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The association between meat consumption and the metabolic syndrome: a cross-sectional study and meta-analysis

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Abstract

The findings regarding the associations between red meat, fish and poultry consumption, and the metabolic syndrome (Mets) have been inconclusive, and evidence from Chinese populations is scarce. A cross-sectional study was performed to investigate the associations between red meat, fish and poultry consumption, and the prevalence of the Mets and its components among the residents of Suzhou Industrial Park, Suzhou, China. A total of 4424 participants were eligible for the analysis. A logistic regression model was used to estimate the OR and 95 % CI for the prevalence of the Mets and its components according to red meat, fish and poultry consumption. In addition, the data of our cross-sectional study were meta-analysed under a random effects model along with those of published observational studies to generate the summary relative risks (RR) of the associations between the highest *v.* lowest categories of red meat, fish and poultry consumption and the Mets and its components. In the cross-sectional study, the multivariable-adjusted OR for the highest *v.* lowest quartiles of consumption was 1·23 (95 % CI 1·02, 1·48) for red meat, 0·83 (95 % CI 0·72, 0·97) for fish and 0·93 (95 % CI 0·74, 1·18) for poultry. In the meta-analysis, the pooled RR for the highest *v.* lowest categories of consumption was 1·20 (95 % CI 1·06, 1·35) for red meat, 0·88 (95 % CI 0·81, 0·96) for fish and 0·97 (95 % CI 0·85, 1·10) for poultry. The findings of both cross-sectional studies and meta-analyses indicated that the association between fish consumption and the Mets may be partly driven by the inverse association of fish consumption with elevated TAG and reduced HDL-cholesterol and, to a lesser extent, fasting plasma glucose. No clear pattern of associations was observed between red meat or poultry consumption and the components of the Mets. The current findings add weight to the evidence that the Mets may be positively associated with red meat consumption, inversely associated with fish consumption and neutrally associated with poultry consumption.

Key words: The metabolic syndrome: Meat: Fish: Poultry: Cholesterol: Blood pressure: Glucose

The metabolic syndrome (Mets) is a cluster of risk factors for type 2 diabetes mellitus and CVD. These risk factors include elevated fasting plasma glucose, elevated blood pressure, elevated TAG, reduced HDL-cholesterol and elevated waist circumference[1]. Dietary factors have been implicated in the cause and prevention of the Mets. Plant-based dietary patterns have been recommended for the prevention and management of the Mets[2]. In contrast, Western-style dietary patterns, which are characterised by a high intake of fats, added sugars, animal-sourced foods and refined carbohydrates, have been suggested to contribute to the development of the Mets[2].

The associations between red meat, fish and poultry consumption are inconclusive and difficult to interpret in aggregate. The associations between red meat[3–16] and fish[17–30] consumption, and the Mets have been inconsistent across different study populations. Some, but not all, studies have

Abbreviations: JIS, joint interim statement; Mets, metabolic syndrome; NCEP-ATP III, National Cholesterol Education Program Adult Treatment Panel III; RR, relative risk.

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demonstrated a positive correlation with high red meat consumption[4,5,7–9,12,14,15] and a negative correlation with high fish consumption[19,21,24,25,27,28,30]. Although the lack of an association between poultry consumption and the Mets has been consistently observed in a few studies[3,6,11,29], their findings need to be replicated and confirmed in different populations.

Evidence on the associations between red meat[9,12,15], fish[29] and poultry[29] consumption, and the Mets in Chinese populations is limited. Moreover, nearly all previous studies[9,12,29] on the topic have investigated red meat, fish or poultry consumption as one of the variables that might be associated with the Mets but not as the main exposure of interest. Thus, variables adjusted in their multivariable analysis may not be appropriate to study the association of red meat, fish and poultry consumption with the Mets. Notably, dietary factors have rarely been adjusted[9,12,29]. Furthermore, no studies have investigated the influence of red meat, fish and poultry consumption on Mets components in Chinese populations. Red meat[8,13], fish[24] and poultry[8] have been shown to have distinct associations with components of the Mets in non-Chinese populations.

To refine and expand upon the evidence of the associations between red meat, fish and poultry consumption, and the Mets in Chinese populations, we conducted a cross-sectional study to investigate the associations between red meat, fish and poultry consumption, and the prevalence of the Mets and its components among the residents of Suzhou Industrial Park, which represent Southeast Chinese populations. Furthermore, the availability of published observational studies on the associations between red meat, fish and poultry consumption, and the Mets offers an opportunity to facilitate a meta-analysis of observational studies that could help understand and interpret these inconclusive associations.

Methods

The present study

Study population. The participants of the present cross-sectional study were random samples of the residents of Suzhou Industrial Park (Suzhou City, Jiangsu Province) aged 18 years and older. They were recruited (on a volunteer basis) to undergo a physical examination, provide overnight fasting blood samples and complete a brief interview at hospitals and health examination centres throughout Suzhou Industrial Park between July 2013 and November 2014[31]. A total of 7998 individuals agreed to participate. Of these 7998 participants, 1339 participants with missing information on red meat, fish and poultry consumption and 2235 participants with missing information on any component of the Mets were excluded. Finally, a total of 4424 participants were eligible for the present analysis. The study protocol was approved by the Ethics Committee of Soochow University. All participants signed an informed consent form.

Data collection. All participants underwent structured interviews, fasting venepuncture and measurement of blood pressure and anthropometrics at enrolment. All interviews, examinations, sample collections and measurements were performed by trained personnel. All study participants were individually interviewed from a structured questionnaire for information on demographic characteristics (age, sex and education level), behavioural characteristics (alcohol consumption, smoking status, physical activity, sleep duration and television watching duration), food group consumption (see section Dietary assessment) and the use of medications for diabetes, dyslipidaemia or hypertension.

Dietary assessment. Dietary information was obtained using an interviewer-administered FFQ[31]. During the interview, the participants were questioned about the frequency and portion size of several food groups (red meat, fish, poultry, fruits, vegetables, soya, nuts, salted vegetables and milk) consumed in the past year. The red meat group included pork, beef, mutton, lamb and goat. The poultry group included chicken, goose and duck. The fish group included freshwater fish and saltwater fish. The FFQ was not designed to differentiate fresh red meat, fish and poultry from processed red meat, fish and poultry. Therefore, the current data did not allow further stratification according to the extent of processing (fresh *v.* processed).

Blood samples and anthropometric measurements. Overnight-fasted (10–12 h) blood samples were drawn by venepuncture for measurement. The concentrations of glucose, total cholesterol, TAG, HDL-cholesterol and LDL-cholesterol in serum were measured enzymatically using an autoanalyser (Olympus AU640). Seated blood pressure was measured three times using a manual mercury sphygmomanometer (Shanghai Zhangdong Med-Tech Ltd). Anthropometrics were measured by trained personnel according to standard protocols. Height and waist circumference were measured to the nearest 0·1 cm, while weight was taken to the nearest 0·1 kg. BMI was calculated by dividing weight in kg by height in metres squared.

Metabolic syndrome definition. The Mets was defined according to the joint interim statement (JIS) of the International Diabetes Federation, National Heart, Lung, and Blood Institute, American Heart Association, World Heart Federation, International Atherosclerosis Society and International Association for the Study of Obesity[1]. Participants were considered to have the Mets if they had three or more of the following components:

1. Elevated waist circumference for Asian populations (≥90 cm in men and ≥80 cm in women).
2. Elevated TAG (≥150 mg/dl (1·7 mmol/l) or on drug treatment for elevated TAG).
3. Reduced HDL-cholesterol (<40 mg/dl (1·04 mmol/l) in men and <50 mg/dl (1·3 mmol/l) in women or on drug treatment for reduced HDL-cholesterol).
4. Elevated blood pressure (≥130 mmHg systolic or ≥85 mmHg diastolic or taking antihypertensive medications).
5. Elevated fasting blood glucose (≥100 mg/dl (5·6 mmol/l) or taking glucose-lowering medications).

Data analysis. The frequency of food consumption was recorded as never, less than once/month, 1–3 times/month, 1–2 times/week, 3–4 times/week, 5–6 times/week, 1 time/d or ≥1 time/d. The portion size of food consumed was estimated

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using traditional Chinese weight units (i.e. 1 jin = 0·5 kg; 1 liang = 50 g). The average daily consumption (g/d) of each food group was estimated by multiplying the standard portion size (g) by the consumption frequency for each food to obtain daily consumption. The participants were categorised into quartiles according to the average daily consumption of red meat, fish and poultry. A χ^2 test (categorical variables) and one-way ANOVA (continuous variables) were used to assess the difference in participant characteristics across the quartiles of red meat, fish and poultry consumption. A multivariable logistic regression model was applied to estimate the OR and 95 % CI for the prevalence of the Mets and its components according to red meat, fish and poultry consumption. The first quartile of red meat, fish and poultry consumption was assigned as the reference category. The multivariable models were adjusted for age, sex, education, smoking, alcohol consumption, physical activity, sleep duration, television watching duration, BMI and consumption of fruits, vegetables, nuts, soya, milk and salted vegetables. All statistical analyses were performed using SPSS version 20.0 (SPSS Inc.). All *P*-values were two-sided, and the level of significance was set at <0·05.

