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Effects of porcine-derived collagen hydrolysates on 24 h blood pressure profiles, markers for endothelial dysfunction and low-grade inflammation and the retinal vasculature in adults with overweight/obesity: a randomized, controlled trial

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In vitro and animal studies have shown promising effects of collagen hydrolysate on blood pressure (BP), serum lipid profiles, and plasma concentrations of endothelial and inflammatory markers. Therefore, we evaluated in humans the effects of a porcine-derived collagen hydrolysates on office and ambulatory blood pressure (ABP) profiles, retinal microvascular calibers, serum lipids, markers for endothelial dysfunction and low-grade inflammation. Given a possible link between peripheral vascular and brain vascular function, effects on cognitive performance were also explored. Therefore, in this randomized, placebo-controlled parallel trial, 56 middle-aged and older adults with overweight/obesity consumed 10 g porcine-derived collagen hydrolysates or placebo (erythritol) daily for four weeks after a 2-week run-in period. Measurements were performed at the end of the run-in and intervention periods. Collagen hydrolysates consumption did not significantly affect office systolic BP (SBP) (−1 mmHg, 95% CI: −3, 2; $p = 0.529$), or diastolic BP (DBP) (−1 mmHg, 95% CI: −2, 1; $p = 0.449$), nor 24-hour SBP (0 mmHg, 95% CI: −4, 4; $p = 0.884$) or DBP (−2 mmHg, 95% CI: −5, 1; $p = 0.195$). No significant changes were observed in mean arterial pressure, pulse pressure, nocturnal BP dipping, retinal microvascular calibers, serum lipids, and markers for endothelial dysfunction and low-grade inflammation. Cognitive performance remained unaffected, except for an unexpected increase in movement reaction time (29 ms, 95% CI: 553; $p = 0.019$). In conclusion, four-week porcine-derived collagen hydrolysate supplementation did not improve cardiometabolic risk markers and cognitive performance in middle-aged and older adults with overweight or obesity. This clinical trial was registered in November 2021 at ClinicalTrials.gov as NCT05282641.

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Introduction

Cardiovascular disease (CVD) remains the global leading cause of death, accounting for approximately 20.5 million deaths globally in 2021.¹ Major risk factors contributing to CVD risk include hypertension, dyslipidemia, type 2 diabetes, and being overweight or obese.^{2,3} These risk factors are associated with endothelial dysfunction and chronic low-grade inflammation, which have been identified as predictors of future cardiovascular events.^{4,5} Preventive strategies to target these risk factors are therefore crucial to reduce the incidence of CVD.

Recently, bioactive peptides derived from protein hydrolysates have received increasing attention to mitigate cardiovascular risk factors.^{6–10} Amongst others, collagen hydrolysates have demonstrated promising results.¹¹ Collagen hydrolysates derived from marine and animal sources, including porcine, may be antihypertensive, possibly due to inhibiting angiotensin I-converting enzyme (ACE). ACE is an important regulator in the renin-angiotensin system, converting angiotensin into the active vasoconstrictor angiotensin 2 that increases the vascular tone and consequently blood pressure (BP).¹² *In vitro* studies and research with hypertensive rats have identified collagen hydrolysate peptides from bovine,¹³ goat,¹⁴ tilapia skin,¹⁵ jellyfish,¹⁶ chicken,¹⁷ or porcine¹⁸ as potential ACE inhibitors. However, human studies evaluating the effects of collagen hydrolysates on BP have yielded mixed results, with some reporting improvements,^{19,20} while others have found no significant effects.^{21,22}

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Besides BP, animal studies have also shown that collagen hydrolysates may lower serum total and low-density lipoprotein cholesterol (LDL-C) concentrations,^{23,24} possibly by modulating the expression of proteins involved in fatty acid and cholesterol synthesis, and β -oxidation,²⁵ which could further reduce the risk of developing atherosclerosis.²⁶ Again, human studies are conflicting with some studies reporting reductions in total cholesterol, LDL-C, and triacylglycerol (TAG),²⁰ along with increases in high-density lipoprotein cholesterol (HDL-C),^{20,27} while others showed no effects.^{19,28,29} Finally, studies using cultured human endothelial cells or apolipoprotein E-deficient (ApoE^{-/-}) mice suggested that collagen hydrolysates reduced concentrations of markers reflecting low-grade inflammation or endothelial dysfunction such as interleukin-6 (IL-6), soluble intercellular adhesion molecule-1 (sICAM-1), and tumor necrosis factor- α (TNF- α).^{30,31} However, the limited number of studies in humans did not show any significant effects on inflammatory markers,^{32,33} while markers of endothelial dysfunction have not been evaluated so far. Changes in retinal arteriolar and venular calibers may indicate functional alterations in the retinal microvasculature that are associated with the risk of developing stroke and coronary heart diseases, even after adjusting for other well-established risk factors.³⁴ Finally, improvements in cardiovascular health are associated with better cognitive performance.³⁵ For instance, individuals with prediabetes, who have impaired endothelial function and consequently an increased CVD risk,³⁶ exhibit reduced cognitive function compared to normoglycemic individuals.³⁷ Specifically, impairments have been observed in the domains of attention and psychomotor speed, executive function, and memory.³⁸ Peripheral endothelial dysfunction has therefore been suggested as a potential mechanistic link between insulin resistance and cognitive decline.³⁹ Thus, improvements in CVD risk associated with collagen hydrolysate consumption may also lead to cognitive benefits.

Therefore, we here evaluated the effects of 4 weeks of daily consumption of 10 g of porcine-derived collagen hydrolysates on CVD risk markers, such as office and 24-hour BP profiles, retinal microvascular calibers, serum lipids and lipoproteins, and markers for endothelial dysfunction and chronic low-grade inflammation, as well as cognitive performance in men and women with overweight or obesity.

Methods

Subjects

Apparently healthy men and women with overweight or obesity (BMI 25–35 kg m⁻²) and between 40–75 years old were recruited *via* posters on websites/social media or advertisements in local newspapers. Those who were interested were pre-screened *via* email or phone. Potential eligible participants were invited for two screening visits at the Metabolic Research Unit Maastricht (MRUM). For each visit, participants were instructed to fast overnight for 12 hours, to come by car or public transport, and to avoid vigorous physical activity and

alcohol consumption for 48 and 24 hours, respectively. After explaining the study and discussing remaining questions, written informed consent was obtained before screening. Additionally, a medical questionnaire as well as the use of medication and supplements were documented. During screening, office BP, anthropometric measurements, and fasting blood samples were obtained as described in detail before.⁴⁰ Participants were eligible after meeting the inclusion criteria: serum total cholesterol < 8.0 mmol L⁻¹, triacylglycerol < 4.52 mmol L⁻¹, nonsmoker or smoking cessation > 1 year; no diabetes; no familial hypercholesterolemia; no abuse of drugs; no > 4 alcoholic consumptions on a day with a maximum of 21 per week; stable body weight (weight gain or loss < 3 kg in the past three months); no use of medication to treat hypertension, lipid or glucose metabolism; no severe medical conditions that might interfere with the study parameters such as epilepsy, asthma, kidney failure or renal insufficiency, chronic obstructive pulmonary disease, inflammatory bowel diseases, autoinflammatory diseases, or rheumatoid arthritis; no active cardiovascular diseases or events such as congestive heart failure, acute myocardial infarction, or cerebrovascular accidents; difficult to venipuncture; no blood donation within the past 12 weeks; engaged in less than 10 hours of sports per week; not working night shifts; no allergies to porcine-derived supplements and agreement to consume the study products. Ethical approval was obtained by the Ethical Committee of azM/UM (IDs NL72922.068.20/METC 20-007). The study was registered at ClinicalTrials.gov (identifier NCT05282641) and was performed according to the principles of the Declaration of Helsinki. The study was carried out between February 2021 and August 2023.

