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Short communication

Blood omega-3 fatty acids and death from COVID-19: A pilot study

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ABSTRACT

Very-long chain omega-3 fatty acids (EPA and DHA) have anti-inflammatory properties that may help reduce morbidity and mortality from COVID-19 infection. We conducted a pilot study in 100 patients to test the hypothesis that RBC EPA+DHA levels (the Omega-3 Index, O3I) would be inversely associated with risk for death by analyzing the O3I in banked blood samples drawn at hospital admission. Fourteen patients died, one of 25 in quartile 4 (Q4) (O3I $\geq 5.7\%$) and 13 of 75 in Q1–3. After adjusting for age and sex, the odds ratio for death in patients with an O3I in Q4 vs Q1–3 was 0.25, $p = 0.07$. Although not meeting the classical criteria for statistical significance, this strong trend suggests that a relationship may indeed exist, but more well-powered studies are clearly needed.

1. Introduction

COVID-19, the illness caused by the severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), has been diagnosed in over 80 million people worldwide as of the end of 2020, and over 1.8 million have died [1]. Although 81% of symptomatic individuals have relatively mild disease, 14% will develop severe disease characterized by dyspnea, hypoxia, or >50 percent lung involvement by imaging, with the remaining 5% developing critical disease characterized by respiratory failure, shock, and/or multiorgan dysfunction [2]. Severe and critical disease from COVID-19 is associated with advancing age (especially over 65 years), male gender, chronic lung disease, obesity, cardiovascular disease including hypertension, diabetes, and other chronic medical conditions.

Severe COVID-19 disease and death is, in part, mediated by rapid elevations of inflammatory cytokines including TNF-alpha, IL-1 β , and IL-6 leading to a cytokine release syndrome or “cytokine storm.” [3] Accordingly, an attractive preventative approach to COVID-19 infection is to minimize cytokine release. Very long-chain omega-3 s (DHA and EPA) found in fish oils have a plethora of biological activities including directly and indirectly modulating inflammatory responses and cytokine

release [4–6]. In non-COVID-19 settings, higher intakes [7,8] and blood levels [9,10] of these omega-3 s are associated with lower levels of circulating inflammatory cytokines, and intervention with fish oils reduces levels [11,12]. EPA and DHA are precursors to a suite of inflammation-resolving mediators (IRMs; resolvins, maresins and protectins [13]) that actively regulate the resolution of acute inflammation. IRMs down-regulate cytokine production and promote a return to homeostasis via monocyte/macrophage-mediated uptake of debris, apoptosis of neutrophils, and clearing of microbes. Accordingly, higher intakes of EPA and DHA (which result in higher RBC EPA+DHA levels, hereafter called the Omega-3 Index, O3I [14,15]) have been proposed to lower the risk for adverse outcomes from COVID-19 [16–22], and case reports suggesting benefit have been published [23,24].

Given the profound public health concerns related to the current COVID-19 pandemic, modifiable risk factors for developing severe and critical complications are urgently needed, especially ones that may be easily implemented and nutritionally based. Despite the known mechanisms by which IRMs and omega-3 fatty acids support the active, endogenous resolution of inflammatory mechanisms, to our knowledge no study has explored the relationship between omega-3 tissue levels and COVID-19 outcomes. The primary objective of this pilot study was

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to define the relationship between O3I and death from COVID-19. We hypothesize that a higher O3I is associated with lower risk for death in these patients.

2. Methods

2.1. Subjects

We studied 100 patients hospitalized at Cedars-Sinai Medical Center from March 1, 2020 onwards with confirmed COVID-19 infection who met the criteria for inclusion, which were the availability of basic demographic data, clinical outcomes and an EDTA blood sample (drawn within 10 days of diagnosis) stored at -80°C at the Cedars-Sinai biorepository. If more than one sample was available, the first sample drawn after the time of diagnosis was utilized. We utilized sample remnant protocol Pro00036514 to obtain blood samples for this study.

Briefly, a protocol was submitted to the Enterprise Information Service (EIS) team and staff members of the Biobank. After review and approval, the EIS/Biobank team pulled the samples and the data, de-identifying each sample by assigning a study-specific number. Using this protocol, we obtained a limited data and blood sample set to conduct this pilot investigation. The study was approved by the IRB of Cedars-Sinai Medical Center (STUDY-00,000,779).

2.2. Clinical outcomes

The primary outcome was death from COVID-19 infection.