Meta-analysis

We performed a meta-analysis that included data from the present study and published observational studies. The research question was defined by the participants, interventions, comparisons, outcomes and study design (online Supplementary Table S1). Briefly, observational studies (cross-sectional and cohort studies) that reported risk estimates (hazard ratios, relative risks (RR) or ORs) with their corresponding 95 % CI were performed to quantify the association between red meat, fish and poultry consumption, and the Mets and its components in adults. The PubMed and Web of Science databases were searched for relevant observational studies published in any language from their inception until 31 December 2020. The following search terms were employed to identify the relevant studies: (meat OR fish OR poultry) AND (metabolic syndrome OR insulin resistance syndrome). The maximally adjusted risk estimates were extracted from each eligible study. For greater statistical ease and simplicity, any risk estimate reported in the included studies was considered equivalent to the RR. The Newcastle Ottawa Scale[32] was used to assess the quality of the included studies. A random effects model[33] was used to estimate the summary RR with their corresponding CI for the associations between the highest *v.* lowest category of red meat, fish and poultry consumption, and the Mets and its components. Subgroup and meta-regression analyses were performed according to the predefined criteria (study design, geographic region, country, Mets criteria, sex, subtypes of exposure and adjustment for total energy intake, BMI, physical activity, alcohol intake, smoking and consumption of vegetables, fruits, milk/dairy, red meat or fish) to investigate the source of heterogeneity and potential effect modifiers. The statistical heterogeneity across studies was determined using the I^2 statistic, for which the degree of heterogeneity was classified using the following cut-off points: <25 % (low heterogeneity), 25–50 % (moderate heterogeneity) and >50 % (high heterogeneity)[34]. Publication bias was assessed using Begg's rank correlation test and Egger's linear regression test[35]. If publication bias was evident, the trim and fill method was performed to adjust the bias[36]. All statistical analyses were performed using STATA software, version 11.0 (STATA Corp.).

Results

The present study

The mean age of the study participants was 55 years. Among the study participants, 53 % were women, 95 % had less than a high school education, 77 % did not consume alcohol weekly and 78 % had never smoked. The characteristics of the study participants according to red meat, fish and poultry consumption are presented in Table 1. In general, the participants in higher quartiles of red meat, fish or poultry consumption were younger, consumed more alcohol, were more likely to be current smokers and had a lower BMI than those in the first quartile. Red meat consumption was inversely associated with vegetable consumption but positively associated with the consumption of fruits, soya, fish, poultry, salted vegetables and nuts. Fish consumption was inversely associated with salted vegetable consumption but positively associated with the consumption of fruits, vegetables, soya, red meat, poultry and nuts. Poultry consumption was positively associated with the consumption of fruits, vegetables, soya, red meat, fish, salted vegetables and nuts.

The multivariable-adjusted OR (95 % CI) for the prevalence of the Mets according to red meat, fish and poultry consumption are presented in Table 2. After adjustment for demographic characteristics, behavioural characteristics and food group consumption, the associations between red meat or fish consumption and the prevalence of the Mets were statistically significant only in the highest quartile. The participants in the highest quartile of red meat consumption had higher odds of having the Mets than those in the lowest quartile (OR 1·23, 95 % CI 1·02, 1·48), whereas participants in the highest quartile of fish consumption had lower odds of having the Mets than those in the lowest quartile (OR 0·83, 95 % CI 0·72, 0·97). The associations between red meat or fish consumption and the prevalence of the Mets appeared to be largely driven by the strong associations between red meat or fish consumption and the prevalence of certain components of the Mets. A higher odds of having elevated waist circumference was observed among participants in the top three quartiles of red meat consumption, whereas a lower odds of having elevated TAG, reduced HDL-cholesterol and elevated fasting blood glucose was observed among participants in the top three quartiles of fish consumption. Poultry consumption was not associated with the odds of having the Mets and its components.

Meta-analysis

The flow chart of the study selection process with the reasons for exclusion is presented in Supplementary Fig. S1. The reference list of the excluded studies is reported in Supplementary Appendix S1. There was complete agreement between the investigators regarding the results of database searches. A prospective cohort study[6] that was conducted in the same study cohort as the included study[21] was not selected owing to the lack of clarity regarding the exposure definition. A prospective

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Table 1. Characteristics of the study participants according to red meat, fish and poultry consumption
(Mean values and standard deviations)

