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1 **Diet quality and risk and severity of COVID-19: a prospective cohort study**

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3 Jordi Merino, Ph.D.;^{1,2,3#} Amit D. Joshi, MBBS, Ph.D.;^{4,5#} Long H. Nguyen, M.D., M.S.;^{4,5,6#}
4 Emily R. Leeming MSc.;⁷ Mohsen Mazidi, Ph.D.;⁷ David A Drew, Ph.D.;^{4,5} Rachel Gibson
5 Ph.D.;⁸ Mark S. Graham Ph.D.;⁹ Chun-Han Lo M.D., M.P.H.;^{4,5} Joan Capdevila, Ph.D.;¹⁰
6 Benjamin Murray, Ph.D.;⁹ Christina Hu, BA.;¹⁰ Somesh Selvachandran, MEng.;¹⁰ Sohee Kwon,
7 Ph.D.;^{4,5} Wenjie Ma, Ph.D.;^{4,5} Cristina Menni, M.D.;⁷ Alexander Hammers, M.D., Ph.D.;^{9,11}
8 Shilpa N. Bhupathiraju, Ph.D.;^{3,12} Shreela V. Sharma, Ph.D.;¹⁴ Carole Sudre Ph.D.;⁹ Christina M.
9 Astley, M.D., Sc.D.;^{2,13} Walter C. Willet, M.D., Dr.P.H.;^{12,15,16} Jorge E. Chavarro, M.D.,
10 Sc.D.;^{12,15,16} Sebastien Ourselin, Ph.D.;⁹ Claire J. Steves, MBBS, M.D.;⁷ Jonathan Wolf, MA.;¹⁰
11 Paul W. Franks, Ph.D.;^{12,17} Tim D. Spector, MBBS, M.D.;^{8*} Sarah E. Berry, Ph.D.;^{8*} Andrew T.
12 Chan, M.D., M.P.H.;^{4,5*}

13
14
15 1. Diabetes Unit and Center for Genomic Medicine, Massachusetts General Hospital, Boston, MA,
16 USA.

17 2. Program in Medical and Population Genetics, Broad Institute, Cambridge, MA, USA.

18 3. Department of Medicine, Harvard Medical School, Boston, MA, USA.

19 4. Clinical and Translational Epidemiology Unit, Massachusetts General Hospital and Harvard
20 Medical School, Boston, MA, USA.

21 5. Division of Gastroenterology, Massachusetts General Hospital and Harvard Medical School,
22 Boston, MA, USA.

23 6. Department of Biostatistics, Harvard T.H. Chan School of Public Health, Boston, MA, USA.

24 7. Department of Twin Research, King's College London, London UK

25 8. Department of Nutritional Sciences, King's College London, London UK

26 9. School of Biomedical Engineering & Imaging Sciences, King's College London, London, UK

27 10. Zoe Global Limited, London, UK

28 11. King's College London & Guy's and St Thomas' PET Centre, King's College London, London,
29 UK

30 12. Department of Nutrition, Harvard TH Chan School of Public Health, Boston, MA, USA

- 31 13. Division of Endocrinology & Computational Epidemiology, Boston Children's Hospital,
32 Harvard Medical School, Boston, M
33 14. Department of Epidemiology, Human Genetics, and Environmental Sciences, UTHealth, School
34 of Public Health, Houston, TX, USA
35 15. Department of Epidemiology, Harvard T.H. Chan School of Public Health, Boston, MA, USA
36 16. Channing Division of Network Medicine, Department of Medicine, Brigham and Women's
37 Hospital and Harvard Medical School, Boston, MA, USA
38 17. Department of Clinical Sciences, Lund University, Malmö, Sweden

39

40 # Authors share co-first authorship

41 * Authors share co-last authorship

42

43

44

45 **Correspondence:**

46 Andrew T. Chan, M.D., M.P.H. Clinical and Translational Epidemiology Unit, Massachusetts
47 General Hospital, 100 Cambridge Street Boston, MA 02114; Phone: 617-726-7802; Fax: 617-
48 643-0195; Email: achan@mgh.harvard.edu

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51

52 **Abstract**

53 **Objective:** Poor metabolic health and certain lifestyle factors have been associated with risk and
54 severity of coronavirus disease 2019 (COVID-19), but data for diet are lacking. We aimed to
55 investigate the association of diet quality with risk and severity of COVID-19 and its intersection
56 with socioeconomic deprivation.

57 **Design:** We used data from 592,571 participants of the smartphone-based COVID Symptom
58 Study. Diet quality was assessed using a healthful plant-based diet score, which emphasizes
59 healthy plant foods such as fruits or vegetables. Multivariable Cox models were fitted to
60 calculate hazard ratios (HR) and 95% confidence intervals (95% CI) for COVID-19 risk and
61 severity defined using a validated symptom-based algorithm or hospitalization with oxygen
62 support, respectively.

63 **Results:** Over 3,886,274 person-months of follow-up, 31,815 COVID-19 cases were
64 documented. Compared with individuals in the lowest quartile of the diet score, high diet quality
65 was associated with lower risk of COVID-19 (HR, 0.91; 95% CI, 0.88-0.94) and severe COVID-
66 19 (HR, 0.59; 95% CI, 0.47-0.74). The joint association of low diet quality and increased
67 deprivation on COVID-19 risk was higher than the sum of the risk associated with each factor
68 alone ($P_{interaction}=0.005$). The corresponding absolute excess rate for lowest vs highest quartile of
69 diet score was 22.5 (95% CI, 18.8-26.3) and 40.8 (95% CI, 31.7-49.8; 10,000 person-months)
70 among persons living in areas with low and high deprivation, respectively.

71 **Conclusions:** A dietary pattern characterized by healthy plant-based foods was associated with
72 lower risk and severity of COVID-19. These association may be particularly evident among
73 individuals living in areas with higher socioeconomic deprivation.