2.3. Laboratory

Blood samples were thawed at the biorepository and one drop was placed on a dried blood spot collection card pre-treated with antioxidants to protect the fatty acids from degradation. The cards were then shipped overnight in batch to OmegaQuant Analytics (Sioux Falls, SD) for analysis of fatty acids and calculation of the Omega-3 Index [25]. Briefly, blood spots were transferred to a reaction vial and FA methyl esters (FAMES) were generated using boron trifluoride in methanol by heating for 45 min at 100°C . FAMES were extracted into hexane (after the addition of water) and analyzed using a GC2010 Gas Chromatograph (Shimadzu Corporation, Columbia, MD) equipped with a SP2560, 100-m column (Supelco, Bellefonte, PA). FAMES were identified by comparison with a standard mixture (GLC, Nucheck Prep, Elysian, MN). Analysis was conducted using an internal-standard-based, three-point calibration curve to quantify levels of 24 FAMES which were each expressed as a percent of total FAs. The O3I was calculated from the dried blood spot EPA+DHA value as described previously [25]. The analytical coefficient of variation for the O3I is $<5\%$.

2.4. Statistical methods

The study sample is described using standard descriptive statistics (means and standard deviations, medians and ranges, and counts and percentages). Additional descriptive summary of the sample is provided by stratifying using quartiles of the O3I or by comparing Q4 to Q1–3. The distribution of age, sex and do not resuscitate (DNR) status by O3I quartiles or top 25%/bottom 75% was tested using an F-test (age) or Chi-squared test (sex, DNR status). The primary analysis examined the hypothesis that O3I is associated with risk for death. We first predicted death using unadjusted logistic regression models by quartiles of the O3I using a Chi-squared test to evaluate overall (4-group) association. We also predicted death by age, sex and DNR status to evaluate and confirm known associations between risk for death and these factors. Subsequently, significant association between O3I quartiles and death was tested using logistic regression and by comparing Q4 with Q1–3 in both unadjusted models and models adjusted for age and sex. To account for the small sample sizes present in this study, primary model results use

Firth's adjustment for small sample sizes in logistic regression using the `logistf` package in R [26]. We also report conventional logistic regression F-test results for comparison. A 2-tailed p-value of 0.05 was used for statistical significance.

3. Results

3.1. Sample description

The study sample is described in Table 1. They were predominantly men, the mean age was over 70, and they were admitted between April and July 2020. Nearly 40% were under a DNR order instituted at some point during the hospitalization, and 14% died during hospitalization. The average O3I was 5.09%, and the median was 4.75%.

Table 2 illustrates the association of the O3I by age, sex and do not resuscitate (DNR) status. Higher O3I values were significantly related to older age, with the highest mean age in the third quartile (79.8 years). Men and those who were not DNR tended to have higher O3I values, but these trends were not statistically significant.

3.2. Unadjusted analyses

Relationships between omega-3 status and fatal outcomes are shown in Table 3. As expected, older patients and those under a DNR order were more likely to die. In O3I Q4, there was one death (a 66-year-old male under a DNR order), whereas there were 13 deaths among the 75 patients in Q1–3. In the unadjusted model (and focusing on the small-sample size p-values), there was a significant difference in risk for death across quartiles of the O3I ($p = 0.047$), with those in the highest O3I quartile (Q4) having an odds ratio (OR) of 0.39 ($p = 0.34$) relative to Q1. In an unadjusted comparison between Q4 and Q1–3, the OR for death in Q4 was 0.28 ($p = 0.11$) or 3.6-fold higher (1/0.28) higher risk in Q1–3 vs. Q4. For comparison, the risk for death from COVID-19 associated with being 1-decade older was about 1.3-fold higher ($p = 0.14$). Hence, a low O3I appeared to be at least as predictive of risk for death as being 10-years older. The higher OR for death in Q3 was largely accounted for by age as the mean age in Q3 was the highest of all. The OR in Q3 was markedly attenuated in the adjusted analysis (Table 4).

3.3. Adjusted analyses

In models adjusted for age and sex (Table 4), the overall relationship across quartiles became somewhat weaker (i.e., from $p = 0.047$ to 0.078), although the OR at Q4 (vs Q1) decreased slightly (0.39 to 0.30; p-value also decreased somewhat from 0.34 to 0.22). Comparing Q4 to Q1–3, the OR decreased slightly (from 0.28 to 0.25), and the p-value also decreased from 0.11 to 0.07. An OR of 0.25 implies that risk for death in COVID-19 patients with an O3I $>5.7\%$ was $\sim 75\%$ less than it was for patients with an O3I $<5.7\%$.

Table 1
Descriptive statistics.

Characteristics of sample	% (X/N) or Mean (SD; min,max)
Sex – Male	59% (59/100)
Age	72.5 (16.5; 25,100)
Month of data collection	April – 47% (47/100)
	May – 25% (25/100)
	June – 15% (15/100)
	July – 13% (13/100)
Red blood cell EPA+DHA (% of RBC fatty acids; the Omega-3 Index, O3I)	5.09% (1.62%; 2.87%, 13.79%)
Died	14% (14/100)
DNR orders	38% (38/100)

Table 2
Demographic profile of participants by category of the O3I.