Study design

The study had a randomized, double-blind, placebo-controlled parallel design, and consisted of a two-week run-in period followed by 4-week of intervention (SI Fig. S1). After inclusion, participants were randomly allocated to the collagen hydrolysates or placebo group using a computer-generated block design by an independent researcher. During the study, participants visited the MRUM five times. The first three visits took place in the run-in period, one at the start (week 0), and twice at the end (both in week 2). Two follow-up visits (4 and 5) were in the last week of the intervention period (week 6). Participants completed two test days: one at the end of the run-in period (visit 3) and the second one at the end of the intervention period (visit 5). During the test day, various measurements were performed. Results on glycemic variability, fasting and postprandial glucose, insulin, and triacylglycerol concentrations, anthropometrical measurements, food intake, and physical activity profiles have already been published.⁴⁰ Here, we report the effects of 4 weeks of consuming the collagen hydrolysates on other cardiometabolic health parameters such as office BP, 24-hour BP profiles, characteristics of the retinal microvasculature, markers reflecting endothelial dysfunction and low-grade systemic inflammation, and cognitive performance.



Study product

Sachets from three different boxes labeled A, B, and C, were stored at 22 °C. An independent researcher performed the randomization procedure and coordinated supplement distribution together with an independent research assistant, who was responsible for packaging and providing the study products to the participants. For the two-week run-in period, sachets from box C were used, while for the 4-week intervention periods, the sachets from either boxes A or B were provided to the volunteers. All sachets had an identical appearance. The sachets containing the collagen hydrolysates consisted of 10 g of porcine-derived collagen hydrolysates (Rousselot, Someren, the Netherlands) plus 5 g of erythritol (Ingrizo, De Pinte, Belgium), while the placebo sachets, including the sachets from box C, contained only 5 g of erythritol (Ingrizo, De Pinte, Belgium). Both researchers as well as participants were blinded to the type of products they received. Every day, participants consumed the content of one sachet in 200 ml of water, preferably 15 min before breakfast. On visit days, participants consumed the product at home post-visit. The code of the study was broken after all statistics had been performed and conclusions had been formulated. Compliance was excellent: $98.8\% \pm 3.7$ and $98.3\% \pm 3.2$ in the collagen hydrolysate group, and $99.4\% \pm 3.0$ and $97.5\% \pm 4.0$ in the placebo group for the run-in and intervention periods, respectively.⁴⁰ Furthermore, participants were instructed to maintain regular levels of physical activity and to keep their dietary habits stable during the study, which was successful.⁴⁰

Office BP and 24-hour ambulatory BP

Office BP was measured after 10 minutes of rest in a supine position using an Omron Intellisense M7 (Cemex Medische Techniek, Nieuwegein, the Netherlands) as already explained.⁴⁰ Moreover, an ambulatory BP monitor device (Mobil-O-Graph; I.E.M. Inc. Stolberg, Germany) was placed on the left arm to assess 24-hour BP profiles during the last weeks of the run-in period (week 2), and the intervention period (week 6). This device was placed at the end of visits 2 and 4. Participants removed the device themselves after 24 hours and returned it to the research team on the following test days for readout. During the 24-hour test days, BP was recorded every 15 min during the daytime (from 07:00 to 22:00) and every 30 min during the nighttime (from 22:00 to 07:00). The ambulatory BP profiles were calculated over 24 hours, as well as separately for daytime and nighttime. The first measurement was discarded in the analysis. Mean systolic BP (SBP), diastolic BP (DBP), mean arterial pressure (MAP), heart rate (HR), pulse pressure (PP), standard deviation (SD) profiles during 24 hours, daytime, and nighttime, as well as nocturnal dipping in SBP and DBP were calculated, as previously described.⁴¹

Retinal microvasculature

During the test days (visits 3 and 5), digital fundus images of the optic disc from the right eye were captured using a non-mydratic retinal camera (TRC-NW300, Topcon Corporation, Tokyo, Japan). These images were used to assess changes in retinal vascular calibers. For this, digital images were analyzed

using the IVAN software (University of Wisconsin, Wisconsin, USA), selecting the diameters of the three widest arterioles and the three widest venules, using exactly the same segments on the images from the run-in phase and the intervention phase within each participant. The Parr-Hubbard formula⁴² was used to calculate the central retinal arteriolar equivalent (CRAE), the central retinal venular equivalent (CRVE), and the arteriolar-to-venular ratio (AVR).

Serum and plasma markers for endothelial dysfunction and low-grade inflammation

Fasting blood samples were collected at the end of the run-in period and at the end of the intervention period from the forearm using serum STT-II separator tubes (Becton, Dickson, and Company) and EDTA-coated vacutainer tubes (Becton, Dickson, and Company). Serum tubes were clotted at room temperature for 30 min and then centrifuged at 1300g for 10 min at 21 °C. EDTA tubes were kept on ice until centrifugation at 1300g for 10 min at 4 °C. Serum and EDTA plasma were portioned into aliquots, frozen in liquid nitrogen, and stored at -80 °C. All samples were analyzed in the same analytical run after completing the study. Serum samples were used to analyze total cholesterol (CHOD-PAP method; Roche Diagnostics, Mannheim, Germany), HDL-C, (precipitation method, Roche Diagnostics, Mannheim, Germany), TAG (TRIGL method, Roche Diagnostics, Mannheim, Germany), and high-sensitive C-reactive protein concentrations (hs-CRP; immunoturbidimetric assay, Horiba ABX, Montpellier, France), while EDTA plasma samples were used to analyze concentrations of IL-6, IL-8, TNF α , soluble vascular adhesion molecule-1 (sVCAM-1), (sICAM-1), serum amyloid A protein (SAA), and soluble endothelial leukocyte adhesion molecule-1 (sE-Selectin) by ELISA (MesoScaleDiscovery, SECTOR Imager 2400, Gaithersburg, Maryland, USA). LDL-C concentrations were calculated using the Friedewald formula.⁴³ Results from serum samples obtained from the last two visits, 2 and 3 of the run period as well as the samples from the two visits, 4 and 5, at the end of the intervention period were averaged.