74 **Introduction**

75 Poor metabolic health^{1,2} has been associated with increased risk and severity of coronavirus
76 disease 2019 (COVID-19), and excess adiposity or preexisting liver disease might be causally
77 associated with increased risk of death from COVID-19.^{3,4} Underlying these conditions is the
78 contribution of a diet, which may be independently associated with COVID-19 risk and severity.
79 On the basis of prior scientific evidence, diet quality scores have been developed to evaluate the
80 healthfulness of dietary patterns.⁵⁻⁷ Dietary patterns capture the complexity of food intakes better
81 than any one individual food item and offer the advantage of describing usual consumption of
82 foods in typical diets.⁸ One such diet score is the healthful plant-based diet index (hPDI), which
83 emphasizes intake of healthy plant foods, such as fruits, vegetables, and whole grains, and has
84 been associated with lower risk of metabolic diseases.^{5,9,10}

85 Adherence to healthful dietary patterns may also be a proximal manifestation of distal social
86 determinants of health.¹¹⁻¹³ Addressing adverse social determinants of health, such as poor
87 nutrition, has been shown to reduce the burden of certain infectious diseases in the past,¹⁴
88 supporting calls for prioritizing social determinants of health in the public health response to
89 COVID-19. However, evidence on the association between diet quality and the risk and severity
90 of COVID-19 is lacking, especially in the context of upstream social determinants of health. To
91 address this evidence gap, we analyzed data for 592,571 United Kingdom (UK) and United
92 States (US) participants from the smartphone-based COVID Symptom Study,¹⁵ to prospectively
93 investigate the association of diet quality with risk and severity of COVID-19 and its intersection
94 with socioeconomic deprivation.

95 **Materials and Methods**

96 **Study design and participants**

97 The COVID Symptom Study is a smartphone-based study conducted in the UK and US. Study
98 design and sampling procedures have been published elsewhere.¹⁵ This analysis included
99 participants recruited from March 24, 2020 and followed until December 2, 2020. Participants
100 who reported any symptoms related to COVID-19 prior to start of follow-up, or reported
101 symptoms that classified them as having predicted COVID-19 within 24 hours of first entry, or
102 who tested positive for COVID-19 at any time prior to start of follow-up or 24 hours after first
103 entry were excluded. We also excluded participants younger than 18 years old, pregnant, and
104 participants who logged only one daily assessment during follow-up. At enrollment, we obtained
105 informed consent to the use of volunteered information for research purposes and shared relevant
106 privacy policies and terms of use agreements. The study protocol was approved by the Mass
107 General Brigham Human Research Committee (protocol 2020P000909) and King's College
108 London Ethics Committee (REMAS ID 18210, LRS-19/20-18210).

109 **Data collection procedures**

110 Information on demographic factors was collected through standardized questionnaires at
111 baseline,¹⁵ including self-reported COVID-19 or any COVID-19 related symptoms and personal
112 medical history including lung disease, diabetes, cardiovascular disease, cancer, kidney disease,
113 and use of medications. During follow-up, daily prompts queried for updates on interim
114 symptoms, health care visits, and COVID-19 testing results. Through software updates, a survey
115 to examine self-reported diet and lifestyle habits during the pre/early-pandemic period was

116 launched between August and September 2020. Details about this survey are available in the
117 Supplementary Methods and published elsewhere.¹⁶

118 **Assessment of diet quality**

119 Diet quality was assessed using information obtained from an amended version of the Leeds
120 Short Form Food Frequency Questionnaire¹⁷ that included 27 food items (online supplementary
121 methods). Participants were asked how often on average they had consumed one portion of each
122 item in a typical week. The responses had eight frequency categories ranging from “rarely or
123 never” to “five or more times per day”.

124 Diet quality was quantified using the validated hPDI score.⁵ To compute the hPDI, the 27 food
125 items were combined into 14 food groups (online supplementary table 1). The original hPDI
126 score included 18 food groups but nuts, vegetable oils, tea or coffee, and animal fat were not
127 specifically queried. Food groups were ranked into quintiles and given positive (healthy plant
128 food groups) or reverse scores (less healthy plant and animal food groups). With positive scores,
129 participants within the highest quintile of a food group received a score of 5, following on
130 through to participants within the lowest quintile who received a score of 1. With reverse scores,
131 this pattern of scoring was inverted. All component scores were summed to obtain a total score
132 ranging from 14 (lowest diet quality) to 70 (highest) points. Criteria for generation of the hPDI
133 are provided in online supplemental table 2. As an additional method to quantify diet quality
134 based on available diet information, we used the Diet Quality Score (DQS).¹⁷ The DQS is a score
135 for adherence to UK dietary guidelines and was computed from five broad categories including
136 fruits, vegetables, total fat, oily fish, and non-milk extrinsic sugars. Each component was scored
137 from 1 (unhealthiest) to 3 (healthiest) points, with intermediate values scored proportionally

138 (online supplementary table 3). All component scores were summed to obtain a total score
139 ranging from 5 (lowest diet quality) to 15 (highest) points (online supplementary table 4).

140 **Assessment of COVID-19 risk and severity**

141 The primary outcome of this analysis was COVID-19 risk defined using a validated symptom-
142 based algorithm,¹⁸ which provides similar estimates of COVID-19 prevalence and incidence as
143 those reported from the Office for National Statistics Community Infection Survey.¹⁹ Details on
144 the symptoms included in the predictive algorithm and corresponding weights are provided in the
145 online supplementary methods. In brief, the symptom-based approach uses an algorithm to
146 predict whether a participant has been infected with SARS-CoV-2 on the basis of their reported
147 symptoms, age, and sex. The rationale for symptom-based classifier as a primary outcome was
148 due to widespread difficulties obtaining testing during the early stages of the pandemic.²⁰

149 Secondary outcomes were confirmed COVID-19 based on a self-report of a reverse transcription
150 polymerase chain reaction (RT-PCR) positive test and COVID-19 severity. COVID-19 severity
151 was ascertained based on a report of the need for a hospital visit which required 1) non-invasive
152 breathing support, 2) invasive breathing support, and 3) administration of antibiotics combined
153 with oxygen support (online supplementary methods).