Categorical by O3I Quartile	Age Mean (SD)	Sex - Male% (x/n)	DNR% (x/n)
Q1 (O3I<4.0%)	63.0 (18.9)	64% (16/25)	44% (11/25)
Q2 (4.0%<O3I<4.7%)	71.0 (16.1)	56% (14/25)	28% (7/25)
Q3 (4.7<O3I<5.7%)	79.8 (13.3)	52% (13/25)	52% (13/25)
Q4 (O3I≥5.7%)	76.3 (12.7)	64% (16/25)	28% (7/25)
P-value ^a	<i>0.0014</i>	0.77	0.20
Comparing O3I Q4 vs Q1–3			
Q1–3: O3I<5.7%	71.3 (17.5)	57.3% (43/75)	41.3% (31/75)
Q4: O3I≥5.7%	76.3 (12.7)	64% (16/25)	28% (7/25)
P-value ^a	0.19	0.56	0.23

^a F-test (age and O3I) or Chi-square test (sex, DNR and O3I).

Table 3
Unadjusted associations of the Omega-3 Index and demographic variables with death.

Risk factor	Death% (x/N)	Unadjusted Models OR (95% CI) ^a	Firth's test P-value ^a	F-test P-value ^b
Female	14.6% (6/41)	1.00		
Male	13.6% (8/59)	0.90 (0.30, 2.83)	0.85	0.88
Age				
Per decade	–	1.33 (0.92, 2.08)	0.14	0.13
DNR				
Yes	34.2% (13/38)	21.76 (4.90, 206.44)	<0.0001	0.001
No	1.6% (1/62)			
Categorical by O3I Quartile		Overall model F-test	0.047	0.03
Q1 (O3I<4.0%)	12.0% (3/25)	1.00		
Q2 (4.0%<O3I<4.7%)	8.0% (2/25)	0.68 (0.11, 3.86)	0.66	0.64
Q3 (4.7<O3I<5.7%)	32.0% (8/25)	3.13 (0.82, 14.30)	0.10	0.10
Q4 (O3I≥5.7%)	4.0% (1/25)	0.39 (0.04, 2.61)	0.34	0.32
Comparing O3I Q4 vs Q1–3				
Q1–3: O3I<5.7%	17.3% (13/75)	1.00		
Q4: O3I≥5.7%	4.0% (1/25)	0.28 (0.03, 1.26)	0.11	0.13

Bold and italics is used for p-values less than the significance level of 0.05.

^a Using the Firth's modified score procedure for small sample sizes.

^b Standard F-test from Logistic Regression ignoring small sample sizes.

4. Discussion

The 2020 COVID-19 pandemic has had devastating effects on morbidity and mortality worldwide. While vaccines may soon slow the spread and drugs may help diminish the adverse effects of infection, preventative measures – ideally ones that are cheap, safe, and readily accessed by large numbers of people – that modulate the most severe disease outcomes are desperately needed. Some evidence is accumulating for a potential benefit of vitamin D [27], and here we examined another nutrient, omega-3 fatty acids, which like vitamin D, have multiple anti-inflammatory effects and may also reduce risk for adverse COVID-19 outcomes.

In this pilot study we compared the associations between the O3I and risk for death from COVID-19 in 100 patients. We found (in age and sex-adjusted models) that those patients with an O3I at 5.7% or greater were at about 75% lower risk for death compared with those below that value

Table 4
Associations of the omega-3 index with death adjusted for age and sex.

Risk factor	Adjusted Models OR (95% CI) ^a	Firth's test P-value ^a	F-test P-value ^b
Categorical by O3I Quartile	Overall model F-test	0.078	0.0499
Q1 (O3I<4.0%)	1.00		
Q2 (4.0%<O3I<4.7%)	0.58 (0.09, 3.35)	0.54	0.52
Q3 (4.7<O3I<5.7%)	2.18 (0.52, 10.80)	0.29	0.28
Q4 (O3I≥5.7%)	0.30 (0.03, 2.08)	0.22	0.22
Comparing O3I Q4 vs Q1–3			
Q1–3: O3I<5.7%	1.00		
Q4: O3I≥5.7%	0.25 (0.03, 1.11)	0.071	0.099

Bold and italics is used for p-values less than the significance level of 0.05.

^a Using the Firth's modified score procedure for small sample sizes.

^b Standard F-test from Logistic Regression ignoring small sample sizes.

($p = 0.071$). Although not meeting the criteria for classical statistical significance, this strong trend suggests that a relationship may indeed exist, but more well-powered studies are clearly needed.