	Red meat									Fish									Poultry								
	Q1 (*n* 1628)		Q2 (*n* 742)		Q3 (*n* 879)		Q4 (*n* 1175)			Q1 (*n* 1280)		Q2 (*n* 991)		Q3 (*n* 718)		Q4 (*n* 1435)			Q1 (*n* 1141)		Q2 (*n* 1073)		Q3 (*n* 1117)		Q4 (*n* 1093)		
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	*P**	Mean	SD	Mean	SD	Mean	SD	Mean	SD	*P**	Mean	SD	Mean	SD	Mean	SD	Mean	SD	*P**
Exposure of interests in g/d																											
Red meat	20·2	9·8	35·7	0·2	53·8	12·2	116·1	61·3	<0·001	32·3	35·2	50·4	39·8	35·2	16·3	90·9	61·5	<0·001	37·6	52·9	32·7	22·8	46·8	28·1	103·2	54·1	<0·001
Poultry	22·5	21·9	29·8	21·9	41·1	42·7	96·1	55·7	<0·001	19·9	18·2	30·0	12·5	37·7	33·1	87·5	61·5	<0·001	6·4	6·3	26·6	3·2	42·0	10·9	114·4	51·6	<0·001
Fish	38·7	40·8	65·0	45·9	108·1	65·2	52·5	59·9	<0·001	19·3	9·4	35·7	0·1	59·8	13·6	127·6	65·9	<0·001	52·7	66·9	35·8	24·8	53·6	38·4	116·9	60·9	<0·001
Demographic characteristic																											
Age in years	56·3	10·4	53·9	9·7	55·1	9·5	54·5	9·9	<0·001	57·2	10·5	53·3	9·1	54·9	9·8	54·8	9·9	<0·001	58·7	10·1	53·7	9·5	53·6	9·4	54·6	10·0	<0·001
	n	%	*n*	%	*n*	%	*n*	%		*n*	%	*n*	%	*n*	%	*n*	%		*n*	%	*n*	%	*n*	%	*n*	%	
Sex																											
Men	678	41·6	358	48·2	454	51·6	624	53·1	<0·001	575	44·9	493	49·7	334	46·5	712	49·6	0·043	478	41·9	482	44·9	600	53·7	554	50·7	<0·001
Women	950	58·4	384	51·8	425	48·4	551	46·9		705	55·1	498	50·3	384	53·5	723	50·4		663	58·1	591	55·1	517	46·3	539	49·3	
Education level																											
<High school	1562	95·9	697	93·9	823	93·6	1100	93·6	0·088	1232	96·3	927	93·5	682	95·0	1341	93·4	0·018	1103	96·7	1015	94·6	1036	92·7	1028	94·1	0·006
High school or vocational school	60	3·7	40	5·4	48	5·5	65	5·5		43	3·3	57	5·8	29	4·0	84	5·9		35	3·1	51	4·8	71	6·4	56	5·1	
≥College	6	0·4	5	0·7	8	0·9	10	0·9		5	0·4	7	0·7	7	1·0	10	0·7		3	0·2	7	0·6	10	0·9	9	0·8	
Behavioural characteristics																											
Physical activity in min/d									0·224									0·156									0·160
Mean	34·7		36·7		35·8		35·7			34·5		35·5		36·9		35·6			34·27		35·6		36·42		35·70		
SD	22·3		23·5		22·7		22·5			22·7		21·5		24·1		22·6			23·08		22·9		22·5		21·9		
Alcohol in times/week																											
0	1312	80·6	572	77·1	676	76·9	856	72·9	<0·001	1004	78·4	762	76·9	576	80·2	1074	74·8	<0·001	949	83·2	841	78·4	820	73·4	806	73·7	<0·001
1–3	105	6·4	73	9·8	68	7·7	179	15·2		109	8·5	72	7·3	51	7·1	193	13·5		78	6·8	74	6·9	103	9·2	170	15·6	
>3	193	11·9	91	12·3	121	13·8	135	11·5		143	11·2	152	15·3	88	12·3	157	10·9		101	8·9	150	14·0	180	16·1	109	10·0	
Unknown	18	1·1	6	0·8	14	1·6	5	0·4		24	1·9	5	0·5	3	0·4	11	0·8		13	1·1	8	0·7	14	1·3	8	0·7	
Smoking																											
Never	1170	71·9	470	63·3	595	67·7	786	66·9	<0·001	881	68·8	652	65·8	508	70·8	980	68·3	<0·001	823	72·1	722	67·3	730	65·3	746	68·3	<0·001
Former	49	3·0	19	2·6	13	1·5	27	2·3		46	3·6	18	1·8	14	1·9	30	2·1		42	3·7	26	2·4	18	1·6	22	2·0	
Current	363	22·3	231	31·1	258	29·3	336	28·6		308	24·1	306	30·9	182	25·3	392	27·3		234	20·5	303	28·2	356	31·9	295	27·0	
Unknown	46	2·8	22	3·0	13	1·5	26	2·2		45	3·5	15	1·5	14	2·0	33	2·3		42	3·7	22	2·1	13	1·2	30	2·7	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD		Mean	SD	Mean	SD	Mean	SD	Mean	SD		Mean	SD	Mean	SD	Mean	SD	Mean	SD	
Sleep duration in h/d	7·3	1·0	7·3	0·9	7·3	1·0	7·3	1·1	0·904	7·3	1·0	7·2	1·0	7·3	0·9	7·3	1·0	0·150	7·3	0·96	7·2	1·0	7·2	1·0	7·3	1·0	0·128
Television watching duration in h/d	4·1	2·9	4·3	2·9	3·9	2·9	4·1	2·9	0·107	4·3	2·9	4·2	2·9	3·9	3·0	4·0	2·9	0·059	4·1	2·9	4·3	2·9	3·9	2·9	4·1 2·9		0·074
Other food groups in g/d																											
Fruits	61·6	75·9	130·8	113·0	109·6	114·0	143·3	108·9	<0·001	63·8	82·6	98·9	103·3	110·7	107·9	143·5	110·7	<0·001	64·9	86·4	68·2	75·1	134·9	116·9	152·6	109·1	<0·001
Vegetables	262·6	124·1	360·3	299·7	314·2	153·7	144·2	169·0	<0·001	264·9	139·7	268·5	105·8	299·5	132·9	367·7	173·8	<0·001	263·9	127·7	284·9	120·8	292·4	138·1	378·7	184·0	<0·001
Soya	26·2	40·9	28·7	55·2	37·7	52·5	96·7	64·9	<0·001	23·8	43·8	27·6	23·8	32·8	33·1	89·9	77·4	<0·001	24·8	44·9	25·2	38·9	34·9	36·4	106·1	72·8	<0·001
Milk	20·8	76·8	20·8	52·9	18·9	58·6	19·4	65·8	0·885	21·5	58·8	18·7	81·3	20·5	61·4	19·5	65·2	0·771	22·6	64·8	18·5	53·0	21·3	81·1	17·7	64·9	0·267
Nuts	8·4	12·8	8·9	12·3	7·2	12·9	9·5	32·0	0·088	7·5	22·5	8·7	13·9	8·3	23·9	10·2	11·5	0·016	6·7	20·6	10·2	12·8	9·0	12·2	8·3	28·8	<0·001
Salted vegetables	14·5	16·3	16·4	16·4	17·7	21·7	41·8	51·5	<0·001	38·5	48·5	16·5	18·4	16·5	17·2	13·3	15·5	<0·001	14·8	35·9	14·8	11·9	17·8	20·2	43·7	43·2	<0·001
BMI in kg/m^2	24·5	3·2	23·5	2·9	23·8	2·9	23·7	2·9	<0·001	24·8	3·2	23·5	3·0	23·8	2·9	23·7	2·9	<0·001	24·9	3·1	23·9	3·2	23·5	2·8	23·6	2·9	<0·001

* The *P* values for differences between quartiles were calculated using χ^2 test (categorical variables) and one-way ANOVA (continuous variables).

Table 2. Multivariable-adjusted OR (95 % CI)* for the prevalence of the metabolic syndrome and its components according to red meat, fish and poultry consumption
(Numbers and percentages; odds ratio and 95 % confidence intervals)

		Red meat				Fish				Poultry			
		Q1 (*n* 1628)	Q2 (*n* 742)	Q3 (*n* 879)	Q4 (*n* 1175)	Q1 (*n* 1280)	Q2 (*n* 991)	Q3 (*n* 718)	Q4 (*n* 1435)	Q1 (*n* 1141)	Q2 (*n* 1073)	Q3 (*n* 1117)	Q4 (*n* 1093)
The metabolic syndrome	*n*	735	328	431	588	641	493	330	618	532	512	552	486
	%	45	44	49	50	50	50	46	47		48	49	44
	OR	1 (ref.)	1·04	1·17	**1·23**	1 (ref.)	0·99	0·95	**0·83**	1 (ref.)	0·95	1·09	0·93
	95 % CI		0·83, 1·29	0·97, 1·42	**1·02, 1·48**		0·85, 1·18	0·79, 1·14	**0·72, 0·97**		0·79, 1·14	0·90, 1·31	0·74, 1·18
Elevated waist circumference	*n*	847	423	554	717	727	561	440	813	608	613	661	659
	%	52	57	63	60	57	57	61	57	53	57	59	60
	OR	1 (ref.)	**1·26**	**1·48**	**1·40**	1 (ref.)	0·96	1·04	1·00	1 (ref.)	1·11	1·17	1·20
	95 % CI		**1·06, 1·49**	**1·23, 1·76**	**1·19, 1·64**		0·81, 1·13	0·87, 1·25	0·86, 1·16		0·94, 1·35	0·98, 1·43	0·96, 1·43
Elevated TAG	*n*	602	242	317	448	501	340	243	525	437	385	393	394
	%	37	38	36	38	39	34	34	36	38	36	35	36
	OR	1 (ref.)	1·05	0·98	1·07	1 (ref.)	**0·79**	**0·79**	**0·82**	1 (ref.)	0·92	0·91	0·97
	95 % CI		0·87, 1·25	0·84, 1·16	0·90, 1·23		**0·65, 0·95**	**0·65, 0·97**	**0·70, 0·97**		0·75, 1·12	0·74, 1·12	0·75, 1·25
Reduced HDL-cholesterol	*n*	963	454	578	673	824	576	438	830	733	678	653	604
	%	59	61	61	57	64	58	61	58	64	63	58	55
	OR	1 (ref.)	1·09	1·11	0·95	1 (ref.)	**0·73**	**0·82**	**0·75**	1 (ref.)	1·00	0·93	0·79
	95 % CI		0·91, 1·30	0·94, 1·33	0·72, 1·10		**0·61, 0·86**	**0·68, 0·99**	**0·65, 0·88**		0·79, 1·26	0·73, 1·19	0·58, 1·09
Elevated blood pressure	*n*	881	410	504	622	698	573	396	750	695	584	592	546
	%	54	55	57	53	54	58	55	52	61	54	53	50
	OR	1 (ref.)	1·07	1·16	1·01	1 (ref.)	1·00	0·97	0·93	1 (ref.)	0·89	0·86	0·80
	95 % CI		0·90, 1·27	0·98, 1·37	0·87, 1·17		0·84, 1·19	0·78, 1·15	0·79, 1·07		0·68, 1·17	0·66, 1·12	0·68, 1·03
Elevated fasting blood glucose	*n*	717	341	416	526	645	447	317	591	540	511	481	468
	%	44	46	47	45	50	45	44	41	47	48	43	43
	OR	1 (ref.)	1·08	1·12	1·06	1 (ref.)	**0·78**	**0·75**	**0·69**	1 (ref.)	0·99	0·86	0·89
	95 % CI		0·91, 1·29	0·95, 1·33	0·92, 1·22		**0·66, 0·93**	**0·65, 0·90**	**0·59, 0·80**		0·82, 1·19	0·71, 1·04	0·70, 1·14

Bold numbers indicate statistical significance ($P < 0·05$).
* Adjusted for age, sex, education, smoking, alcohol, physical activity, sleep duration, television watching duration, BMI and consumption of fruits, vegetables, nuts, soya, milk and salted vegetables; in addition, red meat, fish and poultry consumption were adjusted for one another.