154 **Statistical analysis**

155 We summarized continuous measurements by using medians and interquartile ranges, and
156 present categorical observations as frequency and percentages. Based on zip code (US) or post
157 code (UK) of residence, participants were assigned to country-specific community-level
158 socioeconomic measures including socioeconomic deprivation and population density (online
159 supplementary methods). The methods for classifying socioeconomic deprivation, population
160 density, and other *a priori* selected covariates are provided in online supplementary methods.

161 Multiple imputations by chained equations with five imputations were used to impute missing
162 values. All covariates in the primary analysis were included in the multiple imputation
163 procedure, and estimates generated from each imputed dataset were combined using Rubin's
164 rules.²¹

165 Follow-up time for each participant started 24 hours after first log-in to the time of predicted
166 COVID-19 (or to time of secondary outcomes) or date of last entry prior to December 2, 2020,
167 whichever occurred first. We modeled the diet quality score as a continuous variable and
168 generated categories of the score based on quartiles of the distribution (quartile 1, low diet
169 quality; quartiles 2-3, intermediate diet quality; quartile 4, high diet quality). Cox regression
170 models stratified by calendar date at study entry, country of origin, and 10-year age group were
171 used to calculate hazard ratio (HR) and 95% confidence intervals (95% CI) for COVID-19 risk
172 and severity (age-adjusted model 1). Model 2 was further adjusted for sex, race/ethnicity, index
173 of multiple deprivation, population density, presence of diabetes, cardiovascular disease, lung
174 disease, cancer, kidney disease, and healthcare worker status. Model 3 was further adjusted for
175 body mass index, smoking status, and physical activity. We verified the proportional hazards
176 assumption of the Cox model by using the Schoenfeld residuals technique.²² Absolute risk was
177 calculated as the percentage of COVID-19 cases occurring per 10,000 person-months in a given
178 group. We used restricted cubic splines with four knots (at the 2.5th, 25th, 75th, and 97.5th
179 percentiles) to assess for non-linear associations between diet quality and COVID-19 risk.

180 In secondary analyses, we used a self-report of a positive test to define COVID-19 risk. For these
181 analyses, we used inverse probability-weighted Cox models to account for predictors of
182 obtaining country-specific testing. Inverse probability-weighted analyses included presence of
183 COVID-19-related symptoms, interaction with a person with COVID-19, occupation as a

184 healthcare worker, age group, and race. Inverse probability-weighted Cox models were stratified
185 by 10-year age group and date with additional adjustment for the covariates used in previous
186 models. For severe COVID-19 analyses, we adjusted for the same covariates used in previous
187 models. As an additional method to quantify diet quality we used the DQS and tested for
188 associations between diet quality and COVID-19 risk and severity. In addition, we censored our
189 analyses to cases that occurred after completing the diet survey to investigate potential bias due
190 to time-varying confounding.

191 In subgroup analyses, we assessed the association between diet quality and COVID-19 risk
192 according to comorbidities, demographic, and lifestyle characteristics. We also classified
193 participants according to categories of the diet quality score and socioeconomic deprivation (nine
194 categories based on thirds of diet quality score and deprivation index) and conducted joint
195 analyses for COVID-19 risk. We tested for additive interactions by assessing the relative excess
196 risk due to interaction, and further examined the COVID-19 risk proportions attributable to diet,
197 deprivation, and to their interaction (online supplementary methods).²³

198 We conducted sensitivity analyses to account for regional differences in the effective
199 reproductive number (R_t) or other risk mitigating behaviors such as mask wearing. Details on
200 how we obtained and classified individuals for these analyses are provided in online
201 supplementary methods. Two-sided p-values of <0.05 were considered statistically significant
202 for main analyses. All statistical analyses were performed using R software, version 4.0.3 (R
203 Foundation).

204

205 **Results**

206 Self-reported diet quality was evaluated in 647,137 survey responders, of which 54,566 were
207 excluded due to prevalent COVID (n=1,555), presence of any symptoms at baseline (n=47,594),
208 logged only once (n=1,201), pregnancy (n=1,129), or age under 18 year (n=3,087; online
209 supplementary figure 1). Baseline characteristics of the 592,571 participants included in this
210 study according to categories of the hPDI score are shown in table 1. Participants in the highest
211 quartile of the diet score (reflecting a healthier diet) were more likely than participants in the
212 lowest quartile to be older, female, healthcare workers, of lower BMI, engage in physical
213 activities ≥ 5 days/week, and less likely to reside in areas with higher socioeconomic deprivation.
214 The hPDI score was normally distributed (online supplementary figure 2).

215 Over 3,886,274 person-months of follow-up, 31,815 COVID-19 cases were documented. Crude
216 COVID-19 rates per 10,000 person-months were 72.0 (95% CI, 70.4-73.7) for participants in the
217 highest quartile of the diet score and 104.1 (95% CI, 101.9-106.2) for those in the lowest
218 quartile. The corresponding age-adjusted HR for COVID-19 risk was 0.80 (95% CI, 0.78-0.83,
219 table 2). Differences in the risk of COVID-19 persisted after adjustment for potential
220 confounders. In fully adjusted models, the multivariable-adjusted HR for COVID-19 risk was
221 0.91 (95% CI, 0.88-0.94) when we compared participants with high diet quality to those with
222 low diet quality. We observed non-linear decreasing trends in the risk of COVID-19 with higher
223 diet quality ($P < 0.001$ for non-linearity), in which COVID-19 risk plateau among individuals
224 with a diet quality score > 50 (online supplementary figure 3). The association between diet
225 quality and COVID-19 risk was consistent but attenuated in secondary analyses using the DQS
226 score (HR, 0.92; 95% CI, 0.89-0.95; online supplementary table 5), and became non-significant
227 in fully adjusted models (HR, 1.00; 95% CI, 0.97-1.03). We also investigated whether our

228 primary findings were consistent in an analysis censored to cases that occurred after the
229 completion of the diet survey. These analyses showed that high diet quality, compared to low
230 diet quality, was associated with lower COVID-19 risk (multivariable-adjusted HR 0.88; 95%
231 CI, 0.83-0.93; online supplementary table 6).