Cognitive function tests

During both test days, cognitive performance was evaluated using fully automated Cambridge neuropsychological test automated battery (CANTAB) software using an iPad (iPad 5th generation; Apple, California, USA). CANTAB is a validated computerized assessment tool to evaluate cognitive performance in different domains such as memory, psychomotor speed, and executive function. Participants were first familiarized with the software and the iPad through the motor screening task (MOT), which was not used in the study results. The working memory domain was assessed with the delayed matching to sample (DMS) test, and paired associates learning (PAL) test. Psychomotor speed was assessed with the reaction time (RTI) test. Finally, executive function was assessed *via* the multitasking test (MTT) and the spatial working memory (SWM) test, as previously described.^{44,45}



Statistics

Results are presented as means \pm SDs unless otherwise specified. The power calculation for the study was based on treatment effects on the interstitial glucose area under the curve during daytime and resulted in a sample size of 54 participants, as previously published.⁴⁰ Treatment effects were estimated using a one-factor ANCOVA, with the end-of-study values as the dependent variable, run-in values as covariate, and treatment as factor. When residuals did not follow a normal distribution, one-factor ANCOVA analyses were conducted on log₁₀-transformed values. If the residuals remained not normally distributed as assessed with the Kolmogorov–Smirnov, treatment effects were estimated with Quade's ANCOVA with run-in values as a covariate. Two-sided *p*-values ≤ 0.05 were considered to be statistically significant. Analyses were performed using IBM SPSS Statistics Version 28.0 for Mac (IBM Corporation, Armonk, NY, United States).

Results

Study participants

Sixty-five participants were screened for eligibility, of which sixty-three were enrolled in the study and randomly assigned to either the collagen hydrolysates group (*n* = 32) or the placebo group (*n* = 31). As illustrated in the study flow chart (SI Fig. S2), seven participants discontinued the study. Three of these participants were originally randomized to the collagen hydrolysates group: two withdrew for personal reasons and one for health issues unrelated to the study. The other four participants were allocated to the placebo group: two of them declined for personal reasons, one for starting medication that

could have interfered with the study outcomes, and another due to receiving the diagnosis of arthritis. Therefore, fifty-six participants were included in the statistical analysis, with 28 (women *n* = 16) in the collagen hydrolysates group and 28 (women *n* = 15) in the placebo group. Additionally, two participants were excluded from the retinal microvasculature analysis due to image capture failure. Moreover, fourteen participants were excluded from the ambulatory BP analysis: two participants declined to use the device, two participants encountered technical issues with the device, and ten participants were excluded due to insufficient data collected for analysis due to measurement errors. Finally, all participants completed the cognitive tests. Baseline characteristics of the participants (SI Table S1) have been reported before.⁴⁰

Blood pressure outcomes and retinal microvascular calibers

Four weeks of collagen hydrolysate consumption showed no significant changes in office BP as compared to placebo. Likewise, there were no significant changes in mean BP profiles, heart rate, nocturnal BP dipping, and intra-individual BP variability during the 24-hour BP monitoring (Table 1). Results were similar when the daytime and nighttime data were considered separately (SI Table S2). Furthermore, no significant effects were found on CRAE (1 μ m, 95% CI: -1 to 2; *P* = 0.550), CRVE (0 μ m, 95% CI: -2 to 2; *P* = 0.841), and AVR (0 μ m, 95% CI: 0 to 0; *P* = 0.799) in the collagen hydrolysate group as compared to placebo (Table 1).

Serum lipids and lipoproteins as well as markers for endothelial dysfunction and low-grade inflammation

Serum total cholesterol, HDL-C, and LDL-C concentrations remained unchanged after collagen hydrolysate consumption

Table 1 Effects of 10-gram collagen protein hydrolysates on retinal microvasculature, office blood pressure, and 24-hour blood pressure profiles at the end of the run-in period and at the end of the intervention period per group

	Collagen-hydrolysates group Run-in period	Collagen-hydrolysates group End of study	Placebo group Run-in period	Placebo group End of study	Treatment effect (95% CI)	<i>p</i> -Value
Office blood pressure						
SBP (mmHg)	130 \pm 15	130 \pm 15	127 \pm 14	128 \pm 15	-1 (-3 , 2)	0.529
DBP (mmHg)	81 \pm 7	82 \pm 7	81 \pm 6	83 \pm 8	-1 (-2 , 1)	0.449
24-Hour blood pressure						
SBP (mmHg)	128 \pm 12	124 \pm 10	124 \pm 10	122 \pm 9	0 (-4 , 4)	0.844
DBP (mmHg)	74 \pm 9	75 \pm 8	77 \pm 7	77 \pm 6	-2 (-5 , 1)	0.195
MAP (mmHg)	101 \pm 9	97 \pm 8	99 \pm 8	98 \pm 7	-1 (-5 , 2)	0.402
PP (mmHg)	50 \pm 8	50 \pm 7	46 \pm 7	46 \pm 7	-2 (-5 , 1)	0.195
HR (beats per min)	65 \pm 8	65 \pm 7	67 \pm 8	68 \pm 10	0 (-3 , 3)	0.919
Nocturnal dipping SBP (%)	9 \pm 5	9 \pm 6	11 \pm 6	8 \pm 8	2 (-2 , 6)	0.398
Nocturnal dipping DBP (%)	13 \pm 6	11 \pm 8	15 \pm 7	14 \pm 9	-2 (-7 , 3)	0.377
Retinal microvascular calibers						
CRAE (μ m)	136 \pm 17	136 \pm 18	132 \pm 13	131 \pm 14	1 (-1 , 2)	0.550
CRVE (μ m)	226 \pm 16	227 \pm 16	231 \pm 17	231 \pm 17	0 (-2 , 2)	0.841
AVR	0.60 \pm 0.06	0.60 \pm 0.06	0.57 \pm 0.06	0.57 \pm 0.05	0.00 (-0.01 , 0.01)	0.799

Abbreviations: SBP systolic blood pressure; DBP, diastolic blood pressure; MAP, mean arterial pressure; PP, pulse pressure; HR, heart rate; CRAE, central retinal arteriolar equivalent; CRVE, central retinal venular equivalent; AVR, arteriolar-venular-ratio. Values are mean \pm SD. Treatment effects were evaluated with 1-factor ANCOVA with baseline value as a covariate. Office blood pressure: collagen hydrolysates group *n* = 28, placebo group *n* = 28. 24 h blood pressure: collagen hydrolysates group *n* = 19, placebo group *n* = 23. Retinal microvascular calibers: collagen hydrolysates group *n* = 27, placebo group *n* = 27.



Table 2 Effects of 10-gram collagen protein hydrolysates on biochemical parameters and markers for endothelial dysfunction and low-grade inflammation at the end of the run-in period and at the end of the intervention period per group

