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REVIEW ARTICLE

Comparisons of calorie restriction and structured exercise on reductions in visceral and abdominal subcutaneous adipose tissue: a systematic review

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Abstract

Exercise and low-calorie diets are common approaches taken to produce an energy deficit for weight loss in obesity. Changes in visceral and abdominal subcutaneous fat associated with weight loss are important questions but have not yet been concluded. We investigated the relationship between changes in visceral (VAT) and subcutaneous adipose tissue (SAT) areas obtained by abdominal imaging with the change in total body fat. The relevant databases were searched through January 2021 according to the PRISMA guidelines. Sixty-five studies were included. We found that the change in total body fat was associated with changes in both VAT and abdominal SAT areas, but the relationship between total body fat and the abdominal SAT area appeared stronger. Baseline values of VAT and abdominal SAT area were similar in the three treatment groups (calorie restriction, calorie restriction plus exercise, and exercise alone). The reduction in abdominal SAT area for a loss of 1 kg of total body fat was about 10 cm^2, which was similar among all the treatments. The change in VAT area ($-26.3\ cm^2$) was a similar level as the change in abdominal SAT area ($-31.5\ cm^2$) in the exercise, whereas in the calorie restriction with and without exercise, the change in VAT area (-33.6 and $-51.6\ cm^2$, respectively) was approximately half of the reduction of SAT area (-65.1 and $-87.2\ cm^2$, respectively). Absolute changes in VAT and abdominal SAT areas might differ between interventions for the exercise and calorie restriction with and without exercise.

Introduction

Increases in prevalence rates for obesity, characterized by excess body fat (i.e. adipose tissue), is a worldwide health concern and has distinguished itself as a major threat to public health. According to a previous report [1], which used body mass index (BMI), it was estimated that within the United States, the proportion of overweight and obesity (≥25 kg/m^2) would reach levels of 86.6% and 87.2% in adult (≥20 years old) men and women, respectively by 2030 if current trends are maintained. Furthermore, evidence has suggested that the location of excess fat, particularly that of visceral adipose tissue (VAT) stored around the internal organs, is a greater determinant of adverse health outcomes, as compared to subcutaneous adipose tissue (SAT) [2, 3]. For example, epidemiological studies have repeatedly shown how large amounts of VAT are associated with multiple cardiovascular disease risk factors, which include but not limited to hypertension, dyslipidemia, and diabetes [2]. However, obesity can be interpreted as a modifiable risk factor for the above listed threats of cardiovascular and metabolic disorders [4, 5].

It is known that VAT and SAT differ in their anatomical and metabolic characteristics [6, 7]. Approximately 5–15% of total body fat is considered to be VAT in healthy middle-aged adults and proportions are influenced by age, sex, and degree/types of obesity [8]. Typically, VAT can be identified by having smaller adipocyte size when compared to SAT, and VAT tends to have a rich vascular network

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surrounding the cells, along with being metabolically active [6, 7, 9]. Notably, when the body signals mobilization of fat stores for energy, VAT actively undergoes lipolysis, with nonesterified fatty acids being delivered directly to the liver via the portal vein. Although, if these nonesterified fatty acids are not fully utilized as an energy source, surplus fatty acids can accumulate within the liver and is often viewed as a precursor for insulin resistance [9]. However, if full oxidation does occur, active lipolysis in VAT will be effective in altering its total amount of fat. Taken together, a greater understanding of strategies that are targeting reductions in VAT, over SAT, is necessary when considering the notion of weight loss and subsequent improvements in metabolic health.

Current status of knowledge

For the goal of weight loss, both calorie restriction and exercise are common approaches taken to produce an energy deficit. There are a number of reviews [10–17] that have focused on the specific reduction of VAT as a result of weight loss, but fewer have considered the reduction of VAT and SAT collectively [15–17]. Moreover, since SAT is distributed throughout the body, and VAT is limited to the omentum and mesentery, the amount of measured SAT and VAT will differ depending on the location and the region of measurement (i.e. number of slices between two points) from each study. In other words, the quantity of VAT to SAT is different in a single image of the abdomen, multiple images of the trunk, or the whole body. In the previous reviews [15–17], VAT and SAT were not necessarily analyzed at the same location or region. For example, a change in total body SAT was compared with VAT change (i.e. total body estimate vs. localized region). Thus, there is a need to compare SAT at the same location of VAT. In addition, although the magnitude of weight loss will represent the effects of the intervention, significant reductions in VAT have also been reported in response to exercise, in the absence of substantial global weight loss [4, 11, 14]. Therefore, based on the referenced studies detailing the effects of caloric restriction and exercise on weight loss, we investigated the relationship between changes in VAT and SAT areas obtained by abdominal imaging with the change in total body fat.