232 In secondary analyses for COVID-19 risk based on a positive test, we showed that crude
233 COVID-19 incidence rates per 10,000 person-months were 12.9 (95% CI 12.2-13.6) for
234 individuals with high diet quality and 16.4 (95% CI 15.5-17.2) for individuals with low diet
235 quality. The corresponding multivariable-adjusted HR for risk of COVID-19 was 0.82 (95% CI,
236 0.78-0.86; table 2). For risk of severe COVID-19, crude incidence rates were lower for
237 individuals reporting high diet quality compared to those with low diet quality (1.6 (95% CI, 1.3-
238 1.8) vs. 2.1 (95% CI, 1.9-2.5; per 10,000 person-months) table 2). In the fully adjusted model,
239 high diet quality, as compared to low diet quality, was associated lower risk of severe COVID-19
240 with an a HR of 0.59 (95% CI, 0.47-0.74; table 2).

241 In stratified analyses, the inverse association between diet quality and COVID-19 risk was more
242 evident in participants living in areas of high socioeconomic deprivation and those reporting low
243 physical activity levels ($P < 0.05$; table 3). We found no significant effect modification for other
244 characteristics such age, BMI, race/ethnicity or population density. When diet quality and
245 socioeconomic deprivation were combined, there was a risk gradient with low diet quality and
246 high socioeconomic deprivation. Compared with individuals living in areas with low
247 socioeconomic deprivation and high diet quality, the multivariable-adjusted HR for risk of
248 COVID-19 for low diet quality was 1.08 (95% CI, 1.03-1.14) among those living in areas with
249 low socioeconomic deprivation, 1.23 (95% CI, 1.17-1.29) for those living in areas with
250 intermediate socioeconomic deprivation, and 1.47 (95% CI, 1.38-1.52) for those living in areas

251 with high socioeconomic deprivation (figure 1). The joint associations of diet quality and
252 socioeconomic deprivation was higher than the sum of the risk associated with each factor alone
253 (relative excess risk due to interaction (RERI) = 0.05 (95% CI 0.02-0.08); $P_{interaction}=0.005$;
254 online supplementary table 7). The proportion of contribution to excess COVID-19 risk was
255 estimated to be 31.9% (95% CI, 18.2-45.6) to diet quality, 38.4% (95% CI, 26.5-50.3) to
256 socioeconomic deprivation, and 29.7% (95% CI, 2.1-57.3) to their interaction. The absolute
257 excess rate of COVID-19 per 10,000 person-months for lowest vs highest quartile of the diet
258 score was 22.5 (95% CI, 18.8-26.3) among individuals living in areas with low socioeconomic
259 deprivation and 40.8 (95% CI, 31.7-49.8) among individuals living in areas with high
260 deprivation (online supplementary figure 4)

261 We conducted a series of sensitivity analyses to further account for variation in R_t or mask
262 wearing. For peak R_t censored analyses, crude COVID-19 rates per 10,000 person-months were
263 148.1 (95% CI, 139.9-156.8) among participants with low diet quality and 92.9 (95% CI, 86.6-
264 99.5) for participants with high diet quality. The corresponding multivariable-adjusted HR was
265 0.84 (95% CI, 0.76-0.92, figure 2). The same trend was observed for nadir R_t censored analyses,
266 in which crude COVID-19 rates per 10,000 person-months were 67.1 (95% CI, 61.7-73.0)
267 among participants with low diet quality and 45.8 (95% CI, 41.3-50.5) for participants with high
268 diet quality (multivariable-adjusted HR, 0.89; 95% CI, 0.80-1.00, figure 2). We further adjusted
269 our models for mask wearing. This analysis showed that high diet quality, as compared to low
270 diet quality, was associated with lower risk of COVID-19 with an adjusted HR of 0.88 (95% CI,
271 0.83-0.94; online supplementary table 8).

272

273

274 **Discussion**

275 In this large survey among UK and US participants prospectively assessing risk and severity of
276 COVID-19 infection, we found that a dietary patterns characterized by healthy plant foods was
277 associated with lower risk and severity of COVID-19. We observed a risk gradient of poor diet
278 quality and increased socioeconomic deprivation that departed from the additivity of the risks
279 attributable to each factor separately, suggesting that the beneficial association of diet with
280 COVID-19 may be particularly evident among individuals with higher socioeconomic
281 deprivation.

282 Our findings are aligned with preliminary evidence showing that improving nutrition could help
283 reduce the burden of infectious diseases.^{12,14,24} Early studies have shown that the administration
284 of arachidonic or linoleic acid partially suppresses SARS-CoV-1 and coronavirus 229E viral
285 replication,²⁵ and that specific nutrients or dietary supplements associate with modest reductions
286 in COVID-19 risk.²⁶ Results from this observational study could expand previous single nutrient
287 observations and highlight the beneficial association of healthy dietary patterns, which was most
288 pronounced for risk of severe COVID-19. Our findings also concur with a comparative risk
289 assessment study suggesting that a 10% reduction in the prevalence of diet-related conditions
290 such as obesity and type 2 diabetes would have prevented ~11% of the COVID-19
291 hospitalizations that have occurred among US adults since November 2020.²⁷

292 The association of healthy diet with lower COVID-19 risk appears particularly evident among
293 individuals living in areas of higher socioeconomic deprivation. Our models estimate that nearly
294 a third of COVID-19 cases would have been prevented if one of two exposures (diet and
295 deprivation) were not present. Although these estimated attributable risks should be interpreted
296 in the context of the population-specific prevalence, and are likely to change over time with the

297 prevailing SARS-CoV-2 infection rate, our observations are consistent with data from ecological
298 studies showing that people living in regions with greater social inequalities are likely to have
299 higher rates of COVID-19 incidence and deaths.²⁸ By generating a granular deprivation index
300 based on zip code information our study adds to previous country-level ecological studies. In
301 addition, recent studies on the impact of socioeconomic status on COVID-19 have shown that
302 community-level deprivation indices are strongly associated with COVID-19 risk and
303 mortality.^{29,30} However, it is still possible that differences in deprivation exists within
304 communities. Further studies including information about household characteristics, built
305 environment, or access to healthy foods are needed to expand these initial associations.