	Collagen-hydrolysates group Run-in period	Collagen-hydrolysates group End of study	Placebo group Run-in period	Placebo group End of study	Treatment effect (95% CI)	<i>p</i> -Value
Biochemical parameters						
Total cholesterol (mmol L ⁻¹)	5.68 ± 0.74	5.68 ± 0.62	5.54 ± 0.87	5.59 ± 0.84	-0.02 (-0.21, 0.17)	0.849
HDL-C (mmol L ⁻¹)	1.46 ± 0.33	1.45 ± 0.32	1.51 ± 0.29	1.54 ± 0.29	-0.03 (-0.08, 0.03)	0.281
LDL-C (mmol L ⁻¹)	3.52 ± 0.61	3.53 ± 0.56	3.45 ± 0.71	3.44 ± 0.70	0.02 (-0.14, 0.18)	0.803
Markers for endothelial dysfunction						
sVCAM-1 (ng ml ⁻¹)	402 ± 81	434 ± 83	407 ± 87	430 ± 121	6 (-31, 43)	0.754
sICAM-1 (ng ml ⁻¹)	327 ± 80	357 ± 80	308 ± 65	320 ± 81	18 (-7, 43)	0.161
sE-Selectin (ng ml ⁻¹)	43 ± 18	41 ± 18	42 ± 21	41 ± 19	-1 (-3, 2)	0.563
Markers for low-grade inflammation						
IL-6 (pg ml ⁻¹) ^a	0.72 (0.35, 3.32)	0.74 (0.41, 1.53)	0.71 (0.38, 3.44)	0.66 (0.31, 3.96)		0.673
IL-8 (pg ml ⁻¹)	5.19 ± 2.0	4.77 ± 1.9	4.47 ± 1.30	4.48 ± 1.18	-0.09 (-0.78, 0.60)	0.798
TNFα (pg ml ⁻¹)	1.33 ± 0.44	1.24 ± 0.36	1.36 ± 0.39	1.29 ± 0.34	0.03 (-0.13, 0.07)	0.526
SAA (μg ml ⁻¹) ^a	2.54 (0.73, 89.3)	2.28 (0.96, 35.2)	3.08 (0.72, 20.0)	3.04 (0.86, 21.7)		0.444
hs-CRP (ng mL ⁻¹) ^a	1.81 (0.06, 9.07)	1.42 (0.06, 9.94)	0.73 (0.17, 21.9)	0.70 (0.10, 17.1)		0.625

Abbreviations: HDL-c, high-density lipoprotein cholesterol; LDL-c, low-density lipoprotein cholesterol; sVCAM-1, soluble vascular cell adhesion molecule-1; sICAM-1, soluble intercellular adhesion molecule-1; sE-Selectin, soluble endothelial leukocyte adhesion molecule-1; IL-6, interleukin-6; IL-8, interleukin-8; TNFα Tumor necrosis factor-alpha; SAA, serum amyloid A protein; hs-CRP, high sensitive C-reactive protein. Values are mean ± SD or median (minimum and maximum values). Treatment effects were evaluated with 1-factor ANCOVA with baseline value as a covariate. ^aWhen residuals were not normally distributed, treatment effect changes were evaluated with Quade's ANCOVA with baseline value as a covariate. In bold *p*-value < 0.05. Collagen hydrolysates group *n* = 28, placebo group *n* = 28. IL-6: collagen hydrolysates group *n* = 27, placebo group *n* = 28.

as compared to placebo. Furthermore, markers for endothelial dysfunction (sVCAM-1, sICAM-1, and sE-selectin) or low-grade inflammation (IL-6, IL-8, TNFα, SAA, and hs-CRP) did not significantly change (Table 2).

Cognitive function

In the psychomotor speed domain, collagen hydrolysates consumption significantly increased RTI movement time by 29 ms (95% CI: 5 to 53; *P* = 0.019) as compared to placebo, whereas no significant differences were observed in RTI reaction time (10 ms, 95% CI: -5 to 25; *P* = 0.206) (Table 3). Additionally, no significant changes were observed between the collagen hydrolysates and the placebo group for tests related to memory or executive function domains (Table 3).

Discussion

In this randomized controlled trial including men and women with overweight or obesity, we found that 10 g of daily porcine-collagen hydrolysate consumption did not significantly affect office and 24-hour BP profiles, serum lipids and lipoproteins, markers for low-grade chronic inflammation and endothelial dysfunction, and retinal vascular calibers. For cognitive performance, we observed an unexpected increase in RTI movement time, while no other significant changes were observed in any of the different cognitive outcomes.

In line with other protein hydrolysates, collagen peptides have been suggested to reduce BP by inhibiting ACE.¹¹ However, we here showed that the consumption of porcine-derived collagen hydrolysates for 4 weeks did not improve

office or ambulatory BP profiles. This is in contrast with a recent meta-analysis, which concluded that collagen hydrolysates supplementation reduced SBP by 5 mmHg, but not DBP, based on moderate- and very low-quality evidence, respectively. Moreover, sub-group analyses indicated that this reduction in SBP was limited to unhealthy populations (-8 mmHg)¹¹ with diabetes and/or with mild or moderate hypertension,^{19,20,46} whereas no effects were found in healthy individuals.¹¹ This was also supported by a recent study using fish-derived collagen hydrolysates in healthy populations.²² Consistent with these results for porcine-collagen hydrolysates, long-term egg protein hydrolysate consumption also did not improve ambulatory BP profiles in a normotensive population.⁴⁷ In contrast, the consumption of the same egg protein hydrolysates,⁴⁸ of shrimp-derived,⁴⁹ and of hemp seed-derived protein hydrolysates⁵⁰ significantly reduced ambulatory SBP and DBP in populations with mild or moderate hypertension. In addition, a meta-analysis showed that lactotripeptide intake, peptides derived from milk casein hydrolysis (Isoleucine-Proline-Proline and Valine-Proline-Proline), exhibited a modest BP-lowering effect, which was more pronounced in hypertensive than in normotensive individuals.⁵¹ Overall, the beneficial effects of hydrolysates from collagen or other protein sources on BP profiles have been observed mainly in mild and moderate hypertensive populations. Therefore, it is tempting to suggest that the potential BP-lowering effects of collagen hydrolysates may be restricted to hypertensive individuals, which may explain the absence of an effect in the current study.

Collagen hydrolysates have also been suggested to improve lipid metabolism by modulating the expression of proteins involved in fatty acid and cholesterol synthesis, as well as for



Table 3 Effects of 10-gram collagen protein hydrolysate on cognitive performance at the end of the run-in period and at the end of the intervention period per group

	Collagen-hydrolysates group		Mean difference	Placebo group		Mean difference	Treatment effect (95% CI)	<i>p</i> -Value
	Run-in period	End of study		Run-in period	End of study			
Memory								
DMS (% correct)	78 ± 10	83 ± 13	4 ± 14	81 ± 10	84 ± 10	4 ± 9	-1 (-6, 5)	0.779
PAL (1st attempt memory score)	11 ± 4	11 ± 4	0 ± 4	12 ± 4	12 ± 4	0 ± 5	-1 (-3, 2)	0.274
PAL (total error)	22 ± 15	20 ± 14	-1 ± 5	17 ± 13	15 ± 12	-2 ± 9	2 (-3, 7)	0.359
Psychomotor speed								
RTI movement time (ms)	321 ± 68	328 ± 68	7 ± 35	323 ± 93	300 ± 62	-23 ± 70	29 (5, 53)	0.019
RTI reaction time (ms)	392 ± 36	400 ± 45	8 ± 27	393 ± 36	391 ± 35	-1 ± 30	10 (-5, 25)	0.206
Executive function								
MTT incongruency cost (ms)	117 ± 63	116 ± 50	0 ± 63	97 ± 59	87 ± 48	-10 ± 65	24 (-1, 49)	0.063
MTT multitasking cost (ms)	191 ± 163	204 ± 109	13 ± 175	245 ± 165	223 ± 130	-22 ± 177	-8 (-72, 55)	0.795
MTT reaction latency (ms)	767 ± 128	762 ± 127	-5 ± 99	759 ± 97	740 ± 115	-18 ± 79	16 (-31, 62)	0.505
MTT (total incorrect)	13 ± 14	7 ± 10	-6 ± 10	11 ± 13	6 ± 9	-5 ± 8	0 (-3, 3)	0.984
SWM (between errors)	32 ± 11	32 ± 10	-1 ± 13	32 ± 13	31 ± 14	-1 ± 14	0 (-6, 6)	0.913
SWM (strategy score)	9 ± 2	7 ± 2	-1 ± 2	8 ± 2	7 ± 3	-1 ± 2	0 (-1, 1)	0.787
SWM (total errors)	33 ± 12	33 ± 10	-1 ± 14	33 ± 14	33 ± 16	0 ± 16	0 (7, 7)	0.976

Abbreviations: DMS, delayed matching to sample; PAL, paired associates learning; RTI, reaction time; MTT, multitasking test; SWM, spatial working memory. Values are mean ± SD. Treatment effect changes were evaluated with 1-factor ANCOVA with baseline value as a covariate. Collagen hydrolysates group *n* = 28, placebo group *n* = 28.