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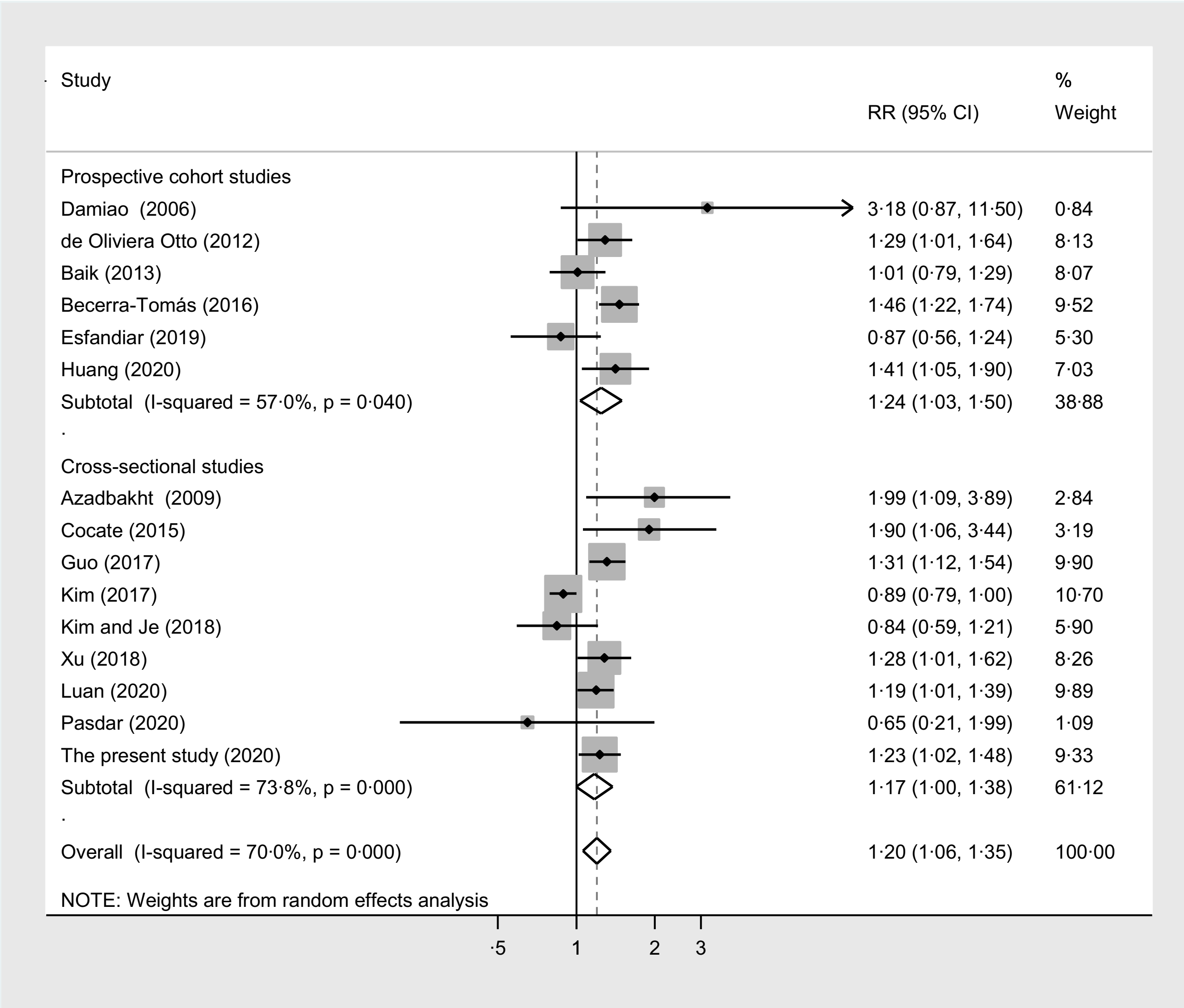

Fig. 1. The association between the highest *v.* lowest categories of red meat consumption and the metabolic syndrome. Weights are from random effects analysis. The I-squared describes the percentage of variation across studies that is due to heterogeneity rather than chance. The *P* value for heterogeneity was calculated from the Q test. RR, relative risk.

cohort study[8] that investigated the association between the consumption of poultry and rabbits and the Mets was excluded from the analysis of poultry consumption because rabbits are not considered poultry, which are domesticated birds kept by humans for their eggs, meat or feathers. A cross-sectional study[16] on the association between poultry and fish consumption and the Mets was not included in the analysis of either fish or poultry because poultry and fish were combined as a single exposure.

In addition to the present cross-sectional study, twenty-eight other observational studies (nine cohort studies[3,5,6,8,13,15,21,25,30] and nineteen cross-sectional studies[4,7,9–12,14,16–20,22–24,26–29]) were also included in the meta-analysis of the associations between the highest *v.* lowest categories of red meat[3–16], fish[17–30] and poultry[3,6,11,29] consumption, and the Mets. The duration of follow-up in the cohort studies ranged from 3·6 to 25 years. Dietary information was assessed using an FFQ in all studies. Although all studies reported adjusted risk estimates, there was substantial variation in the selection and number of variables controlled across studies.

The characteristics of the included studies are summarised in Supplementary Tables S2–S4. Nearly all the studies (26 of 28) were considered to be of good quality (The Newcastle Ottawa Scale ≥ 7) (online Supplementary Tables S5 and S6).

In the meta-analysis of the highest *v.* lowest categories of consumption, high red meat consumption was positively associated with the Mets (RR 1·20, 95 % CI 1·06, 1·35; Fig. 1), whereas high fish consumption was inversely associated with the Mets (RR 0·88, 95 % CI 0·81, 0·96; Fig. 2). No association was observed between high poultry consumption and the Mets (RR 0·97, 95 % CI 0·85, 1·10; Fig. 3). Moderate heterogeneity was observed in the analysis of poultry ($I^2 = 42\,\%$), while high heterogeneity was evident in the analyses of red meat and fish ($I^2 \geq 70\,\%$). There was no evidence of publication bias (all *P* Begg's ≥ 0·48; all *P* Egger's ≥ 0·27).

The subgroup and meta-regression analyses of the associations between the highest *v.* lowest categories of red meat, fish and poultry consumption, and the Mets are presented in Table 3.