306 Our study adds to knowledge by formally investigating how diet quality, in the context of distal
307 social determinants of health, associates with risk and severity of COVID-19. While our study
308 supports the beneficial association of diet quality with COVID-19 risk and severity, particularly
309 among individuals with higher deprivation, we cannot completely rule out the potential for
310 residual confounding. Individuals who eat healthier diets are likely to share other features that
311 might be associated with lower risk of infection such as the adoption of other risk mitigation
312 behaviors, better household conditions and hygiene, or access to care. However, it is reassuring
313 that our findings were consistent despite controlling for additional surrogate markers of SARS-
314 CoV-2 infection such as mask wearing or community transmission rate, two of the most relevant
315 factors associated with virus transmission and COVID-19 risk.³¹ These findings suggest that
316 efforts to address disparities in COVID-19 risk and severity should consider specific attention to
317 access to healthy foods as a social determinants of health.

318 We acknowledge several limitations. First, as an observational study, we are unable to confirm a
319 direct causal association between diet and COVID-risk or infer specific mechanisms. Second,

320 our study population was not a random sampling of the population. Although this limitation is
321 inherent to any study requiring voluntary provision of information, we recognize our participants
322 are mainly white participants and less likely to live in low deprived areas and are less ethnically
323 diverse than the general population.¹⁹ Thus, generalizability of our finding even to the wider
324 British and American population is uncertain. Third, our results could be biased due to the time
325 lapse between the dietary recalls, administered a few months after the relevant period of
326 exposure (pre-pandemic). However, our sensitivity analyses in which we censored cases that had
327 occurred before the administration of the diet survey showed consistent results. Fourth, the self-
328 reported nature of the diet questionnaire is prone to measurement error and bias, and the use of a
329 short food frequency survey could have further reduced the resolution of dietary data collected.
330 More accurate dietary intake assessment methods such as the use of dietary intake biomarkers
331 would be valuable in future studies,³² but also difficult to implement in large-scale and time-
332 sensitive investigations. Fifth, we defined risk of severe COVID-19 according to reports of
333 hospitalization with oxygen support, which may not have captured more severe or fatal cases.

334 **Conclusions**

335 In conclusion, our data provide evidence that a healthy diet was associated with lower risk of
336 COVID-19 and severe COVID-19 even after accounting for other healthy behaviors, social
337 determinants of health, and virus transmission measures. The joint association of diet quality
338 with socioeconomic deprivation was greater than the addition of the risks associated with each
339 individual factor, suggesting that diet quality may play a direct influence in COVID-19
340 susceptibility and progression. Our findings suggest that public health interventions to improve
341 nutrition and poor metabolic health and address social determinants of health may be important
342 for reducing the burden of the pandemic.

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350 in <https://doi.org/10.1017/S1368980016001099> and listed in the Nutritools (www.nutritools.org)
351 library.

352

353 **Conflict of Interest:**

354 JW, CH, SS, and JC are employees of Zoe Global Ltd. TDS, ERL, SEB, area consultant to Zoe
355 Global Ltd. DAD, JM, and ATC previously served as investigators on a clinical trial of diet and
356 lifestyle using a separate mobile application that was supported by Zoe Global Ltd. Other authors
357 have no conflict of interest to declare.

358

359 **Contributions:**

360 JM, ADJ, LHN, ERL, TDS, SEB, and ATC conceived the study design. JM, ADJ, ERL, MSG,
361 JC, BM, SS contributed to the statistical analysis. All authors were involved in acquisition,
362 analysis, or interpretation of data. JM, LHN, and DAD wrote the first draft of the manuscript.
363 DAD, WCW, SO, CJS, JW, PWF, TDS, SEB, ATC obtained funding. JM, ADJ, LHN provided
364 administrative, technical, or material support. TDS, SEB, ATC jointly supervised this work. All
365 authors contributed to the critical revision of the manuscript for important intellectual content

366 and approved the final version of the manuscript. The corresponding authors attest that all listed
367 authors meet authorship criteria and that no others meeting the criteria have been omitted.

368

369

370 **Data availability statement:**

371 Zoe Platform data used in this study is available to researchers through UK Health Data

372 Research using the following link:

373 <https://web.www.healthdatagateway.org/dataset/fddcb382-3051-4394-8436-b92295f14259>. The

374 diet quality data used for this study are held by the department of Twin Research at Kings’

375 College London. The data can be released to bona fide researchers using our normal procedures

376 overseen by the Wellcome Trust and its guidelines as part of our core funding. We receive

377 around 100 requests per year for our datasets and have a meeting three times a month with

378 independent members to assess proposals. Application is via [https://twinsuk.ac.uk/resources-for-](https://twinsuk.ac.uk/resources-for-researchers/access-our-data/)

379 [researchers/access-our-data/](https://twinsuk.ac.uk/resources-for-researchers/access-our-data/). This means that the data needs to be anonymized and conform to

380 GDPR standards.

381

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477 **Figure legends**

478 **Figure 1.**

479 **Title:** Risk of COVID-19 according to diet quality and socioeconomic deprivation.

480 **Figure legend:** Shown are adjusted hazard ratios and 95% confidence interval of the estimate for
481 predicted COVID-19 according to categories of diet quality and socioeconomic deprivation. Cox
482 model stratified by calendar date at study entry, country of origin, and 10-year age group, and
483 adjusted for sex, race/ethnicity, index of multiple deprivation, population density, presence of
484 diabetes, cardiovascular disease, lung disease, cancer, kidney disease, healthcare worker status,
485 body mass index, smoking status, and physical activity. In these comparisons, participants with
486 high-quality diet and low socioeconomic deprivation served as the reference group.