The OR for death was higher in Q3 than in the other quartiles including Q4. Part of the reason for this was the mean age (and the percent of patients with DNR orders) was the highest in Q3. Accordingly, in the age-adjusted model the OR in Q3 dropped by a third. The comparison of Q4 to Q1–3 has historical precedents. For example, in the Framingham Heart Study, significantly larger brain volumes and better cognitive function were observed in Q4 vs Q1–3 [28], and 10-year risk for dementia was 47% lower in subjects with omega-3 levels in Q4 vs Q1–Q3 [29]. More generally, higher omega-3 FA blood levels have been associated with the better clinical outcomes for cardiovascular disease [30,31], post-MI cardiac remodeling [32], telomere attrition [33], attempted suicide [34] and total mortality [35]. These data suggest that in some settings there may be threshold effects of the O3I.

This study used the O3I as a biomarker of omega-3 FA status. This RBC-based metric has advantages, particularly in the acute hospitalization setting. This is because, much like a hemoglobin A1C versus plasma glucose, the O3I is a better long-term reflection of tissue omega-3 levels versus plasma omega-3 levels [36], and it would thus be less affected by an acute change in omega-3 intake, as might happen with hospitalization for an acute illness [37]. The O3I has been validated [25] and used in several interventional [14] and prospective cohort studies such as the Framingham Heart Study [31] and the Women's Health Initiative Memory Study [38]. The O3I is also easily modified by increasing the intake of oily fish (e.g., salmon, herring, mackerel, albacore tuna, etc.) which are rich in EPA and DHA, and dietary supplements of omega-3 will also raise levels [15]. The average O3I in this study was 5.1% which is similar to that seen other US-based studies [39, 40]. We also examined the associations between risk for death and EPA and DHA individually and with the omega-6:omega-3 ratio. We found the same directional relationships as with the O3I but they were not as statistically strong (data not shown).

Multiple randomized clinical trials (RCTs) are currently (as of January 2021) underway testing the hypothesis that treatment with omega-3 fatty acids (EPA and DHA) will have beneficial effects on a variety of aspects of COVID-19 infection. Although their outcomes are not yet known, there are compelling scientific reasons to expect that these studies will be positive (and these same reasons formed the foundation for the present study). The data supporting a possible beneficial role for omega-3 fatty acids in COVID-19 infection come from past epidemiological, interventional, therapeutic, and basic science studies. For example, in the Framingham Offspring study [41], the O3I was inversely associated with 10 separate inflammatory biomarkers (e.g., CRP, IL-6, ICAM-1, LpPLA2, TNF receptor 2, and osteoprotegerin). In intervention studies [11], EPA supplementation alone (3 g/d for 10

weeks) significantly reduced the expression of TNF α from LPS-stimulated monocytes as did a similar dose of DHA which, in addition, lowered IL-6 and MCP-1. EPA+DHA supplements had similar effects [42]. Meta-analyses of multiple RCTs confirmed that treatment with omega-3 fatty acids routinely lowers cytokine levels [43–45]. More important than studies of effects on intermediate markers are clinical findings from RCTs. Langlois et al. [5] summarized the results of 12 RCTs of omega-3 treatment in 1280 intensive-care-unit patients with acute respiratory distress syndrome. There was a significant improvement in measures of blood oxygenation in the treated patients and strong trends ($p \leq 0.08$) for reduced ICU length of stay and duration of mechanical ventilation. Overall mortality, hospital length of stay and infectious complications were unaffected.

As noted earlier, the potential mechanisms underlying these actions are multiple. EPA/DHA are substrates for the production of IRMs which cannot be made if the parent compounds are not present. Examples of some of the functions of IRMs were summarized by Calder as, “Resolvin E1, resolvin D1 and protectin D1 all inhibit trans-endothelial migration of neutrophils, so preventing the infiltration of neutrophils into sites of inflammation; resolvin D1 inhibits IL-1 β production and protectin D1 inhibits TNF- α and IL-1 β production.” [46] Higher EPA/DHA levels reduce arachidonic acid (the omega-6 cousin of EPA) membrane levels [47] for the production of some pro-inflammatory oxylipins (certain prostaglandins and leukotrienes). Quite independently of the synthesis of these mediators, the presence of EPA/DHA in inflammatory cells blocks the activation of the key pro-inflammatory transcription factor, nuclear factor kappa B thus retarding the entire intracellular inflammatory cascade [48,49]. This effect is downstream from the action of these fatty acids on membrane G-protein coupled receptors GPR40 and GPR120 and nuclear peroxisome proliferator-activated receptors (reviewed in [50]). Finally, EPA/DHA insert into cell membrane phospholipids and disrupts lipid rafts so as to disassemble surface receptors thereby blocking incoming inflammatory signals [51]. All of these actions together result in a muted “cytokine storm” which, in alveolar macrophages and elsewhere, can result in death from COVID-19 [3].

