression of disease in mice consuming the high \( \omega-3 \) diet than in mice consuming the high \( \omega-6 \) diet at each time point (Figure 2). At 24 weeks, there was a significantly low proportion of LGPIN incidence (45% in CO–CO versus 64% in CO-FS) and significantly high proportion of HGPIN incidence (55% in CO–CO versus 36% in CO-FS) in CO–CO group compared with CO-FS group (by Fischer’s exact test at \( P < 0.05 \)). No ADCs were observed in mice at 24 weeks. There was a significantly lower proportion of LGPIN incidence and higher proportion of ADC incidence in CO–CO group compared with CO-FS group at 40 weeks (by Fischer’s exact test at \( P < 0.05 \)). At 40 weeks, the CO–CO group had 18% LGPIN, 46% HGPIN and 36% ADC, whereas the CO-FS group had 36% LGPIN, 46% HGPIN and 18% ADC.
Effect of diets on plasma estrogen and testosterone levels and expression of AR

Plasma testosterone and estradiol levels were measured by enzyme immunoassays. Testosterone levels were not significantly different due to age or diet (Figure 3A). To further test the effect of diet on testosterone action, AR expression in the DL was analyzed by immunohistochemistry. The expression level of AR in DL was significantly higher in mice consuming the high ω-6 diet than in mice consuming the high ω-3 diet at 40 weeks but not at 24 weeks (Figure 3B). There were significant differences in the levels of estradiol in mice consuming high ω-6 diet compared with mice consuming high ω-3 diet at 24 and 40 weeks of age (Figure 3C). Estradiol level was significantly increased in mice that consumed high ω-3 diet compared with mice that consumed high ω-6 diet at 24 weeks. However, at 40 weeks, estradiol level was significantly less in mice that consumed high ω-3 diet compared with mice that consumed high ω-6 diet (15.89 pg/ml). Consumption of high ω-3 diet resulted in a significant decrease in estradiol level as mice progressed in age, whereas consumption of high ω-6 diet resulted in slight increase in estradiol level as mice progressed in age.

Effect of diets on gene and protein expression in the DL prostate at 24 weeks of age

To investigate the molecular mechanism by which high ω-3 diet may be slowing down the progression of prostate tumorigenesis in the DL prostate, we analyzed the expression of several genes involved in signal transduction pathways. We chose the 24 weeks time point because mice are in the early stages of prostate carcinogenesis, therefore gene expression difference due to the diet and not to the tumor progression is expected to be most prominent at this stage.

<table>
<thead>
<tr>
<th>Gene name</th>
<th>Symbol</th>
<th>Fold difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Early growth response 1</td>
<td>Egr1</td>
<td>2.45</td>
</tr>
<tr>
<td>Engrailed 1</td>
<td>Eri1</td>
<td>3.18</td>
</tr>
<tr>
<td>Fas ligand (TNF superfamily, member 6)</td>
<td>Fasl</td>
<td>2.98</td>
</tr>
<tr>
<td>Fatty acid synthase</td>
<td>Fasn</td>
<td>2.15</td>
</tr>
<tr>
<td>Fibroblast growth factor 4</td>
<td>Fgfr4</td>
<td>4.44</td>
</tr>
<tr>
<td>Forkhead box A2</td>
<td>Foxa2</td>
<td>3.87</td>
</tr>
<tr>
<td>Homeobox A1</td>
<td>Hoxa1</td>
<td>3.31</td>
</tr>
<tr>
<td>Insulin-like growth factor binding protein 3</td>
<td>Igfbp3</td>
<td>2.15</td>
</tr>
<tr>
<td>Interleukin 1 alpha</td>
<td>Il1a</td>
<td>21.61</td>
</tr>
<tr>
<td>Lymphoid enhancer binding factor 1</td>
<td>Lef1</td>
<td>3.1</td>
</tr>
<tr>
<td>Matrix metalloproteinase 10</td>
<td>Mmp10</td>
<td>2.5</td>
</tr>
<tr>
<td>Peroxisome proliferator activated receptor gamma</td>
<td>Ppar</td>
<td>7.6</td>
</tr>
<tr>
<td>Retinol binding protein 1, cellular</td>
<td>Rbp1</td>
<td>2.08</td>
</tr>
<tr>
<td>Transcription factor 7, T-cell specific</td>
<td>Tcf7</td>
<td>2.51</td>
</tr>
<tr>
<td>Telomerase reverse transcriptase</td>
<td>Tert</td>
<td>3.35</td>
</tr>
<tr>
<td>Prostate transmembrane protein, androgen induced 1</td>
<td>Pmea1</td>
<td>3.41</td>
</tr>
<tr>
<td>Vascular cell adhesion molecule 1</td>
<td>Vcam1</td>
<td>2.35</td>
</tr>
<tr>
<td>WNT1 inducible signaling pathway protein 1</td>
<td>Wisp1</td>
<td>9.67</td>
</tr>
<tr>
<td>Wingless-related MMTV integration site 2</td>
<td>Wnt2</td>
<td>2.66</td>
</tr>
</tbody>
</table>