487

488 **Figure 2.**

489 **Title:** Risk of COVID-19 according to community transmission rate and diet quality

490 **Figure legend:** COVID-19 incidence rate per 10,000 person-month and 95% confidence interval
491 of the estimate based on different community transmission rate and diet quality categories. Peak
492 R_t and nadir R_t were defined using (methods). Adjusted hazard ratios and 95% confidence
493 interval of the estimate for risk of COVID-19 were obtained from fully adjusted Cox models.

494

495

496 **TABLES and FIGURES**

497 **Table 1.** Baseline characteristics of study participants according to categories of the diet quality
498 score

	All participants (n=592,571)	Low hPDI (Q1; n=148,143)	Intermediate hPDI (Q2-Q3; n=296,286)	High hPDI (Q4; n=148,142)
hPDI score, median [IQR]	50 (47 to 54)	45 (43-47)	51 (49-52)	56 (55-58)
Demographic characteristics				
Age, years	56 (44-65)	52 (41-62)	57 (45-66)	57 (45-65)
≥18-24	14,397 (2.4)	5,146 (3.4)	5,846 (2.0)	3,405 (2.3)
25-34	52,922 (8.9)	16,535 (11.2)	23,150 (7.8)	13,237 (8.9)
35-44	86,251 (14.6)	26,907 (18.2)	40,145 (13.5)	19,199 (13.0)
45-54	125,802 (21.2)	34,890 (23.6)	62,491 (21.1)	28,421 (19.2)
55-64	158,637 (26.8)	34,279 (23.1)	81,837 (27.6)	42,521 (28.7)
≥65	153,810 (26.0)	30,215 (20.4)	82,413 (27.8)	41,182 (27.8)
Missing	752 (0.1)	171 (0.1)	404 (0.1)	177 (0.1)
Sex, No. (%)				
Male	187,450 (31.6)	58,199 (39.3)	93,162 (31.4)	36,089 (24.4)
Female	404,126 (68.2)	89,706 (60.5)	202,605 (68.4)	111,815 (75.5)
Prefer not to say	995 (0.2)	238 (0.2)	519 (0.2)	238 (0.2)
Race ^e , No. (%),				
White	568,770 (96.0)	141,365 (95.4)	284,804 (96.1)	142,601 (96.3)
Black	4,328 (0.7)	1,466 (1.0)	2,053 (0.7)	809 (0.5)
Asian	10,435 (1.8)	2,954 (1.9)	5,043 (1.7)	2,438 (1.6)
Other	7,228 (1.2)	1,925 (1.3)	3,463 (1.2)	1,840 (1.2)
Missing	1,810 (0.3)	433 (0.3)	923 (0.3)	454 (0.3)
Country, No. (%)				
UK	543,984 (91.8)	135,360 (91.4)	272,494 (92.0)	136,130 (91.9)
US	48,587 (8.2)	12,783 (8.6)	23,792 (8.0)	12,012 (8.1)
Index of deprivation, No. (%) ^f				
Most deprived, decile 1	1,3416 (2.3)	4,696 (3.1)	6,163 (2.1)	2,557 (1.7)
Least deprived, decile 10	103,608 (17.5)	23,122 (15.6)	53,652 (18.1)	26,834 (18.1)
Missing	40,759 (6.9)	10,489 (7.1)	20,249 (6.8)	10,021 (6.8)
Population density, km ² , No. (%) ^f				
<500	119,782 (20.2)	28,139 (19.0)	61,230 (20.7)	30,413 (20.5)
500-1,999	90,541 (15.3)	23,631 (16.0)	45,902 (15.5)	21,008 (14.2)
2,000 4,999	94,345 (15.9)	24,813 (16.7)	47,233 (15.9)	22,299 (15.1)
≥5,000	244,295 (41.2)	60,156 (40.6)	120,319 (40.6)	63,820 (43.1)
Missing	43,608 (7.4)	11,404 (7.7)	21,602 (7.3)	10,602 (7.2)
Healthcare worker, yes, No. (%)	41,141 (6.9)	10,633 (2.3)	20,183 (6.8)	10,325 (7.0)
Lifestyle characteristics				

Smoking status, No (%)				
Never	475,347 (81.9)	113,165 (79.0)	238,192 (81.9)	123,990 (84.6)
Former	87,901 (15.1)	22,683 (15.8)	44,771 (15.4)	20,447 (13.9)
Current	17,401 (3.0)	7,402 (5.2)	7,837 (2.6)	2,162 (1.5)
Physical activity				
< 1 day/week	106,294 (17.9)	37,258 (25.2)	50,713 (17.1)	18,323 (12.4)
1-2 days/week	224,606 (37.9)	59,325 (40.0)	113,749 (38.4)	51,532 (34.8)
3-4 days/week	143,548 (24.2)	30,009 (20.3)	73,601 (24.8)	39,938 (27.0)
≥ 5 days/week	117,007 (19.7)	21,164 (14.3)	57,701 (19.5)	38,142 (25.7)
Missing	1,116 (0.2)	387 (0.3)	522 (0.2)	207 (0.1)
Body mass index, Kg/m ²				
<18.5	12,004 (2.0)	2,680 (1.8)	5,540 (1.9)	3,784 (2.6)
18.5-24.9	277,536 (46.8)	52,109 (35.2)	138,503 (46.7)	86,924 (58.7)
25-29.9	189,197 (31.9)	51,517 (34.8)	97,919 (33.0)	39,761 (26.8)
≥30	113,056 (19.1)	41,655 (28.1)	53,909 (18.2)	17,492 (11.8)
Missing	778 (0.1)	182 (0.1)	415 (0.1)	181 (0.1)
Mask wearing, No (%) [†]				
Most of the time / always	437,782 (73.9)	113,202 (76.4)	218,402 (73.7)	106,178 (71.6)
Never / sometimes	152,551 (25.7)	34,240 (23.1)	76,809 (25.9)	41,502 (28.0)
Missing	2,238 (0.4)	701 (0.5)	1,075 (0.4)	462 (0.3)
Clinical history, yes, No. (%)				
Diabetes	20,058 (3.4)	6,079 (4.1)	10,158 (3.4)	3,821 (2.6)
Heart disease	20,376 (3.4)	5,200 (3.5)	10,660 (3.6)	4,516 (3.0)
Cancer	6,559 (1.9)	1,643 (1.8)	3,348 (1.9)	1,568 (1.8)
Lung disease	62,999 (10.6)	17,534 (11.8)	31,227 (10.5)	14,238 (9.6)
Kidney disease	5,134 (0.9)	1,492 (1.0)	2,594 (0.9)	1,048 (0.7)