β-oxidation.²⁵ However, in the present study, porcine-derived collagen hydrolysate supplementation had no significant effect on serum total cholesterol, LDL-C, or HDL-C concentrations. This contrasts a recent meta-analysis, which suggested a modest but significant reduction in serum LDL-C concentrations (-0.11 mmol L⁻¹), without significant changes in HDL-C and total cholesterol concentrations, although the quality of evidence was considered to be very low.¹¹ However, further research is warranted, as several other studies that were not included in the meta-analysis found, consistent with our findings, no effects on serum total cholesterol^{19,27,29} and LDL-C²⁷ concentrations. Finally, as previously reported and discussed, no significant changes were observed in TAG concentrations.⁴⁰

To our knowledge, this is the first study to examine the effects of collagen hydrolysate consumption on markers for endothelial dysfunction. We observed no significant effects on sVCAM-1, sICAM-1, or sE-Selectin, which aligns with observations using hydrolyzed⁵² or whole protein intake⁵³ in healthy populations. In contrast, protein supplementation has been shown to reduce sVCAM-1⁵⁴ and sICAM-1^{54,55} in adults with prehypertension and mild hypertension. This might be explained by the fact that hypertensive individuals exhibit higher expression of adhesion molecules and E-selectin⁵⁶ than normotensive individuals, due to endothelial activation induced by inflammatory mediators,⁵⁷ thereby providing more room for improvement. Similarly, we did not observe significant changes in IL-6, IL-8, TNFα, SAA, and hs-CRP, markers for low-grade chronic inflammation. These findings are consistent with two previous studies providing 10 g of bovine-collagen hydrolysates for 12 weeks³² or 15 g for 7 days.³³ Additionally, other studies did not report significant reductions in hs-CRP

following collagen hydrolysate intake.^{20,58,59} Overall, it can be concluded that collagen hydrolysates may not improve markers for low-grade inflammation, but studies in patients with elevated concentrations of these markers at baseline are missing. The absence of effects on BP, lipids, and lipoproteins, and markers for endothelial dysfunction and low-grade inflammation might explain the lack of effects on microvascular calibers in the retina after consuming the porcine-collagen hydrolysates.

Finally, for cognitive performance, we observed an unexpected – but significant – increased movement time during the psychomotor speed test. In contrast, a study investigating the effect of 15 g of bovine-based collagen hydrolysates supplementation for 7 days before bedtime showed no significant effect on a simple reaction time and a choice test.³³ Additionally, other protein hydrolysates have yielded mixed effects on reaction time tests. For instance, a tryptophan-rich protein hydrolysate reduced both simple and complex reaction time in women,⁶⁰ while other protein hydrolysates found no significant effects,^{44,61–63} Furthermore, the reaction time during the RTI test did not change. Thus, our findings indicate no changes in attention, and processing speed from the onset of a stimulus to the initiation of a response. However, a slower movement time was noted. The 29 ms increased RTI movement time falls within the suggested range of normal test-retest variability for this test (90% Reliable Change Index: 50.36 to -54.01 ms) in a healthy population.⁶⁴ This might indicate that our observed increase in RTI movement time could be a chance finding.

The strengths and limitations of this study with respect to the potential impact of timing, dosage, and preparation methods on the outcomes have previously been discussed.⁴⁰



An additional strength of the study results reported here is the use of an ambulatory BP device, which is a better predictor for cardiovascular disease risk as compared to traditional office BP measurements.⁶⁵ A limitation, however; is that 25% of the ambulatory blood pressure data could not be included in the analysis. Furthermore, although we measured markers of endothelial dysfunction, we did not include vascular function measurements in our study. Collagen hydrolysates may improve arterial stiffness by lowering brachial-ankle pulse wave velocity after 12 months,^{21,46} while no studies have yet evaluated changes in endothelial dysfunction measured through flow-mediated dilatation. Therefore, it can be speculated that longer intervention periods are needed to detect potential benefits of collagen hydrolysate consumption on cardiometabolic parameters. Furthermore, combining collagen hydrolysate supplementation with exercise may result in more pronounced improvements in cardiometabolic parameters.⁶⁶

Conclusion

In conclusion, we here show that daily consumption of 10 g of porcine-derived collagen for four weeks did not significantly change office and ambulatory BP profiles, serum lipids and lipoproteins, retinal vascular calibers, and markers for endothelial dysfunction and low-grade chronic inflammation in apparently healthy middle-aged and older adults with overweight or obesity. In addition, cognitive performance was not affected. However, its effects on individuals at higher cardiovascular risk, such as those with hypertension or diabetes, are uncertain and require further research.

Author contributions

MACA, RPM, PJJ and JP contributed intellectually and directly to the manuscript. Data collection was conducted by MACA.

Conflicts of interest

The authors declare no conflicts of interest.

Abbreviations

CVD	Cardiovascular diseases
ACE	Angiotensin I-converting enzyme
SBP	Systolic blood pressure
DBP	Diastolic blood pressure
LDL-C	Low-density lipoprotein cholesterol
TAG	Triacylglycerol
HDL-C	High-density lipoprotein cholesterol
IL-6	Interleukin-6
sICAM-1	Soluble intercellular adhesion molecule-1
(TNF- α)	Tumor necrosis factor-alpha
MAP	Mean arterial pressure

HR	Heart rate
PP	Pulse pressure
SD	Standard deviation
CRAE	Central retinal arteriolar equivalent
CRVE	Central retinal venular equivalent
AVR	Arteriolar-to-venular ratio
IL-8	Interleukin-8
hs-CRP	High-sensitive C reactive protein
sVCAM-1	Soluble vascular adhesion molecule-1
SAA	Serum amyloid A protein
sE-Selectin	Soluble endothelial leukocyte adhesion molecule-1
CANTAB	Cambridge neuropsychological test automated battery
MOT	Motor screening task
DMS	Delayed matching to sample
PAL	Paired associates learning
RTI	Reaction time
MTT	Multitasking test
SWM	Spatial working memory

Data availability

The datasets used and/or analyzed during the study are available from the corresponding author on reasonable request.

Supplementary information (SI) is available. See DOI: <https://doi.org/10.1039/d5fo01261a>.