Methods

Following the preferred reporting items for systematic reviews and meta-analyses [18], a search using the electronic databases (PubMed and Scopus) was conducted, and intervention trials that reported changes in total body fat and in both VAT and abdominal SAT areas measured before and after negative energy balance treatments, were considered eligible for this study. The database searches were performed using the terms “weight reduction AND magnetic resonance imaging (MRI)” OR “weight reduction AND computed tomography (CT)” OR “visceral fat AND diet” OR “visceral fat AND exercise” and limiting the search to clinical trials (searched up to January 2021). After eliminating duplications, the search results were screened by one investigator (TA) against the eligibility criteria, and those studies which could not be eliminated by title or abstract were independently reviewed by two reviewers (TA, VW). References from pertinent articles and the names of the authors cited were cross-referenced to locate any further relevant articles not found with the initial search. The inclusion criteria were as follows: (a) intervention: the study needed to include a negative energy balance induced by caloric restriction (CR), exercise (EX), or a combination of the two (CR+EX); (b) participants: the study needed to include individuals with overweight and/or obese (defined according to group means ≥25 kg/m^2 BMI and over 18 years of age); (c) outcome measures: the study needed to measure both total body fat mass (using dual-energy X-ray absorptiometry, densitometry such as underwater weighing or air displacement plethysmography, bioimpedance, and MRI) and VAT and abdominal SAT areas (using CT and MRI) at baseline and after the intervention; (d) language: the search was limited to original research that was written in English. Studies were included if a study measured non-single (2–3 scans) abdominal image and calculated average values of VAT and abdominal SAT areas. If a study did not report absolute and/or relative change in outcome measures between baseline and after the intervention, then we calculated the variables using reported mean values. When mean values were only illustrated in graph form, a graph digitizer (Plot Digitizer, version 2.6.8) was used to estimate the values. Although each section included studies using similar outcomes, we elected not to do a meta-analysis because the variability of the change (i.e., denominator of the effect size calculation) would have to be estimated for the majority of the studies.

The methodological quality of each eligible study was critically appraised using the McMaster Critical Appraisal Tool for Quantitative Studies [19], which was independently assessed by two authors (TA and JSS). Quantitative studies were assessed over eight main components (i.e. study purpose, literature review, study design, sample, outcomes, intervention, results, and conclusions). Each item within these components was rated (‘yes’ = 1; ‘no’ or ‘not addressed’ = 0) and scored, while items rated as ‘not applicable’ were omitted from the total score, with the maximum total score of fourteen. According to the previous review [14], only studies with a minimum score of 10 out of 14 items were eligible for inclusion (Table S1).