499

500 **Table Legend:** Values are median (IQR) for continuous variables; numbers and (percentages) for categorical
 501 variables.

502 ^ε Race was self-reported by the participants.

503 [¶] Index of deprivation and population density were generated using zipcode or postcode information linked with
 504 census track data. Country-specific deprivation indices were generated (supplement).

505 [†] Mask wearing information was collapsed into two categories: participants who wore masks ‘none of the time or
 506 sometimes’, and those who reported wearing masks ‘most of time/ always’.

507 ^{*} hPDI ranges from 0 to 70, with higher scores indicating higher adherence to a healthy plant-based diet.

508

509

510

Table 2. Adjusted hazard ratios of COVID-19 risk and severity according to healthful plant-based dietary index scores.

	Low hPDI (Q1; n=148,143)	Intermediate hPDI (Q2-Q3; n=296,286)	High hPDI (Q4; n=148,142)	P for trend
hPDI score, median (IQR)	45 (43-47)	51 (49-52)	56 (55-58)	
COVID-19 risk				
No. of events/person-months	8,739 / 839,747	15,733 / 2,026,824	7,359 / 1,022,078	—
Incidence rate (10,000 person-months; 95% CI)	104.1 (101.9-106.2)	77.6 (76.4-78.8)	72.0 (70.4-73.7)	—
Age-adjusted model	1.00 (Ref)	0.85 (0.82-0.87)	0.80 (0.78-0.83)	<0.001
Multivariable model 2	1.00 (Ref)	0.85 (0.83-0.87)	0.81 (0.78-0.83)	<0.001
Multivariable model 3	1.00 (Ref)	0.91 (0.89-0.93)	0.91 (0.88-0.94)	<0.001
COVID-19 risk (positive test)				
No. of events/person-months	1,423 / 869,664	2,829 / 2,081,970	1,350 / 1,046,887	—
Incidence rate (10,000 person-months; 95% CI)	16.4 (15.5-17.2)	13.6 (13.1-14.1)	12.9 (12.2-13.6)	—
Age-adjusted model ^s	1.00 (Ref)	0.86 (0.83-0.90)	0.79 (0.75-0.83)	<0.001
Multivariable model 2 ^s	1.00 (Ref)	0.87 (0.84-0.91)	0.80 (0.76-0.84)	<0.001
Multivariable model 3 ^s	1.00 (Ref)	0.88 (0.85-0.92)	0.82 (0.78-0.86)	<0.001
Severe COVID-19				
No. of events/person-months	187 / 871,995	390 / 2,086,790	163 / 1,049,476	—
Incidence rate (10,000 person-months; 95% CI)	2.1 (1.9-2.5)	1.9 (1.7-2.1)	1.6 (1.3-1.8)	—
Age-adjusted model	1.00 (Ref)	0.66 (0.56-0.77)	0.45 (0.36-0.57)	<0.001
Multivariable model 2	1.00 (Ref)	0.66 (0.57-0.78)	0.45 (0.36-0.57)	<0.001
Multivariable model 3	1.00 (Ref)	0.77 (0.66-0.91)	0.59 (0.47-0.74)	<0.001

Table Legend: Hazards ratios and 95% CI for COVID-19 risk and severity. COVID-19 risk defined using a validated symptom-based model. COVID-19 or a RT-PCR positive test report. COVID-19 severity was defined based on hospitalization with requirement of oxygen support (methods, supplement).

Cox proportional hazards models were stratified by calendar date at study entry, country of origin, and 10-year age group (Age-adjusted model).

Multivariable model 2 was further adjusted for sex (male, female), race/ethnicity (White, Black, Asian, Other), index of multiple deprivation (most deprived <3, intermediate deprived 3 to 7, less deprived >7), population density (<500 individuals/km², 500 to 1,999 individuals/km², 2,000 to 4,999 individuals/km², and ≥ 5,000 individuals/km²), and healthcare worker status (yes with interaction with COVID-19 patients, yes without interaction with COVID-19 patients, no).

Model 3 was further adjusted for presence of comorbidities [diabetes (yes, no), cardiovascular disease (yes, no), lung disease (yes, no), cancer (yes, no), kidney disease (yes, no)], body mass index (<18.5 kg/m², 18.5 to 24.9 kg/m², 25.0 to 29.9 kg/m², and ≥30 kg/m²), smoking status (yes, no), and physical activity (<1 day/week, 1 to 2 days/week, 3 to 4 days/week, ≥5 days/week).

^s Inverse probability-weighted analyses were conducted to account for predictors of obtaining RT-PCR testing (presence of COVID-19-related symptoms, interaction with a COVID-19 case, healthcare worker, age group, and race). Inverse probability-weighted Cox proportional hazards models were stratified by 10-year age group and date with additional adjustment for the covariates used in previous models.