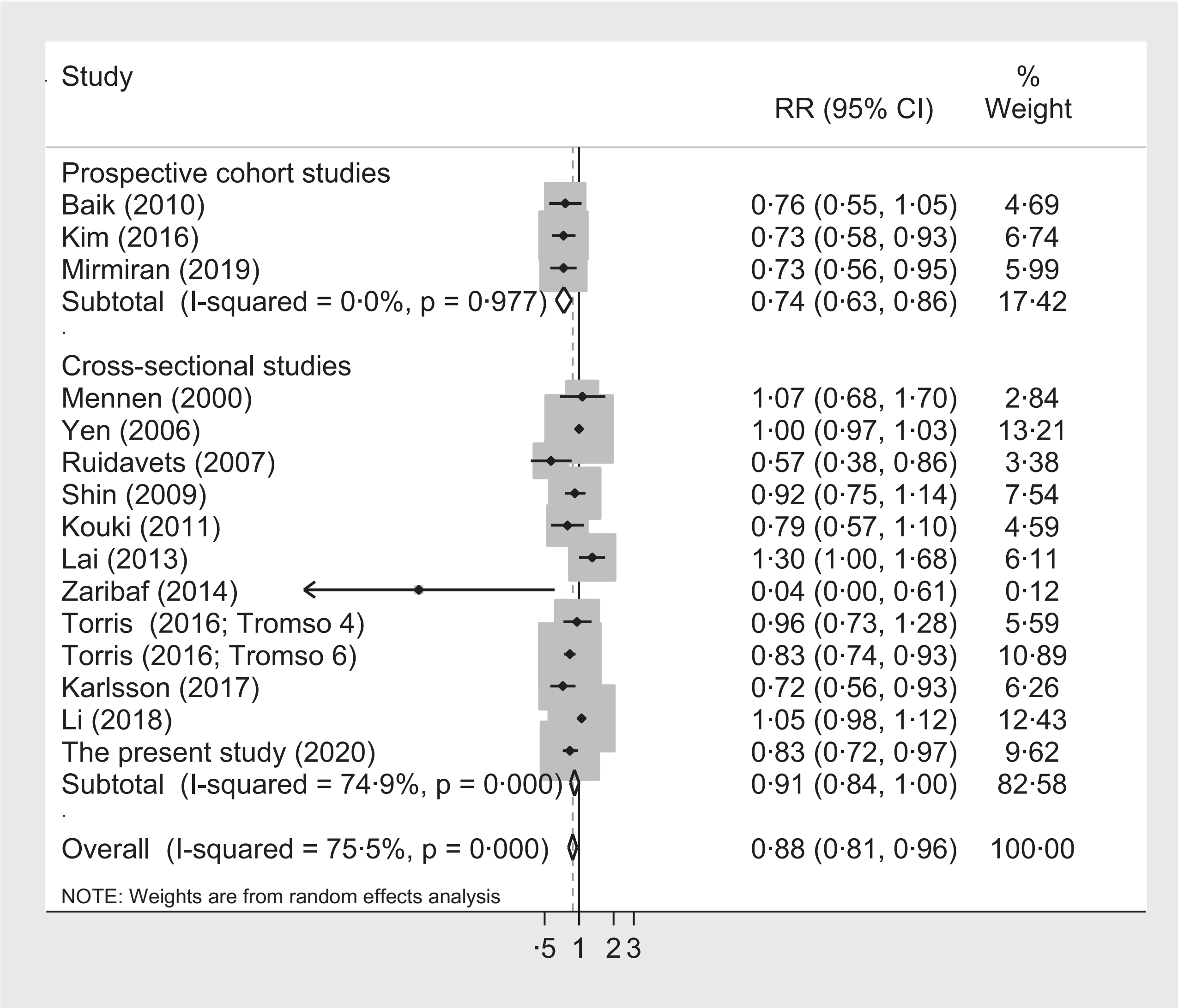

Fig. 2. The association between the highest *v.* lowest categories of fish consumption and the metabolic syndrome. Weights are from random effects analysis. The I-squared describes the percentage of variation across studies that is due to heterogeneity rather than chance. The *P* value for heterogeneity was calculated from the Q test. RR, relative risk.

The lack of an association between high poultry consumption and the Mets was consistently observed across subgroups. A tendency towards positive and inverse associations was observed across subgroups with high red meat consumption and high fish consumption, respectively. Although meta-regression analyses revealed that the overall associations between high consumption of red meat or fish and the Mets did not appear to be modified by study design, region, Mets criteria, subtypes of exposure and adjustment for certain variables (all P meta-regression $\geq 0{\cdot}10$), these associations did not consistently reach statistical significance throughout the subgroups. Stratification by study design did not significantly alter the association between high consumption of red meat or fish and the Mets. The association between high consumption of red meat or fish and the Mets became statistically non-significant after stratification by sex. A significant association between high consumption of red meat or fish and the Mets was evident only in the studies that used the JIS criteria (but not the National Cholesterol Education Program Adult Treatment Panel III (NCEP-ATP III) criteria) and in the studies that were conducted in American and European countries (but not Asian countries). In the country-specific meta-analysis, a positive association between high red meat consumption and the Mets was observed in Chinese and Brazilian studies. The inverse association between high fish consumption and the Mets was observed in Norwegian studies. By subtype of exposure, high consumption of processed or unprocessed red meat was positively associated with the Mets; in addition, higher lean fish, but not fatty fish, consumption was inversely associated with the Mets. The association between red meat or fish consumption and the Mets was nullified in the studies that adjusted for certain variables (BMI for red meat and consumption of vegetables or fruits for fish).

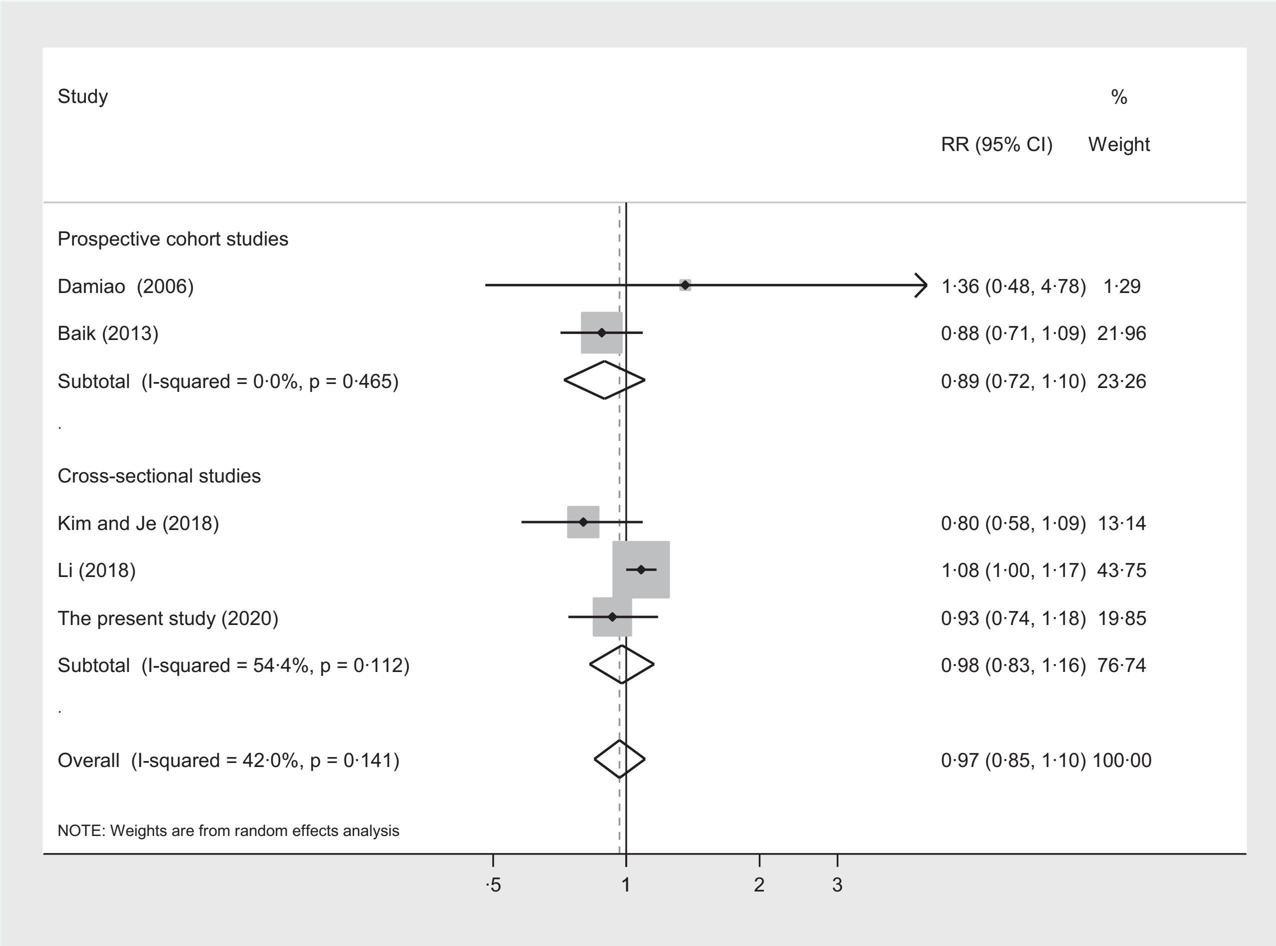

Fig. 3. The association between the highest *v.* lowest categories of poultry consumption and the metabolic syndrome. Weights are from random effects analysis. The I-squared describes the percentage of variation across studies that is due to heterogeneity rather than chance. The *P* value for heterogeneity was calculated from the Q test. RR, relative risk.

In the analyses of the components of the Mets, high red meat consumption was not associated with any components of the Mets (Fig. 4). High fish consumption was inversely associated with elevated TAG, reduced HDL-cholesterol and elevated fasting plasma glucose (Fig. 5). High poultry consumption was inversely associated with elevated blood pressure (Fig. 6).

Discussion

The present study

Our findings are in line with the majority of previous studies in non-Chinese populations and showed that the Mets was positively associated with red meat consumption[4,5,7,8,14], inversely associated with fish consumption[19,21,24,25,27,28,30] and not associated with poultry consumption[3,6,11]. Furthermore, the present cross-sectional study adds to the limited evidence available on the associations between red meat[9,12,15], fish[29] and poultry[29] consumption, and the Mets in Chinese populations. The present data replicate and extend previous research findings that high red meat consumption (>100 g/d) is positively associated with the Mets in Chinese adults[9,12,15]. Only one study[29] has investigated the association between fish or poultry consumption and the Mets in Chinese adults. The lack of an association between poultry consumption and prevalent Mets was observed in our study and a previous cross-sectional study[29]. However, our results of the reduced prevalence of the Mets among participants with the highest levels of fish consumption are in contrast with the null association between fish consumption and the prevalence of the Mets that was observed in a previous cross-sectional study[29]. Since both studies used comparable study designs and cut-offs for the identification of Mets cases, the discrepancy in these findings could be partly explained by the lack of adjustment for dietary variables, particularly consumption of other food groups, in the previous cross-sectional study[29].