4.1. Limitations

Given the pilot nature of this exploratory study, a number of limitations are acknowledged. Firstly, the sample size was small and further studies are needed to replicate this finding and to explore potential risk thresholds of the O3I. Secondly, the limited resources and resulting access to the full electronic medical record for more detailed chart review significantly reduced the amount of potentially relevant information on comorbidities and other demographic data besides age and sex (e.g., BMI). Although data on maximal interventions applied during hospitalization were available, the reasons why any given patient was administered a given treatment are not known and could obviously have been influenced by external factors (e.g., ventilator availability) or internal factors (e.g., a DNR order). Accordingly, such information was deemed to be of little utility in this pilot study. The population of patients in this study had an O3I that was typical of the US[39], which unfortunately means that levels were generally low. Future studies should endeavor to include patients with a wider range of O3I to examine these relationships more clearly.

4.2. Conclusions

Given the profound public health concerns related to the current COVID-19 pandemic, modifiable risk factors for developing severe and critical complications are urgently needed. Despite the known mechanisms by which IRMs and omega-3 fatty acids support the active, endogenous resolution of inflammatory mechanisms, to our knowledge this is the first study that has explored the relationship between omega 3 tissue levels and the most severe COVID-19 outcome, death. Larger studies are urgently needed to confirm these findings. If an association is

confirmed with a larger sample size, then this would lay the groundwork for testing the effects of increased oily fish intake and/or an inexpensive, safe, and widely available dietary supplement (DHA/EPA capsules) to optimize outcomes during this public health crisis.

Author disclosure statements

WSH holds an interest in OmegaQuant Analytics, LLC; and is a member of the Schiff Science and Innovation Advisory Board. The other authors have no conflicts of interest to disclose.

Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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CRediT authorship contribution statement

Arash Asher: Conceptualization, Investigation, Methodology, Project administration, Supervision, Writing - original draft. **Nathan L. Tintle:** Formal analysis, Writing - review & editing. **Michael Myers:** Conceptualization, Resources, Methodology, Writing - review & editing. **Laura Lockshon:** Project administration, Writing - review & editing. **Heribert Bacarezza:** Project administration, Writing - review & editing. **William S. Harris:** Conceptualization, Methodology, Resources, Writing - original draft.

References

- [1] World Health Organization Coronavirus Disease (COVID-19) Dashboard. <https://covid19.who.int/>. Last accessed 01/20/2021.
- [2] Z. Wu, J.M. McGoogan, Characteristics of and important lessons from the coronavirus disease 2019 (COVID-19) outbreak in China: summary of a report of 72 314 cases from the Chinese Center for Disease Control and Prevention, *JAMA* 323 (2020) 1239–1242.
- [3] D.C. Fajgenbaum, C.H. June, Cytokine storm, *NEJM* 383 (2020) 2255–2273.
- [4] P.C. Calder, Marine omega-3 fatty acids and inflammatory processes: effects, mechanisms and clinical relevance, *Biochim. Biophys. Acta* 1851 (2015) 469–484.
- [5] P.L. Langlois, F. D’Aragon, G. Hardy, W. Manzanarez, Omega-3 polyunsaturated fatty acids in critically ill patients with acute respiratory distress syndrome: a systematic review and meta-analysis, *Nutrition* 61 (2019) 84–92.
- [6] M.O. Husson, D. Ley, C. Portal, M. Gottrand, T. Hueso, J.L. Dessey, F. Gottrand, Modulation of host defence against bacterial and viral infections by omega-3 polyunsaturated fatty acids, *J Infect* 73 (2016) 523–535.
- [7] E. Lopez-Garcia, M.B. Schulze, J.E. Manson, J.B. Meigs, C.M. Albert, N. Rifai, W. C. Willett, F.B. Hu, Consumption of (n-3) fatty acids is related to plasma biomarkers of inflammation and endothelial activation in women, *J. Nutr.* 134 (2004) 1806–1811.
- [8] K. Niu, A. Hozawa, S. Kuriyama, K. Ohmori-Matsuda, T. Shimazu, N. Nakaya, K. Fujita, I. Tsuji, R. Nagatomi, Dietary long-chain n-3 fatty acids of marine origin and serum C-reactive protein concentrations are associated in a population with a diet rich in marine products, *Am. J. Clin. Nutr.* 84 (2006) 223–229.
- [9] R. Farzaneh-Far, W.S. Harris, S. Garg, B. Na, M.A. Whooley, Inverse association of erythrocyte n-3 fatty acid levels with inflammatory biomarkers in patients with stable coronary artery disease: The Heart and Soul Study, *Atherosclerosis* 205 (2009) 538–543.
- [10] S.M. Grenon, M.S. Conte, E. Nosova, H. Alley, K. Chong, W.S. Harris, E. Vittinghoff, C.D. Owens, Association between n-3 polyunsaturated fatty acid content of red blood cells and inflammatory biomarkers in patients with peripheral artery disease, *J. Vascular Surgery* 58 (2013) 1283–1290.
- [11] J. So, D. Wu, A.H. Lichtenstein, A.K. Tai, N.R. Matthan, K.R. Maddipati, S. Lamont-Fava, EPA and DHA differentially modulate monocyte inflammatory response in subjects with chronic inflammation in part via plasma specialized pro-resolving lipid mediators: a randomized, double-blind, crossover study, *Atherosclerosis* (2020), 316:90-98.
- [12] J. Allaire, P. Couture, M. Leclerc, A. Charest, J. Marin, M.C. Lepine, D. Talbot, A. Tchernof, B. Lamarche, A randomized, crossover, head-to-head comparison of eicosapentaenoic acid and docosahexaenoic acid supplementation to reduce