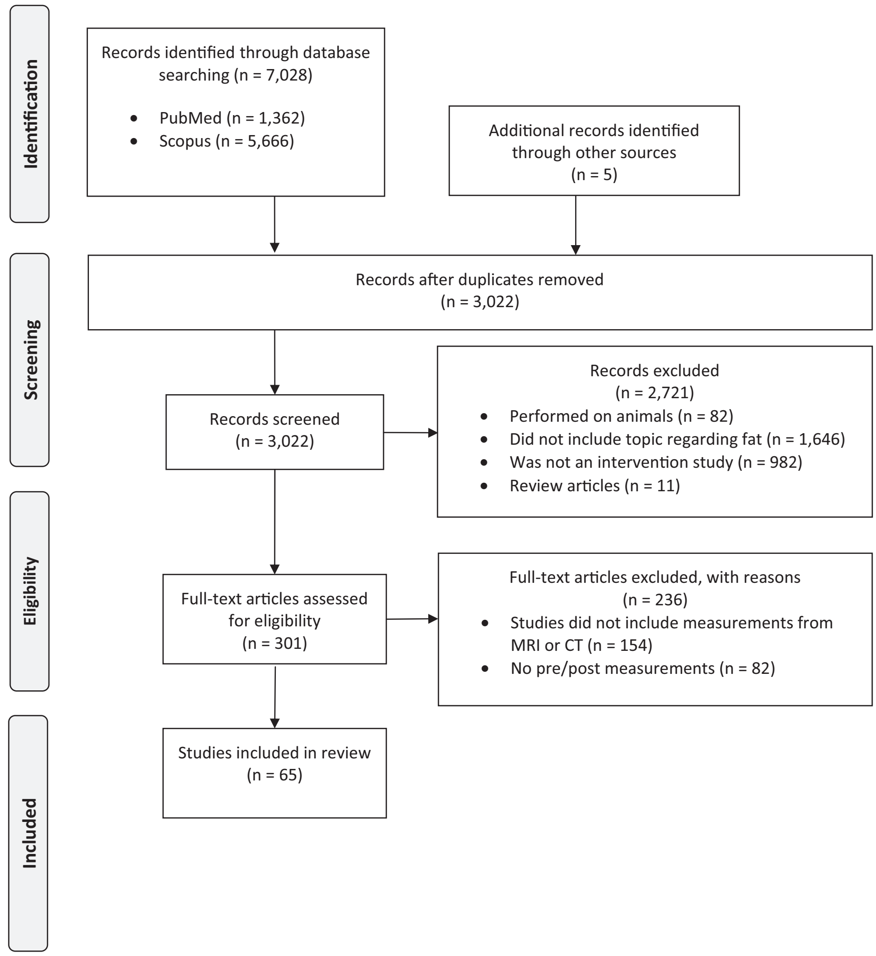

Fig. 1 PRISMA flowchart of outcomes of search strategy.

Findings

Included studies and participant and research protocol characteristics

The original article search resulted in 7028 studies. Five more studies were found from the reference lists of the included papers. After removal of duplicates and elimination of papers based on the eligibility criteria, 65 studies [20–84] were included in this review (Fig. 1). Of those studies, 32 included a total of 45 experimental groups assigned to a low-calorie diet (CR: totaling 218 men, 691 women, and 136 mixed) [20, 21, 24, 25, 29–31, 33, 35, 38, 39, 42–44, 47, 49, 51, 57, 58, 60, 64–66, 68, 72, 74, 76, 77, 80–83] (Table 1), 27 included a total of 38 experimental groups assigned to a combination of calorie restriction plus exercise (CR+EX: totaling 63 men, 992 women, and 373 mixed) [28, 32, 34, 36, 38, 41, 44, 46, 50–57, 60, 62, 64, 67, 70–72, 76, 81–83] (Table 2), and 18 included a total of 24 experimental groups assigned to increasing energy expenditure by exercise (~90 min) while maintaining energy intake (EX: totaling 167 men, 298 women, and 213 mixed) [22, 23, 26, 27, 37, 40, 45, 48, 59, 61, 63, 69, 72, 75, 78–80, 84] (Table 3).

There were two dietary treatment options, specific for promoting weight loss. In 23 studies, participants consumed a fixed known calorie diet [20, 21, 24, 25, 28–31, 38, 39, 41, 42, 44, 45, 47, 49, 51, 53, 55–57, 65, 74]. Twenty-five studies used restriction of calorie intake below the baseline values (weight-stable phase) or below the estimated energy requirement from resting energy expenditure [32–36, 43, 50, 52, 54, 58, 60, 62, 64, 66–68, 70–72, 76, 77, 80–83]. The common fixed calorie diet was 1000 kcal per day (4.2 MJ/day) [20, 24, 25, 28, 30, 38, 55, 56, 65] or 1200 kcal per day [31, 39, 49]. Very low-calorie diet (800 kcal per day) [42, 47, 74] and dietary calorie changes during the intervention period (e.g. ~800 kcal/day to 1200 kcal/day) [21, 29] were also used. Furthermore, the common calorie restriction was 500–700 kcal/day below the baseline setting value in the CR [33, 43, 66, 68, 77] and 250–350 kcal/day below the baseline setting value in the CR+EX [32, 34, 36, 50, 54, 60, 82].

The most common interventions for the EX was aerobic exercise such as running, cycling, and walking ($n = 17$) [22, 23, 26, 37, 40, 45, 48, 59, 61, 63, 73, 79–84], resistance

Table 1 Age, number of subjects, total body fat, and visceral and abdominal subcutaneous adipose tissue areas in low-calorie diet intervention groups.