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References

- 1 M. Lindstrom, N. DeCleene, H. Dorsey, V. Fuster, C. O. Johnson, K. E. LeGrand, G. A. Mensah, C. Razo, B. Stark, J. Varieur Turco and G. A. Roth, Global burden of cardiovascular diseases and risks collaboration, 1990–2021, *J. Am. Coll. Cardiol.*, 2022, **80**, 2372–2425.
- 2 C. M. Lawes, S. Vander Hoorn and A. Rodgers, Global burden of blood-pressure-related disease, 2001, *Lancet*, 2008, **371**, 1513–1518.
- 3 E. Dąbrowska and K. Narkiewicz, Hypertension and dyslipidemia: the two partners in endothelium-related crime, *Curr. Atheroscler. Rep.*, 2023, **25**, 605–612.
- 4 T. A. Pearson, G. A. Mensah, R. W. Alexander, J. L. Anderson, R. O. Cannon 3rd, M. Criqui, Y. Y. Fadl, S. P. Fortmann, Y. Hong, G. L. Myers, N. Rifai, S. C. Smith



- Jr., K. Taubert, R. P. Tracy and F. Vinicor, Markers of inflammation and cardiovascular disease: application to clinical and public health practice: A statement for health-care professionals from the Centers for Disease Control and Prevention and the American Heart Association, *Circulation*, 2003, **107**, 499–511.
- 5 J. Constans and C. Conri, Circulating markers of endothelial function in cardiovascular disease, *Clin. Chim. Acta*, 2006, **368**, 33–47.
 - 6 K. Wang, Z. Fu, X. Li, H. Hong, X. Zhan, X. Guo, Y. Luo and Y. Tan, Whey protein hydrolysate alleviated atherosclerosis and hepatic steatosis by regulating lipid metabolism in apoE(-/-) mice fed a western diet, *Food Res. Int.*, 2022, **157**, 111419.
 - 7 B. Bjørndal, T. A. Aloysius, A. Lund, R. Slizyte, P. Bohov, A. K. Carvajal and R. K. Berge, A chicken protein hydrolysate exerts anti-atherosclerotic effect beyond plasma cholesterol-lowering activity in ApoE(-/-) mice, *Food Sci. Nutr.*, 2020, **8**, 3052–3060.
 - 8 P. Maneesai, J. Wattanathorn, P. Potue, J. Khamsekaew, S. Rattanakanokchai, W. Thukham-Mee, S. Muchimapura and P. Pakdeechote, Cardiovascular complications are resolved by tuna protein hydrolysate supplementation in rats fed with a high-fat diet, *Sci. Rep.*, 2023, **13**, 12280.
 - 9 G. V. Oliveira, M. Volino-Souza, E. M. Cordeiro, C. A. Conte-Junior and T. S. Alvares, Effects of fish protein hydrolysate ingestion on endothelial function compared to whey protein hydrolysate in humans, *Int. J. Food Sci. Nutr.*, 2020, **71**, 242–248.
 - 10 S. Zhou, T. Xu, X. Zhang, J. Luo, P. An and Y. Luo, Effect of casein hydrolysate on cardiovascular risk factors: a systematic review and meta-analysis of randomized controlled trials, *Nutrients*, 2022, **14**, 4207.
 - 11 Z. Jalili, F. Jalili, S. Moradi, R. Bagheri, S. P. Moosavian, F. Naeini, H. Mohammadi, S. Mojtaba Ghoreishy, A. Wong, N. Travica, M. A. Hojjati Kermani and C. Jalili, Effects of collagen peptide supplementation on cardiovascular markers: a systematic review and meta-analysis of randomised, placebo-controlled trials, *Br. J. Nutr.*, 2023, **129**, 779–794.
 - 12 U. Eriksson, U. Danilczyk and J. M. Penninger, Just the beginning: novel functions for angiotensin-converting enzymes, *Curr. Biol.*, 2002, **12**, R745–R752.
 - 13 Y. Fu, J. F. Young, T. K. Dalsgaard and M. Therkildsen, Separation of angiotensin I-converting enzyme inhibitory peptides from bovine connective tissue and their stability towards temperature, pH and digestive enzymes, *Int. J. Food Sci. Technol.*, 2015, **50**, 1234–1243.
 - 14 A. Pratiwi, T. R. Hakim, M. Z. Abidin, N. A. Fitriyanto, J. Jamhari, R. Rusman and Y. Erwanto, Angiotensin-converting enzyme inhibitor activity of peptides derived from Kacang goat skin collagen through thermolysin hydrolysis, *Vet. World*, 2021, **14**, 161–167.
 - 15 Y. Dong, W. Yan, Y.-Q. Zhang and Z.-Y. Dai, A novel angiotensin-converting enzyme (ACE) inhibitory peptide from tilapia skin: preparation, identification and its potential antihypertensive mechanism, *Food Chem.*, 2024, **430**, 137074.
 - 16 Z. Barzideh, A. A. Latiff, C. Y. Gan, M. Z. Abedin and A. K. Alias, ACE inhibitory and antioxidant activities of collagen hydrolysates from the ribbon jellyfish (*chrysaora* sp.), *Food Technol. Biotechnol.*, 2014, **52**, 495–504.
 - 17 Y. Zhang, T. Kouguchi, M. Shimizu, T. Ohmori, Y. Takahata and F. Morimatsu, Chicken collagen hydrolysate protects rats from hypertension and cardiovascular damage, *J. Med. Food*, 2010, **13**, 399–405.
 - 18 T. Ichimura, A. Yamanaka, T. Otsuka, E. Yamashita and S. Maruyama, Antihypertensive effect of enzymatic hydrolysate of collagen and gly-pro in spontaneously hypertensive rats, *Biosci., Biotechnol., Biochem.*, 2009, **73**, 2317–2319.
 - 19 A. Saiga-Egusa, K. Iwai, T. Hayakawa, Y. Takahata and F. Morimatsu, Antihypertensive effects and endothelial progenitor cell activation by intake of chicken collagen hydrolysate in pre- and mild-hypertension, *Biosci., Biotechnol., Biochem.*, 2009, **73**, 422–424.
 - 20 C.-F. Zhu, G.-Z. Li, H.-B. Peng, Y. Li, F. Zhang and Y. Chen, Therapeutic effects of marine collagen peptides on chinese patients with type 2 diabetes mellitus and primary hypertension, *Am. J. Med. Sci.*, 2010, **340**, 360–366.
 - 21 M. Igase, K. Kohara, Y. Okada, M. Ochi, K. Igase, N. Inoue, T. Kutsuna, H. Miura and Y. Ohyagi, A double-blind, placebo-controlled, randomised clinical study of the effect of pork collagen peptide supplementation on atherosclerosis in healthy older individuals, *Biosci., Biotechnol., Biochem.*, 2018, **82**, 893–895.
 - 22 S. Koizumi, Y. Okada, S. Miura, Y. Imai, K. Igase, Y. Ohyagi and M. Igase, Ingestion of a collagen peptide containing high concentrations of prolyl-hydroxyproline and hydroxyprolyl-glycine reduces advanced glycation end products levels in the skin and subcutaneous blood vessel walls: a randomized, double-blind, placebo-controlled study, *Biosci., Biotechnol., Biochem.*, 2023, **87**, 883–889.
 - 23 C. Tometsuka, N. Funato, K. Mizuno and Y. Taga, Long-term intake of ginger protease-degraded collagen hydrolysate reduces blood lipid levels and adipocyte size in mice, *Curr. Res. Food Sci.*, 2021, **4**, 175–181.
 - 24 Y.-i. Koyama and M. Kusubata, Effects of collagen peptide ingestion on blood lipids in rats fed a high-lipid and high-Sucrose diet, *Food Sci. Technol. Res.*, 2013, **19**, 1149–1153.
 - 25 C. Tometsuka, Y. I. Koyama, T. Ishijima, T. Toyoda, M. Teranishi, K. Takehana, K. Abe and Y. Nakai, Collagen peptide ingestion alters lipid metabolism-related gene expression and the unfolded protein response in mouse liver, *Br. J. Nutr.*, 2017, **117**, 1–11.
 - 26 P. N. Patel and R. P. Giugliano, Low-density lipoprotein cholesterol lowering therapy for the secondary prevention of atherosclerotic cardiovascular disease, *Glob. Cardiol. Sci. Pract.*, 2020, **2020**, e202039.
 - 27 N. Tomosugi, S. Yamamoto, M. Takeuchi, H. Yonekura, Y. Ishigaki, N. Numata, S. Katsuda and Y. Sakai, Effect of collagen tripeptide on atherosclerosis in healthy humans, *J. Atheroscler. Thromb.*, 2017, **24**, 530–538.