The associations between red meat[9,12,15], fish[29] and poultry[29] consumption, and the components of the Mets have not been reported in previous Chinese studies. In the present study, the inverse association between fish consumption and the prevalence of the Mets appeared to be mainly driven by reduced prevalence of elevated TAG, reduced HDL-cholesterol and elevated fasting blood glucose. The positive association between red meat consumption and the prevalence of the Mets appeared to be largely driven by increased prevalence of elevated waist circumference. A relatively similar (but not identical) pattern

Table 3. Subgroup and meta-regression analyses of the associations between the highest *v.* lowest categories of red meat, fish and poultry consumption and the metabolic syndrome (Risk ratios (RR) and 95 % confidence intervals)

	Red meat					Fish					Poultry				
	No. of studies*	RR	95 % CI	I^2, %‡	*P*§	No. of studies*	RR	95 % CI	I^2, %‡	*P*§	No. of studies*	RR	95 % CI	I^2, %‡	*P*§
Overall	14 + 1	**1·20**	**1·06, 1·35**	70	–	14 + 1	**0·88**	**0·81, 0·96**	75·5	–	4 + 1	0·97	0·85, 1·10	42	–
Study design															
Prospective cohort	6	**1·24**	**1·03, 1·50**	57	0·65	3	**0·74**	**0·63, 0·86**	0	0·16	2	0·89	0·72, 1·10	0	0·67
Cross-sectional	8 + 1	**1·17**	**1·00, 1·38**	73·8		11 + 1	**0·91**	**0·84, 1·00**	74·9		2 + 1	0·98	0·83, 1·16	54·4	
Geographic region															
Europe and America	5	**1·35**	**1·16, 1·57**	34·9	0·12	8	**0·85**	**0·73, 0·99**	63·6	0·68	1	1·36	0·43, 4·29	–	–
Asia	9 + 1	1·12	0·96, 1·30	70·6		6 + 1	0·92	0·84, 1·01	74		3 + 1	0·96	0·83, 1·10	55	
Country															
China	3 + 1	**1·29**	**1·17, 1·43**	0	0·28	1 + 1	0·94	0·75, 1·19	87·4	0·28	1 + 1	1·05	0·93, 1·18	29·4	
South Korea	3	0·91	0·82, 1·00	0		2	0·87	0·73, 1·04	0		2	0·85	0·72, 1·02	0	
Iran	3	1·10	0·58, 2·06	63·2		2	0·23	0·01, 3·69	80·3		–	NA		–	
Brazil	2	**2·08**	**1·22, 3·55**	0		–	NA		–		–	NA		–	
Norway	–	NA		–		3	**0·83**	**0·74, 0·92**	10·5		–	NA		–	
France	–	NA		–		2	0·77	0·42, 1·43	75·3		–	NA		–	
Metabolic syndrome criteria															
JIS	10 + 1	**1·20**	**1·06, 1·36**	74·1	0·82	6 + 1	**0·85**	**0·74, 0·97**	78	0·76	1	1·36	0·43, 4·29	–	–
NCEP-ATP III	3	1·53	0·72, 3·24	71·9		7	0·87	0·72, 1·05	77·4		3 + 1	0·96	0·83, 1·10	55	
Sex															
Men	5	1·15	0·72, 1·84	68	0·90	8	0·90	0·80, 1·01	71·8	0·64	3	1·06	0·94, 1·19	0	0·89
Women	3	1·08	0·65, 1·81	78·5		6	0·94	0·76, 1·17	57·5		2	1·02	0·80, 1·31	35·6	
Subtypes of exposure															
Processed red meat	4	**1·18**	**1·03, 1·35**	42·7	0·68	–	NA		–	–	–	NA		–	–
Unprocessed red meat	4	**1·22**	**1·09, 1·38**	38		–	NA		–		–	NA		–	
Fatty fish	–	NA		–	–	3	0·98	0·79, 1·23	79·4	0·32	–	NA		–	–
Lean fish	–	NA		–		3	**0·86**	**0·78, 0·94**	0		–	NA		–	
Adjustment															
Total energy intake															
Yes	11	**1·19**	**1·01, 1·40**	75·4	0·40	8	**0·79**	**0·63, 0·99**	71·8	0·27	3	0·86	0·72, 1·03	0	0·13
No	3 + 1	**1·27**	**1·14, 1·41**	0		6 + 1	0·93	0·86, 1·01	70·4		1 + 1	1·05	0·93, 1·18	29·4	
Vegetable consumption															
Yes	6 + 1	**1·23**	**1·10, 1·37**	49·6	0·79	5 + 1	0·88	0·73, 1·06	81·8	0·78	2 + 1	0·88	0·77, 1·01	0	0·09
No	8	1·21	0·95, 1·55	72		9	**0·86**	**0·75, 0·98**	71·6		2	1·08	1·00, 1·17	0	
Fruit consumption															
Yes	6 + 1	**1·23**	**1·10, 1·37**	49·6	0·79	4 + 1	0·92	0·76, 1·13	81·3	0·47	2 + 1	0·88	0·77, 1·01	0	0·09
No	8	1·21	0·95, 1·55	72		10	**0·84**	**0·74, 0·96**	72·4		2	1·08	1·00, 1·17	0	
Milk/dairy consumption															
Yes	4 + 1	**1·20**	**1·00, 1·47**	68·2	0·96	10	**0·83**	**0·68, 1·00**	79·7	0·67	2 + 1	0·88	0·77, 1·01	0	0·09
No	10	**1·20**	**1·02, 1·40**	71·7		4 + 1	0·88	0·78, 1·01	75·3		2	1·08	1·00, 1·17	0	
Red meat consumption															
Yes	–	NA		–	–	12	**0·75**	**0·51, 0·99**	65·2	0·45	2 + 1	0·88	0·77, 1·01	0	0·09
No	–	NA		–		2 + 1	**0·90**	**0·82, 0·98**	74·8		2	1·08	1·00, 1·17	0	
Fish consumption															
Yes	4 + 1	**1·17**	**1·01, 1·36**	61·6	0·69	–	Not Applicable		–	–	2 + 1	0·88	0·77, 1·01	0	0·09
No	10	**1·24**	**1·03, 1·5**	76·1		–	Not Applicable		–		2	1·08	1·00, 1·17	0	
BMI															
Yes	5 + 1	1·16	0·95, 1·42	60·9	0·73	6 + 1	**0·80**	**0·66, 0·96**	81·8	0·29	2 + 1	0·98	0·83, 1·16	54·4	0·67
No	9	**1·22**	**1·04, 1·44**	74		8	0·93	0·82, 1·05	69·8		2	0·89	0·72, 1·10	0	

Table 3. (*Continued*)

	Red meat					Fish					Poultry				
	No. of studies*	RR	95 % CI	I^2, %‡	P§	No. of studies*	RR	95 % CI	I^2, %‡	P§	No. of studies*	RR	95 % CI	I^2, %‡	P§
Physical activity or exercise															
Yes	11 + 1	**1·26**	**1·13, 1·41**	43·4	0·15	11 + 1	**0·87**	**0·79, 0·96**	80	0·77	4 + 1	0·97	0·85, 1·10	42	–
No	3	1·02	0·76, 1·38	86·8		3	0·90	0·77, 1·06	0		–	–	–	–	
Alcohol															
Yes	10 + 1	**1·26**	**1·15, 1·38**	37·1	0·11	9 + 1	**0·89**	**0·81, 0·98**	75·9	0·78	4 + 1	0·97	0·85, 1·10	42	–
No	4	0·99	0·72, 1·35	52·7		5	0·84	0·69, 1·03	54		–	–	–	–	
Smoking															
Yes	11 + 1	**1·24**	**1·12, 1·36**	42·6	0·10	10 + 1	**0·88**	**0·80, 0·97**	76·4	0·89	4 + 1	0·97	0·85, 1·10	42	–
No	3	1·09	0·60, 1·96	68·2		4	0·89	0·67, 1·16	60·2		–	–	–	–	

JIS, Joint Interim Statement; NA, Not applicable; NCEP-ATP III, National Cholesterol Education Program Adult Treatment Panel III; RR, relative risk.
Bold numbers indicate statistical significance ($P < 0·05$).
* +1 refers to the present cross-sectional study of the residents of Suzhou Industrial Park.
‡ I^2 describes the percentage of variation across studies that is due to heterogeneity rather than chance.
§ P value for heterogeneity between subgroups according to meta-regression analyses.

of associations between red meat[8,14] and fish[21,24,25] consumption and certain components of the Mets was also seen in non-Chinese populations.

Several caveats need to be considered when interpreting the results of the present cross-sectional study. First, cross-sectional data cannot be used to infer a causal relationship between exposure and outcome. Second, dietary information was collected using an FFQ, which is prone to biases related to memory and sincerity. Third, although we adjusted for major lifestyle factors and major food groups related to the Mets[2], the information on total energy intake and dietary nutrient intake was not assessed in the FFQ. Therefore, our inability to control potentially important dietary factors in our analyses may have led to an imprecise estimate of the true associations. Finally, the extent of processing, preparation methods and fat contents of the red meat, fish and poultry consumed could not be investigated in the present study. The influence of meat consumption on cardiometabolic health could vary depending on processing[37], preparation methods[38] and fat contents[25–27].