Mice were placed on either corn oil diet or transferred to fish oil diet at 7 weeks of age. Gene expression in the DL prostate of mice at 24 weeks of age was performed by real time reverse transcriptase. Genes with >2-fold differences in mRNA expression are shown. Results are from three replicates for each group.
A total of 84 genes was quantitatively assayed using the Mouse Signal Transduction Pathway Finder™ RT2 profiler™ PCR Array. Table I presents 31 genes with 2-fold differences (using SuperArray statistical analyses software) between CO-FS and CO–CO group at 24 weeks of age. We further analyzed the genes using the Ingenuity Systems software (IPA 8.0), and this showed that a number of the altered genes are associated with NF-κB and apoptosis pathways (data not shown). We chose NF-κB inhibitor alpha (IKα), IκB kinase beta (IKKβ), NF-κBp65 and NOS2 from NF-κB pathway and B-cell leukemia/lymphoma 2 (BCL2) from apoptosis pathway for Western blot analysis. Western blot results showed the expressions of Iκα protein (Figure 4A) to be slightly higher and BCL2 protein (Figure 4B) to be significantly lower due to consumption of high ω-3 fat diet. Expressions of NF-κBp65, IKKβ and NOS2 proteins were significantly lower due to consumption of high ω-3 fat diet (Figure 4A).

**Figure 4.** Effect of diets on proteins in NF-κB and apoptosis pathways in DL prostate. (A) Protein expression of NF-κBp65, IKα, IKKβ and NOS2 in the DL prostate and their corresponding densitometric analyses in 24 weeks old mice. Expression of IKα protein was slightly higher, whereas the expressions of NF-κBp65, IKKβ and NOS2 proteins were significantly lower in DL prostate of mice that consumed high ω-3 fat diet than mice that consumed high ω-6 fat diet. (B) Protein expression of BCL2 in the DL prostate and the densitometric analysis in 24 weeks old mice. Expression of BCL2 protein was lower significantly in the DL prostate of mice that consumed high ω-3 fat diet compared with mice that consumed high ω-6 fat diet. Equal loading of protein in the lanes was confirmed by β-actin. Values are relative density corrected for β-actin. *Significantly different at *P* < 0.05, *n* = 3–5/group. Arrow bars represent SD or SEM where applicable.

**Effect of diets on cell proliferation and apoptosis in the DLs**

We further tested the molecular mechanism by which diet may be influencing the progression of prostate tumorigenesis by comparing the proliferation and apoptosis in the areas of lesions in DL prostate of mice from the two groups. Proliferation was significantly lower (Figure 5E) and apoptosis was significantly higher (Figure 5J) in prostate epithelial cells in mice that consumed high ω-3 fat diet compared with mice that consumed high ω-6 diet.

**Discussion**

One obvious characteristic of the Western diet is the high intake of high ω-6 fat, which has been associated with high prostate cancer risk in epidemiologic studies (19–21). These studies also suggest that
consumption of fish or fish oil, which are very high in ω-3 fatty acids, may reduce prostate cancer risk (10,21). We investigated the role of high ω-3/ω-6 diet in the prevention of prostate cancer risk and the molecular mechanism, which might be involved. The 24 and 40 weeks intervention time points were chosen as adequate time for early-stage disease progression and advanced disease progression since studies indicate that C3(1)Tag male mice on a usual diet develop HGPIN beginning ~20 weeks and progresses to prostate carcinoma from 28 weeks (14,22). We chose the C3(1) Tag model for this study for its well characterized disease progression from normal to PIN to ADC (14).