- inflammation markers in men and women: the Comparing EPA to DHA (ComparED) Study, *Am. J. Clin. Nutr.* 104 (2016) 280–287.
- [13] C.N. Serhan, B.D. Levy, Resolvins in inflammation: emergence of the pro-resolving superfamily of mediators, *J. Clin. Invest.* 128 (2018) 2657–2669.
- [14] R.E. Walker, K.H. Jackson, N.L. Tintle, G.C. Shearer, A. Bernasconi, S. Masson, R. Latini, B. Heydari, R.Y. Kwong, M. Flock, P.M. Kris-Etherton, A. Hedengran, R. M. Carney, A. Skulas-Ray, S.S. Gidding, A. Dewell, C.D. Gardner, S.M. Grenon, B. Sarter, J.W. Newman, T.L. Pedersen, M.K. Larson, W.S. Harris, Predicting the effects of supplemental EPA and DHA on the omega-3 index, *Am. J. Clin. Nutr.* 110 (2019) 1034–1040.
- [15] K.H. Jackson, J.M. Polreis, N.L. Tintle, P.M. Kris-Etherton, W.S. Harris, Association of reported fish intake and supplementation status with the omega-3 index, *Prostaglandins Leukot. Essent. Fatty Acids* 142 (2019) 4–10.
- [16] D. Panigrahy, M.M. Gilligan, S. Huang, A. Gartung, I. Cortés-Puch, P.J. Sime, R. P. Phipps, C.N. Serhan, B.D. Hammock, Inflammation resolution: a dual-pronged approach to averting cytokine storms in COVID-19? *Cancer Metastasis Rev.* 39 (2020) 337–340.
- [17] K.S.D. Kothapalli, H.G. Park, J.T. Brenna, Polyunsaturated fatty acid biosynthesis pathway and genetics. implications for interindividual variability in prothrombotic, inflammatory conditions such as COVID-19, *Prostaglandins Leukot. Essent. Fatty Acids* 162 (2020), 102183.
- [18] D. Hathaway, K. Pandav, M. Patel, A. Riva-Moscato, B.M. Singh, A. Patel, Z.C. Min, S. Singh-Makkar, M.K. Sana, R. Sanchez-Dopazo, R. Desir, M.M.M. Fahem, S. Manella, I. Rodriguez, A. Alvarez, R. Abreu, Omega 3 Fatty Acids and COVID-19: a comprehensive review, *Infect. Chemother.* 52 (2020) 478–495.
- [19] P. Weill, C. Plissonneau, P. Legrand, V. Rioux, R. Thibault, May omega-3 fatty acid dietary supplementation help reduce severe complications in Covid-19 patients? *Biochimie* 179 (2020) 275–280.
- [20] J.P. Chang, C.M. Pariante, K.P. Su, Omega-3 fatty acids in the psychological and physiological resilience against COVID-19, *Prostaglandins Leukot. Essent. Fatty Acids* 161 (2020), 102177.
- [21] P.A. Regidor, F.G. Santos, J.M. Rizo, F.M. Egea, Pro resolving inflammatory effects of the lipid mediators of omega 3 fatty acids and its implication in SARS COVID-19, *Med. Hypotheses* 145 (2020), 110340.
- [22] M.M. Rogero, M.C. Leão, T.M. Santana, M. Pimentel, G.C.G. Carlini, T.F.F. da Silveira, R.C. Gonçalves, I.A. Castro, Potential benefits and risks of omega-3 fatty acids supplementation to patients with COVID-19, *Free Radic. Biol. Med.* 156 (2020) 190–199.
- [23] A.A. Berger, R. Sherburne, I. Urits, H. Patel, J. Eskander, Icosapent ethyl - a successful treatment for symptomatic COVID-19 infection, *Cureus* 12 (2020) e10211.
- [24] W. Suh, I. Urits, O. Viswanath, A.D. Kaye, H. Patel, W. Hall, J.P. Eskander, Three cases of COVID-19 pneumonia that responded to icosapent ethyl supportive treatment, *Am. J. Case. Rep.* 21 (2020), e928422.
- [25] W.S. Harris, J. Polreis, Measurement of the Omega-3 Index in Dried Blood Spots, *Ann Clin Lab Res* 4 (2016) 137–144.
- [26] R-Project, version 3. www.r-project.org.
- [27] N. Liu, J. Sun, X. Wang, T. Zhang, M. Zhao, H. Li, Low vitamin D status is associated with coronavirus disease 2019 outcomes: a systematic review and meta-analysis, *Int. J. Infect. Dis.* (2021), 104:58-64.