1 **Table 3.** Adjusted hazard ratios of COVID risk according to healthful plant-based dietary index
 2 scores stratified by sociodemographic and clinical characteristics.
 3

Factor	No. of events/ person-months [#]	HR per 1-SD increase in diet quality score	P value
Age,			
<60	25,329 / 2,285,329	0.94 (0.93-0.95)	
≥60	6,486 / 1,600,945	0.94 (0.92-0.97)	0.63
Sex,			
Male	9,338 / 1,232,656	0.95 (0.93-0.97)	
Female	22,428 / 2,647,254	0.96 (0.95-0.98)	0.21
Race,			
White	30,335 / 3,736,972	0.96 (0.95-0.97)	
Non-white	1,480 / 149,303	0.96 (0.91-1.01)	0.95
Socioeconomic deprivation*			
High	5,244 / 45,6271	0.94 (0.91-0.96)	
Intermediate	13,172 / 1,567,516	0.96 (0.94-0.98)	
Low	13,399 / 1,862,489	0.97 (0.95-0.99)	0.04
Population density, km ² , No.			
<2000	10,581 / 1,490,084	0.96 (0.94-0.98)	
≥2,000	21,234 / 2,396,190	0.96 (0.94-0.97)	0.74
Healthcare worker			
Yes	2,908 / 140,087	0.95 (0.92-0.99)	
No	28,907 / 3,638,588	0.96 (0.95-0.97)	0.78
Body mass index, Kg/m ²			
<25	13,989 / 1,905,517	0.96 (0.94-0.97)	
25-30	9,854 / 1,252,222	0.96 (0.94-0.98)	
≥30	7,972 / 728,536	0.96 (0.94-0.98)	0.73
Physical activity			
< 1 day/week	6,751 / 683,562	0.94 (0.91-0.96)	
1-4 day/week	19,476 / 2,425,198	0.96 (0.94-0.97)	
≥ 5 day/week	5,588 / 777,515	0.99 (0.96-1.01)	0.01

4
 5 **Table Legend:** Association between predicted COVID-19 and diet quality according to sociodemographic and
 6 clinical characteristics. *Socioeconomic deprivation categories were based on deciles of the deprivation index
 7 (methods). Cox models were adjusted for the same covariates as previous model 3. P-values obtained using the Q
 8 test for heterogeneity

9 # Number of observations varies among imputations.

Figure 1

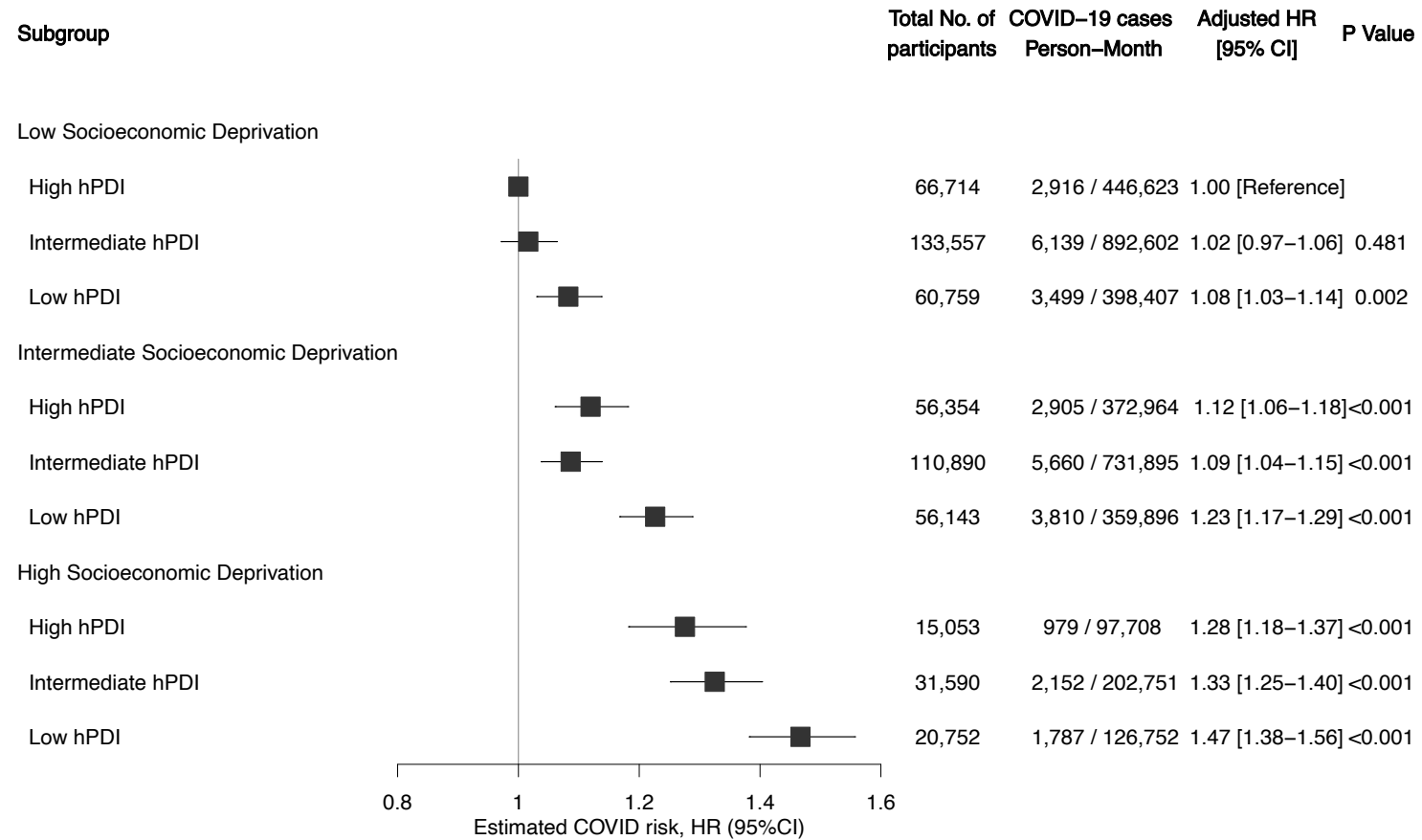


Figure 2