- 28 S. Devasia, S. Kumar, S. Ps, N. Inoue, F. Sugihara, S. Koizumi, A. Matsushita and S. Vt, Diabetes & metabolism a double blind, randomised, four arm clinical study to evaluate the safety, efficacy and tolerability of collagen peptide as a nutraceutical therapy in the management of type II diabetes mellitus, *Diabetes Metab. J.*, 2020, **10**, 1–7.
- 29 F. Sugihara, N. Inoue and S. Venkateswarathirukumara, Ingestion of bioactive collagen hydrolysates enhanced pressure ulcer healing in a randomized double-blind placebo-controlled clinical study, *Sci. Rep.*, 2018, **8**, 11403.
- 30 H. Liu, Y. Yang, Y. Liu, L. Cui, L. Fu and B. Li, Various bioactive peptides in collagen hydrolysate from salmo salar skin and the combined inhibitory effects on atherosclerosis in vitro and in vivo, *Food Res. Int.*, 2022, **157**, 111281.
- 31 T. Kouguchi, A. Ito, K. Iwai, M. Shimizu, Y. Takahata, T. Suzuki, F. Morimatsu and S. Tanabe, Chicken collagen hydrolysate-derived peptides inhibit tumor necrosis factor—alpha induced inflammatory response in endothelial cells, *Food Sci. Technol. Res.*, 2012, **18**, 667–671.
- 32 C. Bongers, D. ten Haaf, M. Catoire, B. Kersten, J. A. Wouters, T. M. H. Eijsvogels and M. T. E. Hopman, Effectiveness of collagen supplementation on pain scores in healthy individuals with self-reported knee pain: a randomized controlled trial, *Appl. Physiol., Nutr., Metab.*, 2020, **45**, 793–800.
- 33 C. Thomas, R. N. Kingshott, K. M. Allott, J. C. Y. Tang, R. Dunn, W. D. Fraser, J. Thorley, N. Virgilio, J. Prawitt, E. Hogervorst, J. Škarabot and T. Clifford, Collagen peptide supplementation before bedtime reduces sleep fragmentation and improves cognitive function in physically active males with sleep complaints, *Eur. J. Nutr.*, 2024, **63**, 323–335.
- 34 T. Y. Wong, A. Kaminen, R. Klein, A. R. Sharrett, B. E. Klein, D. S. Siscovick, M. Cushman and B. B. Duncan, Quantitative retinal venular caliber and risk of cardiovascular disease in older persons: the cardiovascular health study, *Arch. Intern. Med.*, 2006, **166**, 2388–2394.
- 35 A. Kulshreshtha, M. Goetz, A. Alonso, A. J. Shah, J. D. Bremner, J. Goldberg and V. Vaccarino, Association between cardiovascular health and cognitive performance: A twins study, *J. Alzheimer's Dis.*, 2019, **71**, 957–968.
- 36 S. Lamprou, N. Koletsos, G. Mintziori, P. Anyfanti, C. Trakatelli, V. Kotsis, E. Gkaliagkousi and A. Triantafyllou, Microvascular and endothelial dysfunction in prediabetes, *Life*, 2023, **13**, 644.
- 37 K. Yaffe, T. Blackwell, A. M. Kanaya, N. Davidowitz, E. Barrett-Connor and K. Krueger, Diabetes, impaired fasting glucose, and development of cognitive impairment in older women, *Neurology*, 2004, **63**, 658–663.
- 38 M. Karvani, P. Simos, S. Stavrakaki and D. Kapoukranidou, Neurocognitive impairment in type 2 diabetes mellitus, *Hormones*, 2019, **18**, 523–534.
- 39 A. Convit, Links between cognitive impairment in insulin resistance: an explanatory model, *Neurobiol. Aging*, 2005, **26**(Suppl 1), 31–35.
- 40 M. A. Chavez-Alfaro, R. P. Mensink and J. Plat, Effects of four-weeks porcine-collagen hydrolysate consumption on glucose concentrations, glycemic variability, and fasting/postprandial cardiometabolic risk markers in men and women with overweight or obesity: A randomized, controlled trial, *Clin. Nutr.*, 2025, **46**, 60–71.
- 41 M. A. Chavez-Alfaro, R. P. Mensink, E. Gravesteyn, P. J. Joris and J. Plat, Effects of long-term almond consumption on markers for vascular function and cardiometabolic risk in men and women with prediabetes: results of a randomized, controlled cross-over trial, *Eur. J. Nutr.*, 2024, **64**, 7.
- 42 L. D. Hubbard, R. J. Brothers, W. N. King, L. X. Clegg, R. Klein, L. S. Cooper, A. R. Sharrett, M. D. Davis and J. Cai, Methods for evaluation of retinal microvascular abnormalities associated with hypertension/sclerosis in the atherosclerosis risk in communities study, *Ophthalmol.*, 1999, **106**, 2269–2280.
- 43 W. T. Friedewald, R. I. Levy and D. S. Fredrickson, Estimation of the concentration of low-density lipoprotein cholesterol in plasma, without use of the preparative ultracentrifuge, *Clin. Chem.*, 1972, **18**, 499–502.
- 44 M. S. Adams, R. P. Mensink, J. Plat and P. J. Joris, Long-term effects of an egg-protein hydrolysate on cognitive performance and brain vascular function: a double-blind randomized controlled trial in adults with elevated subjective cognitive failures, *Eur. J. Nutr.*, 2024, **63**, 2095–2107.
- 45 C. C. Limited, CANTAB connect research: admin application user guide, <https://gbiomed.kuleuven.be/english/research/50000737/research/pash/pasoca/documenten/CANTAB%20Connect%20Research%20Admin%20Application%20User%20Guide.pdf>, 2024.
- 46 T. Kouguchi, T. Ohmori, M. Shimizu, Y. Takahata, Y. Maeyama, T. Suzuki, F. Morimatsu and S. Tanabe, Effects of a chicken collagen hydrolysate on the circulation system in subjects with mild hypertension or high-normal blood pressure, *Biosci., Biotechnol., Biochem.*, 2013, **77**, 691–696.
- 47 M. S. Adams, R. P. Mensink, J. Plat, B. Winkens and P. J. Joris, Long-term egg-protein hydrolysate consumption improves endothelial function: a randomized, double-blind, placebo-controlled trial in older adults with overweight or obesity, *Eur. J. Nutr.*, 2024, **64**, 54.
- 48 J. Plat, N. Severins, S. Morrison and R. P. Mensink, Effects of NWT-03, an egg-protein hydrolysate, on blood pressure in normotensive, high-normotensive and mild-hypertensive men and women: a dose-finding study, *Br. J. Nutr.*, 2017, **117**, 942–950.
- 49 K. Musa-Veloso, L. Paulionis, T. Pelipyagina and M. Evans, A randomized, double-blind, placebo-controlled, multicentre trial of the effects of a shrimp protein hydrolysate on blood pressure, *Int. J. Hypertens.*, 2019, **2019**, 2345042.
- 50 M. Samsamikor, D. S. Mackay, R. C. Mollard, A. M. Alashi and R. E. Aluko, Hemp seed protein and its hydrolysate compared with casein protein consumption in adults with hypertension: a double-blind crossover study, *Am. J. Clin. Nutr.*, 2024, **120**, 56–65.