Meta-analysis

In the meta-analysis of the highest *v.* lowest categories of consumption, the Mets was positively associated with red meat and inversely associated with fish but was not associated with poultry. Similar findings were observed in both prospective cohort and cross-sectional studies. In the subgroup analyses, the lack of an association between poultry consumption and the Mets was observed across subgroups, while the association of red meat or fish consumption with the Mets did not reach significance in studies that used NCEP-ATP III criteria, in those that were conducted in Asian countries and in those that adjusted for certain variables (BMI for red meat and consumption of fruits or vegetables for fish).

The association between high red meat or fish consumption and the Mets was evident in the studies that used the JIS criteria but not in those that used the NCEP-ATP III criteria. The NCEP-ATP III criteria[39] have higher cut-offs for fasting blood glucose (≥6·1 mmol/l *v.* ≥5·6 mmol/l) and waist circumference (if not modified according to populations or ethnic groups) than the JIS criteria[1]. Therefore, fewer individuals could be diagnosed with the Mets if higher cut-offs were used (or vice versa), which may explain the weak association for the NCEP-ATP III criteria and strong association for the JIS criteria.

The association between high red meat or fish consumption and the Mets was only observed in the studies conducted in American and European countries but not in those conducted in Asian countries. The geographic discrepancies of the association between high red meat or fish consumption and the Mets could be partly explained by the differences in the amounts, frequency and species of red meat or fish consumed within and between populations.

The positive association between high red meat consumption and the Mets was not evident in the studies that adjusted for BMI, while the inverse association between high fish consumption and the Mets was not observed in the studies that adjusted for fruit or vegetable consumption. Cumulative epidemiological evidence suggests that red meat consumption is positively associated with adiposity measures (BMI and waist circumference)

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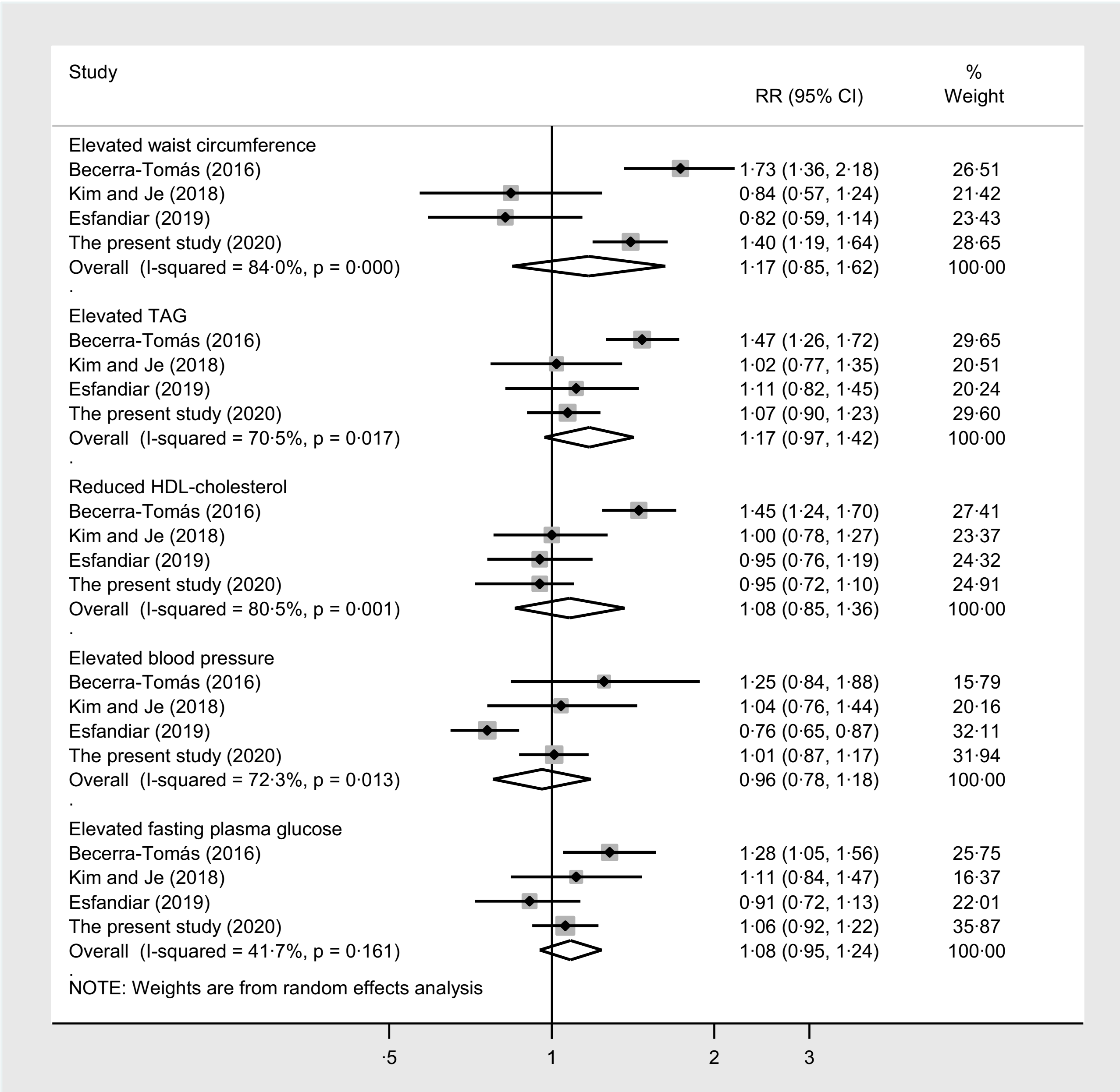

Fig. 4. The associations between the highest *v.* lowest categories of red meat consumption and the components of the metabolic syndrome. Weights are from random effects analysis. The I-squared describes the percentage of variation across studies that is due to heterogeneity rather than chance. The *P* value for heterogeneity was calculated from the Q test. RR, relative risk.

and obesity risk[40]. Excess adiposity is a well-established risk factor for cardiometabolic conditions. Thus, the positive association between red meat consumption and the Mets could have been confounded by BMI. There is evidence that fish consumption is positively associated with the consumption of foods perceived as healthy, particularly fruits and vegetables[41–43], in certain populations. High fruit or vegetable consumption has been shown to be inversely associated with the Mets[44]. Therefore, the inverse association between high fish consumption might be partly explained by the positive correlations of fish with fruits or vegetables.

No clear pattern of associations was observed between red meat or poultry consumption and Mets components. However, the association between high fish consumption and the Mets appeared to be partly driven by the inverse association of fish consumption with elevated TAG and reduced HDL-cholesterol and, to a lesser extent, fasting plasma glucose. Among individual studies investigating the association between fish consumption and the Mets, the inverse associations of high fish consumption with elevated TAG and reduced HDL-cholesterol were consistently observed in all studies[21,24,25], including our study; however, such