A switch from high ω-6 diet to a high ω-3 diet at postpuberty was chosen for this study because adults are able to make diet choices. Postpuberty consumption of high ω-3 fat diet significantly slowed down the progression of prostate tumorigenesis in mice as observed...
by the slowed development of high-grade prostate lesions in mice that consumed high ω-3 diet compared with mice that consumed high ω-6 diet. The ability of high ω-3 diet to slow promotion of tumorigenesis in our mouse model was also observed as less GU and prostate weights in mice that consumed high ω-3 diet. At the molecular level, mice that consumed high ω-3 diet showed greater apoptosis and less proliferation in epithelial cells of the prostate as confirmed by less expression of the antiapoptotic gene BCL2 at messenger RNA and protein levels and less staining for PCNA compared with mice that consumed high ω-6 diet. The EPA and DHA in the high ω-3 diet were accumulated in the prostate of mice that consumed high ω-3 diet, which likely induced suppression of disease progression. This is supported by Rose et al. (7), indicating that EPA and DHA suppress proliferation and promote apoptosis in prostate cancer cells.

To identify the underlying molecular factors by which high ω-3 diet may be slowing down the progression of prostate tumorigenesis, we analyzed for the expression of some genes involved in NF-κB pathway because further analysis of the gene array into pathway-focused array (IPA 8.0) showed the NF-κB pathway to be differentially activated. NF-κB is a key mediator of survival, and is upregulated during prostate cancer progression (23,24). NF-κB is complexed with the inhibitor of NF-κB (IK) in the cytosol. When activated, the inhibitor of NF-κB kinase (IKK) phosphorylates the IK protein, resulting in the dissociation of IK from NF-κB. The activated NF-κB is then translocated into the nucleus to regulate the expression of downstream genes. The expression of IK was slightly higher and the expression of IKK was significantly lower in mice that consumed high ω-3 diet as shown in the Western blot results (Figure 4A). The messenger RNA expression fold for IK and IKK was 1.2 and −1.97 (CO-FS versus CO–CO), respectively. The expressions of NF-κBp65 subunit and NO2S, a downstream gene in the NF-κB pathway, were significantly less in mice that consumed high ω-3 fat diet. NO2S is highly expressed in prostate tumors (25).

We also investigated the effect that high ω-3 diet may have on testosterone and estradiol levels in circulation. Testosterone has been vigorously studied because of its role in promoting prostate cancer, but the role of estrogen in prostate disease process has received very little attention despite reports that estrogen may promote prostate tumorigenesis (26–29). Serum testosterone level declines in the aging male, whereas estrogen level increases and remains constant (30,31). However, rising estradiol levels may increase prostate sensitivity to testosterone via upregulation of AR (32,33). We showed that consumption of high ω-3 diet resulted in significantly lower estradiol level at 40 weeks and slightly lower testosterone level with a concomitant significant decrease in the expression level of AR at 40 weeks, suggesting a decrease in androgen stimulation due to consumption of high ω-3 diet.

We conclude that high ω-3 diet slowed prostate tumorigenesis in C3(1)Tag mouse model, and the mechanisms involved are due to lower levels of testosterone and estradiol resulting in lower expression of AR and less expressions of genes in the NF-κB and the antiapoptotic BCL2 pathways. These molecular changes suppressed proliferation and promote apoptosis in the epithelial cells in areas of lesions in mouse dorsolateral prostate. By extrapolation of our findings to humans, a dietary change by humans that involves consumption of more ω-3 fat such as obtained from fish and fish oil, instead of corn oil with little or no ω-3 fat, may be helpful in the suppression and prevention of prostate cancer risk, especially for those who are at the high risk of developing the disease.

Supplementary material
Supplementary Tables I and II and Figure 1 can be found at http://carcin.oxfordjournals.org.

Funding
This work was supported by Grant Number R01CA114018 (to W.E.H.) and a training supplement to that grant. The content is solely the responsibility of the authors and does not necessarily represent the official views of the National Cancer Institute or the National Institutes of Health. COBRE (5P20RR020180); and WV-INBRE (5P20RR016477) grants provided support for the Genomic cores.

Acknowledgements
The authors gratefully acknowledge Dr. Jeffrey E. Green for providing the C3(1) Tag mouse breeding pairs. We thank Dana-Farber/Harvard Cancer Center in Boston, MA, for the use of the Rodent Histopathology Core, which provided tissue processing and pathological diagnosis services. Dana-Farber/Harvard Cancer Center is supported in part by an NCI Cancer Center Support Grant # NIH 5 P30 CA06516.

Conflict of Interest Statement: None declared.

References


*Received May 26, 2011; revised August 11, 2011; accepted October 13, 2011*