- [28] Z.S. Tan, W.S. Harris, A.S. Beiser, R. Au, J.J. Himali, S. Debette, A. Pikula, C. Decarli, P.A. Wolf, R.S. Vasan, S.J. Robins, S. Seshadri, Red blood cell omega-3 fatty acid levels and markers of accelerated brain aging, *Neurology* 78 (2012) 658–664.
- [29] E.J. Schaefer, V. Bongard, A.S. Beiser, S. Lamón-Fava, S.J. Robins, R. Au, K. L. Tucker, D.J. Kyle, P.W. Wilson, P.A. Wolf, Plasma phosphatidylcholine docosahexaenoic acid content and risk of dementia and Alzheimer disease: the Framingham Heart Study, *Arch.Neurol.* 63 (2006) 1545–1550.
- [30] L.C. Del Gobbo, F. Imamura, S. Aslibekyan, M. Marklund, J.K. Virtanen, M. Wennberg, M.Y. Yakoob, S.E. Chiuve, L. Dela Cruz, A.C. Frazier-Wood, A. M. Fretts, E. Guallar, C. Matsumoto, K. Prem, T. Tanaka, J.H. Wu, X. Zhou, C. Helmer, E. Ingelsson, J.M. Yuan, P. Barberger-Gateau, H. Campos, P.H. Chaves, L. Djousse, G.G. Giles, J. Gomez-Aracena, A.M. Hodge, F.B. Hu, J.H. Jansson, I. Johansson, K.T. Khaw, W.P. Koh, R.N. Lemaitre, L. Lind, R.N. Luben, E.B. Rimm, U. Riserus, C. Samieri, P.W. Franks, D.S. Siscovick, M. Stampfer, L.M. Steffen, B. T. Steffen, M.Y. Tsai, R.M. van Dam, S. Voutilainen, W.C. Willett, M. Woodward, D. Mozaffarian, Omega-3 polyunsaturated fatty acid biomarkers and coronary heart disease: pooling project of 19 cohort studies, *JAMA Intern. Med.* 176 (2016) 1155–1166.
- [31] W.S. Harris, N.L. Tintle, M.R. Etherton, R.S. Vasan, Erythrocyte long-chain omega-3 fatty acid levels are inversely associated with mortality and with incident cardiovascular disease: the Framingham Heart Study, *J. Clin. Lipidol.* 12 (2018) 718–724.
- [32] B. Heydari, S. Abdullah, J.V. Pottala, R. Shah, S. Abbasi, D. Mandry, S.A. Francis, H. Lumish, B.B. Ghoshhajra, U. Hoffmann, E. Appelbaum, J.H. Feng, R. Blankstein, M. Steigner, J.P. McConnell, W. Harris, E.M. Antman, M. Jerosch-Herold, R. Y. Kwong, Effect of omega-3 acid ethyl esters on left ventricular remodeling after acute myocardial infarction: perspective: the OMEGA-REMODEL randomized clinical trial, *Circulation* 134 (2016) 378–391.
- [33] R. Farzaneh-Far, J. Lin, E.S. Epel, W.S. Harris, E.H. Blackburn, M.A. Whooley, Association of marine omega-3 fatty acid levels with telomeric aging in patients with coronary heart disease, *JAMA* 303 (2010) 250–257.
- [34] M. Huan, K. Hamazaki, Y. Sun, M. Itomura, H. Liu, W. Kang, S. Watanabe, K. Terasawa, T. Hamazaki, Suicide attempt and n-3 fatty acid levels in red blood cells: a case control study in China, *Biol. Psychiatry* 56 (2004) 490–496.
- [35] M.E. Kleber, G.E. Delgado, S. Lorkowski, W. Marz, C. von Schacky, Omega-3 fatty acids and mortality in patients referred for coronary angiography. The Ludwigshafen risk and cardiovascular health study, *Atherosclerosis* 252 (2016) 175–181.
- [36] W.S. Harris, R.M. Thomas, Biological variability of blood omega-3 biomarkers, *Clin. Biochem.* 43 (2010) 338–340.
- [37] W.S. Harris, S.A. Varvel, J.V. Pottala, G.R. Warnick, J.P. McConnell, Comparative effects of an acute dose of fish oil on omega-3 fatty acid levels in red blood cells versus plasma: implications for clinical utility, *J Clin Lipidol* 7 (2013) 433–440.