- 51 L. Q. Qin, J. Y. Xu, J. Y. Dong, Y. Zhao, P. van Bladeren and W. Zhang, Lactotripeptides intake and blood pressure management: a meta-analysis of randomised controlled clinical trials, *Nutr., Metab. Cardiovasc. Dis.*, 2013, **23**, 395–402.
- 52 K. D. Ballard, R. S. Bruno, R. L. Seip, E. E. Quann, B. M. Volk, D. J. Freidenreich, D. M. Kawiecki, B. R. Kupchak, M.-Y. Chung, W. J. Kraemer and J. S. Volek, Acute ingestion of a novel whey-derived peptide improves vascular endothelial responses in healthy individuals: a randomized, placebo controlled trial, *Nutr. J.*, 2009, **8**, 34.
- 53 F. Mariotti, M. Valette, C. Lopez, H. Fouillet, M.-H. Famelart, V. Mathé, G. Airinei, R. Benamouzig, C. Gaudichon, D. Tomé, D. Tsikas and J. F. Huneau, Casein compared with whey proteins affects the organization of dietary fat during digestion and attenuates the postprandial triglyceride response to a mixed high-fat meal in healthy, overweight men, *J. Nutr.*, 2015, **145**, 2657–2664.
- 54 A. Fekete, C. Giromini, Y. Chatzidiakou, D. I. Givens and J. A. Lovegrove, Whey protein lowers blood pressure and improves endothelial function and lipid biomarkers in adults with prehypertension and mild hypertension: results from the chronic Whey2Go randomized controlled trial, *Am. J. Clin. Nutr.*, 2016, **104**, 1534–1544.
- 55 K. F. M. Teunissen-Beekman, J. Dopheide, J. M. Geleijnse, S. J. L. Bakker, E. J. Brink, P. W. de Leeuw, C. G. Schalkwijk and M. A. van Baak, Dietary proteins improve endothelial function under fasting conditions but not in the postprandial state, with no effects on markers of low-grade inflammation, *Br. J. Nutr.*, 2015, **114**, 1819–1828.
- 56 M. Buemi, A. Allegra, C. Aloisi, F. Corica, A. Alonci, A. Ruello, G. Montalto and N. Frisina, Cold pressor test raises serum concentrations of ICAM-1, VCAM-1, and E-selectin in normotensive and hypertensive patients, *Hypertens.*, 1997, **30**, 845–847.
- 57 N. Milošević, M. Rütter and A. David, Endothelial cell adhesion molecules- (un)attainable targets for nanomedicines, *Front. Med. Technol.*, 2022, **4**, 846065.
- 58 E. Alipoor, M. J. Hosseinzadeh-Attar, S. Salehi, M. Dahmardehei, M. Yaseri, M. R. Emami, M. Hajian, S. M. Rezayat and S. Jazayeri, Effect of collagen hydrolysate and fish oil on high-sensitivity C-reactive protein and glucose homeostasis in patients with severe burn; a randomized clinical trial, *Arch. Acad. Emerg. Med.*, 2021, **9**, e50.
- 59 Y. J. Tak, Y. J. Kim, J. G. Lee, Y. H. Yi, Y. H. Cho, G. H. Kang and S. Y. Lee, Effect of oral ingestion of low-molecular collagen peptides derived from skate (*raja kenogei*) skin on body fat in overweight adults: A randomized, double-blind, placebo-controlled trial, *Mar. Drugs*, 2019, **17**, 157.
- 60 M. H. Mohajeri, J. Wittwer, K. Vargas, E. Hogan, A. Holmes, P. J. Rogers, R. Goralczyk and E. L. Gibson, Chronic treatment with a tryptophan-rich protein hydrolysate improves emotional processing, mental energy levels and reaction time in middle-aged women, *Br. J. Nutr.*, 2015, **113**, 350–365.
- 61 N. Akazawa, A. Hamasaki, K. Tanahashi, K. Kosaki, T. Yoshikawa, K. Myoenzono and S. Maeda, Lactotripeptide ingestion increases cerebral blood flow velocity in middle-aged and older adults, *Nutr. Res.*, 2018, **53**, 61–66.
- 62 D. Wu, C. C. Yang, K. Y. Chen, Y. C. Lin, P. J. Wu, P. H. Hsieh, Y. Nakao, M. Y. L. Ow, Y. C. Hsieh and C. J. Hu, Hydrolyzed chicken extract (ProBeptigen®) on cognitive function in healthy middle-aged people: a randomized double-blind trial, *Nutrients*, 2020, **12**, 1362.
- 63 E. Gravesteyn, J. J. Adam, R. P. Mensink, B. Winkens and J. Plat, Effects of the egg protein hydrolysate NWT-03 on cognitive function in men and women with the metabolic syndrome: a randomized, double-blind, placebo-controlled study, *Nutr. Neurosci.*, 2023, **26**, 1212–1221.
- 64 R. H. Karlsen, J. E. Karr, S. B. Saksvik, A. J. Lundervold, O. Hjemdal, A. Olsen, G. L. Iverson and T. Skandsen, Examining 3-month test-retest reliability and reliable change using the Cambridge neuropsychological test automated battery, *Appl. Neuropsychol. Adult*, 2022, **29**, 146–154.
- 65 B. Williams, G. Mancina, W. Spiering, E. Agabiti Rosei, M. Azizi, M. Burnier, D. L. Clement, A. Coca, G. de Simone, A. Dominiczak, T. Kahan, F. Mahfoud, J. Redon, L. Ruilope, A. Zanchetti, M. Kerins, S. E. Kjeldsen, R. Kreutz, S. Laurent, G. Y. H. Lip, R. McManus, K. Narkiewicz, F. Ruschitzka, R. E. Schmieder, E. Shlyakhto, C. Tsioufis, V. Aboyans, I. Desormais and E. S. D. Group, 2018 ESC/ESH guidelines for the management of arterial hypertension: the task force for the management of arterial hypertension of the European Society of Cardiology (ESC) and the European Society of Hypertension (ESH), *Eur. Heart J.*, 2018, **39**, 3021–3104.
- 66 P. Jendricke, J. Kohl, C. Centner, A. Gollhofer and D. König, Influence of specific collagen peptides and concurrent training on cardiometabolic parameters and performance indices in women: a randomized controlled trial, *Front. Nutr.*, 2020, **7**, 580918.