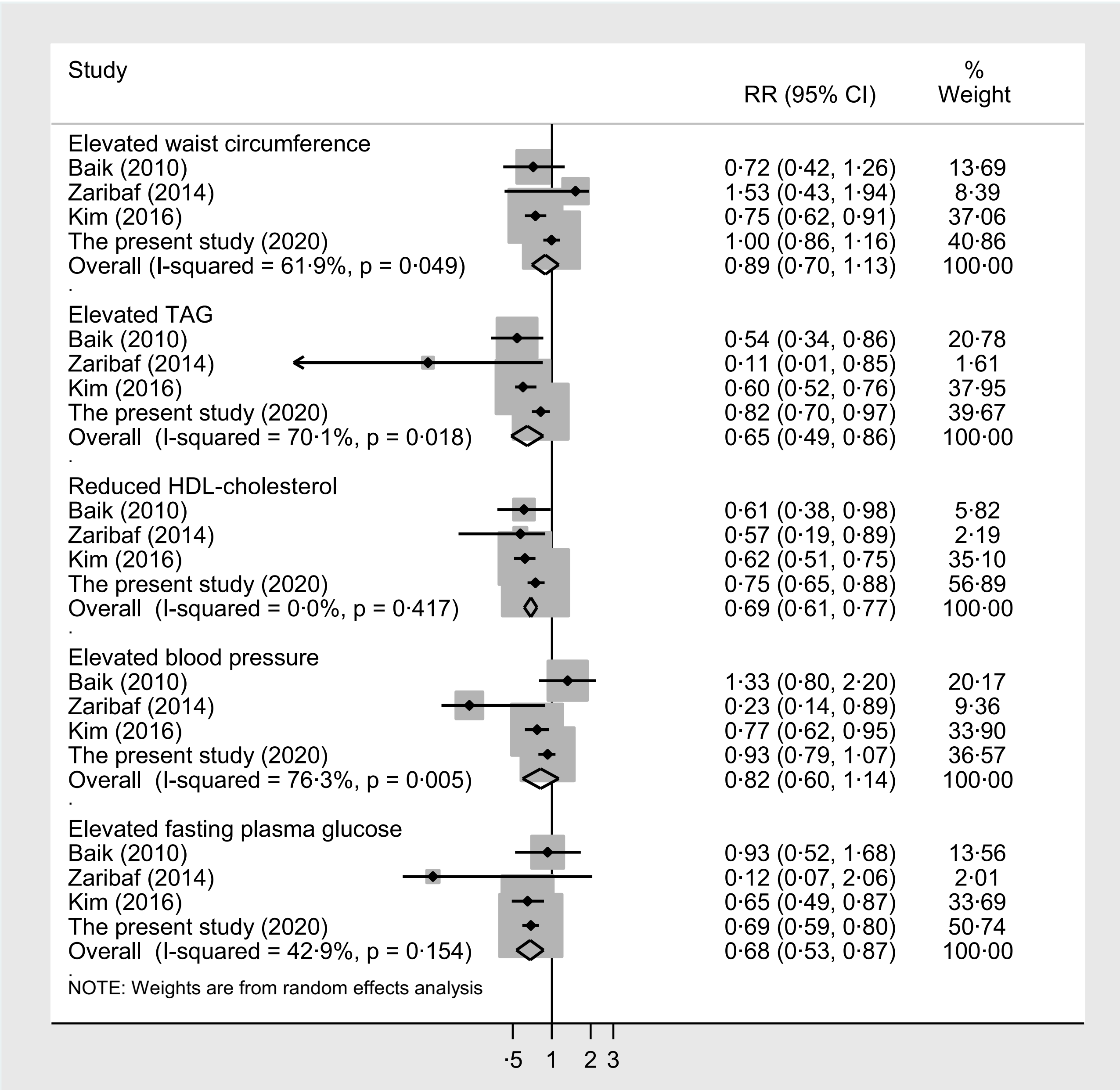

Fig. 5. The associations between the highest *v.* lowest categories of fish consumption and the components of the metabolic syndrome. Weights are from random effects analysis. The I-squared describes the percentage of variation across studies that is due to heterogeneity rather than chance. The *P* value for heterogeneity was calculated from the Q test. RR, relative risk.

associations were less consistently observed with other components of the Mets. The distinct influence of fish consumption on the components of the Mets could partly be explained by the differential effects of fish nutrients, such as marine *n*-3 fatty acids, on the components of the Mets. Fish, particularly fatty fish, are an important source of marine *n*-3 fatty acids, EPA and DHA[45]. Accumulating evidence from randomised controlled trials suggests that *n*-3 fatty acid supplementation[46] may reduce TAG levels and increase HDL-cholesterol levels. However, marine *n*-3 fatty acid supplementation fails to convincingly improve other components of the Mets[46–48].

There are several limitations to consider when interpreting the findings of the present meta-analysis of observational studies. First, the possibility that the observed findings might be due to residual or unmeasured confounders cannot be ruled out. Second, the limited number of available prospective cohort studies for each analysis limits the ability to draw more conclusive evidence. Third, the presence of heterogeneity in all analyses suggests that the results should be cautiously interpreted. Although we could not pinpoint the exact source of heterogeneity, the variations in the study and participant characteristics may contribute to differences in the strength and, in some cases, the direction of associations, leading to

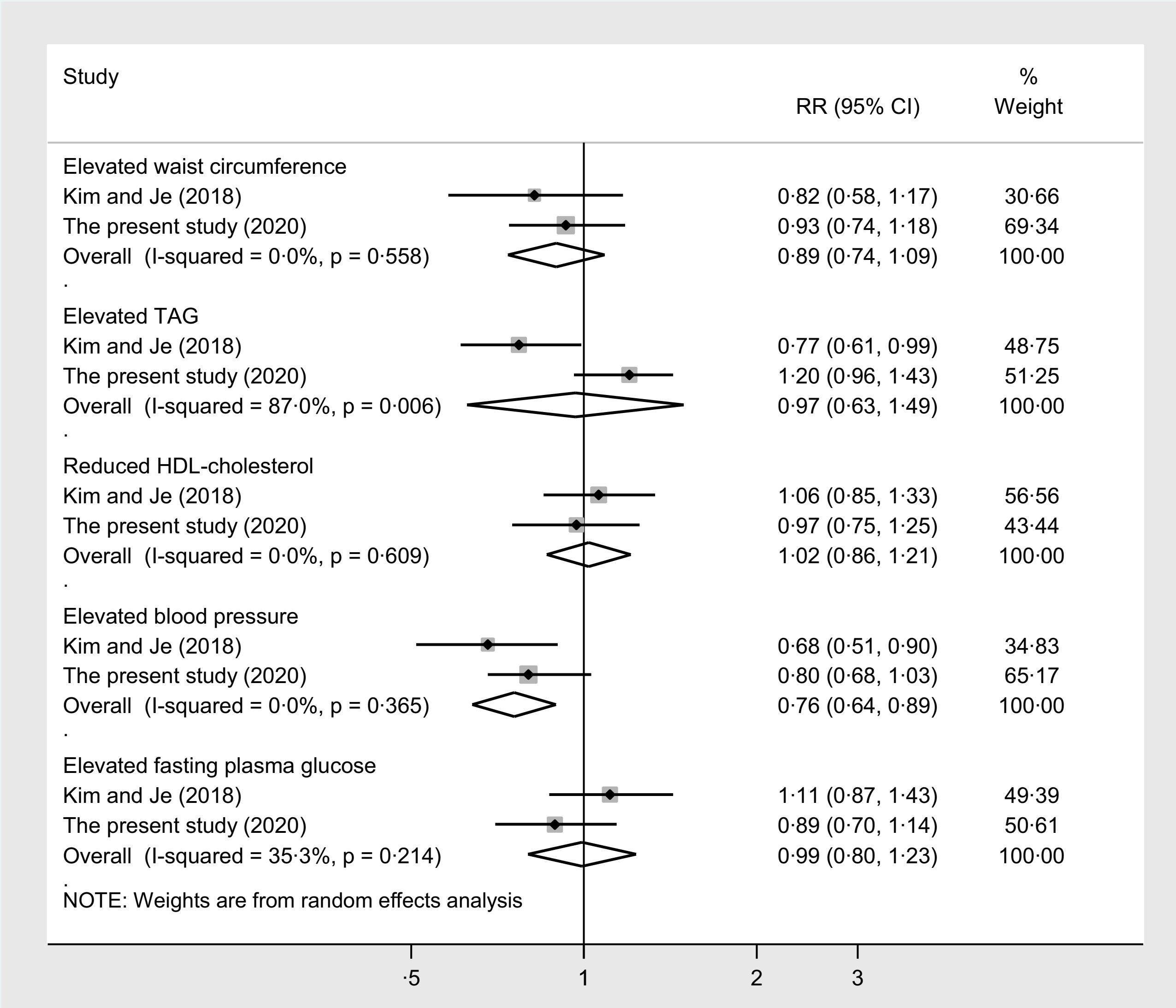

Fig. 6. The associations between the highest *v.* lowest categories of poultry consumption and the components of the metabolic syndrome. Weights are from random effects analysis. The I-squared describes the percentage of variation across studies that is due to heterogeneity rather than chance. The *P* value for heterogeneity was calculated from the Q test. RR, relative risk.

heterogeneity across studies. Fourth, the findings of the analyses of Mets components may not accurately represent the estimates because the majority of the included studies did not report the associations between the exposure of interest and the components of the Mets.

Conclusions

In summary, the findings from the present cross-sectional study and meta-analysis of observational studies add weight to the evidence that the Mets may be positively associated with red meat consumption, inversely associated with fish consumption and neutrally associated with poultry consumption. Additional data from prospective cohort studies investigating the associations between red meat, fish and poultry consumption, and the incidence of the Mets across different subpopulations are warranted to determine the nature of our findings.

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Curation, Funding acquisition, Project Administration; Li-Qiang Qin: Data Curation, Supervision, Funding acquisition, Writing-Reviewing and Editing.

The authors report no conflicts of interest relevant to this article.

Supplementary material

For supplementary material accompanying this paper visit https://doi.org/10.1017/S0007114521002452

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