- [38] W.S. Harris, J. Luo, J.V. Pottala, M.A. Espeland, K.L. Margolis, J.E. Manson, L. Wang, T.M. Brasky, J.G. Robinson, Red blood cell polyunsaturated fatty acids and mortality in the Women's Health Initiative Memory Study, *J Clin Lipidol* 11 (2017) 250–259.
- [39] W.S. Harris, J.V. Pottala, S.A. Varvel, J.J. Borowski, J.N. Ward, J.P. McConnell, Erythrocyte omega-3 fatty acids increase and linoleic acid decreases with age: observations from 160,000 patients, *Prostaglandins Leukot. Essent. Fatty Acids* 88 (2013) 257–263.
- [40] J.V. Pottala, M.A. Espeland, J. Polreis, J. Robinson, W.S. Harris, Correcting the effects of -20 °C storage and aliquot size on erythrocyte fatty acid content in the women's health initiative, *Lipids* 47 (2012) 835–846.
- [41] J.D. Fontes, F. Rahman, S. Lacey, M.G. Larson, R.S. Vasan, E.J. Benjamin, W. S. Harris, S.J. Robins, Red blood cell fatty acids and biomarkers of inflammation: a cross-sectional study in a community-based cohort, *Atherosclerosis* 240 (2015) 431–436.
- [42] A. Tan, B. Sullenbarger, R. Prakash, J.C. McDaniel, Supplementation with eicosapentaenoic acid and docosahexaenoic acid reduces high levels of circulating proinflammatory cytokines in aging adults: a randomized, controlled study, *Prostaglandins Leukot. Essent. Fatty Acids* 132 (2018) 23–29.
- [43] S. AbuMweis, S. Jew, R. Tayyem, L. Agraib, Eicosapentaenoic acid and docosahexaenoic acid containing supplements modulate risk factors for cardiovascular disease: a meta-analysis of randomised placebo-control human clinical trials, *J. Hum. Nutr. Diet.* 31 (2018) 67–84.
- [44] L.L. O'Mahoney, J. Matu, O.J. Price, K.M. Birch, R.A. Ajjan, D. Farrar, R. Tapp, D. J. West, K. Deighton, M.D. Campbell, Omega-3 polyunsaturated fatty acids favourably modulate cardiometabolic biomarkers in type 2 diabetes: a meta-analysis and meta-regression of randomized controlled trials, *Cardiovasc. Diabetol.* 17 (2018) 98.
- [45] K. Li, T. Huang, J. Zheng, K. Wu, D. Li, Effect of marine-derived n-3 polyunsaturated fatty acids on C-reactive protein, interleukin 6 and tumor necrosis factor alpha: a meta-analysis, *PLoS ONE* 9 (2014) e88103.
- [46] P.C. Calder, Omega-3 fatty acids and inflammatory processes: from molecules to man, *Biochem. Soc. Trans.* 45 (2017) 1105–1115.
- [47] J. Allaire, W.S. Harris, C. Vors, A. Charest, J. Marin, K.H. Jackson, A. Tchernof, P. Couture, B. Lamarche, Supplementation with high-dose docosahexaenoic acid increases the Omega-3 Index more than high-dose eicosapentaenoic acid, *Prostaglandins Leukot. Essent. Fatty Acids* 120 (2017) 8–14.
- [48] A. Denys, A. Hichami, N.A. Khan, n-3 PUFAs modulate T-cell activation via protein kinase C-alpha and -epsilon and the NF-kappaB signaling pathway, *J. Lipid Res.* 46 (2005) 752–758.
- [49] T.E. Novak, T.A. Babcock, D.H. Jho, W.S. Helton, N.J. Espat, NF-kappa B inhibition by omega -3 fatty acids modulates LPS-stimulated macrophage TNF-alpha transcription, *Am. J. Physiol. Lung Cell Mol. Physiol.* 284 (2003) L84–L89.
- [50] P.C. Calder, Omega-3 polyunsaturated fatty acids and inflammatory processes: nutrition or pharmacology? *Br. J. Clin. Pharmacol.* 75 (2013) 645–662.
- [51] S.R. Shaikh, J.J. Kinnun, X. Leng, J.A. Williams, S.R. Wassall, How polyunsaturated fatty acids modify molecular organization in membranes: insight from NMR studies of model systems, *Biochim. Biophys. Acta* 1848 (2015) 211–219.