				Total fat mass (kg)					SAT area (cm^2)		VAT area (cm^2)	
Author [Reference #]	Group	Subject	Age (years)	Method	Baseline	ΔChange	Method	Level	Baseline	ΔChange	Baseline	ΔChange
Weits [20]	CR	W20	43.0 ± 12.9	UWW	40.5	−3.3	CT	Umbil	439.5	−46.7	161.4	−24.4
Stallone [21]	CR	W11	52	UWW	43.7	−14.8	CT	L4	461.4	−152.8	148	−52.9
Leenen [24]	CR	W40	39 ± 6	UWW	37.9	−10.3	MRI	Rib-Ilia	390	−117	106	−35
	CR	M38	41 ± 6	UWW	32.7	−9.8	MRI	Rib-Ilia	314	−113	156	−61
Leenen [25]	CR	W33	39 ± 5	UWW	38.6	−11.5	MRI	Rib-Ilia	395	−117	103	−33
	CR	M37	40 ± 6	UWW	32.7	−11.0	MRI	Rib-Ilia	314	−114	155	−61
Goodpaster [29]	CR	W17	38.7 ± 5.6	DXA	39.1	−9.5	CT	L4-L5	520	−117	147	−44
	CR	M15		DXA	34.6	−12.3	CT	L4-L5	465	−159	167	−78
Kockx [30]	CR	W25	38.4 ± 5.5	UWW	37.2	−9.8	MRI	Rib-Ilia	402	−121	98	−32
	CR	M25	40.2 ± 6.2	UWW	30.8	−9.1	MRI	Rib-Ilia	312	−110	155	−60
Tchernof [31]	CR	W11	57.5 ± 5.4	DXA	44.0	−10.0	CT	L4-L5	500	−109	176	−46
	CR	W13	58.0 ± 3.8	DXA	43.8	−11.5	CT	L4-L5	504	−142	211	−81
Doucet [33]	CR	M19	NR	UWW	38.3	−9.6	CT	L4-L5	394.1	−83.8	208.5	−79
	CR	W23	NR	UWW	46.0	−5.6	CT	L4-L5	557.3	−56	152.5	−27.8
Yip [35]	CR	MW20	50.6 ± 6.3	BIA	40.5	−8.8	CT	L2	355.6	−93.2	204.1	−72.5
Janssen [38]	CR	W13	40.1 ± 6.7	MRI	41.2	−7.8	MRI	L4-L5	444	−82	131	−51
Tchernof [39]	CR	W25	56.4 ± 5.2	DXA	42.4	−10.4	CT	L4-L5	500	−115	202	−74
Gower [42]	CR	W18	37.5 ± 5.5	DXA	33.3	−11.2	CT	L4-L5	331	−109.2	116.2	−47.1
	CR	W19	35.3 ± 6.2	DXA	32.3	−11.2	CT	L4-L5	359.4	−152.1	65.2	−25.1
Doucet [43]	CR	M17	43.9 ± 6.2	UWW	38.7	−10.2	CT	L4-L5	397.7	−88.9	216.3	−89.1
	CR	W17	41.2 ± 4.9	UWW	44.5	−7.2	CT	L4-L5	531.1	−83.6	148.5	−34.5
Okura [44]	CR	W14	50.9 ± 5.6	DXA	23.4	−5.4	CT	L4-L5	261.5	−73.2	82.5	−33.2
	CR	W12	52.7 ± 7.6	DXA	25.3	−4.7	CT	L4-L5	278.6	−65.1	141.2	−51
Laaksonen [47]	CR	MW20	46.7 ± 8.7	BIA	32.8	−9.6	CT	L4	413	−73	216	−68
Brochu [49]	CR	W15	57.3 ± 4.7	DXA	43.5	−8.0	CT	L4-L5	514	−75	236	−65
	CR	W10	59.3 ± 7.2	DXA	38.5	−13.4	CT	L4-L5	468	−177	198	−102
Okura [51]	CR	W35	49 ± 8	DXA	26.7	−5.0	CT	L4-L5	271	−50	147	−40
Okura [57]	CR	W34	21–66	BIA	26.1	−4.9	CT	L4-L5	266	−44	148	−37
	CR	W34		BIA	22.7	−5.3	CT	L4-L5	264	−67	68	−23
Alvarez [58]	CR	M10	32.9 ± 7.3	DXA	27.6	−4.1	CT	L4-L5	337	−51	135	−28
	CR	M6	60 ± 6.6	DXA	21.2	−4.5	CT	L4-L5	333	−59	184	−44
Ryan [60]	CR	W16	56 ± 4	DXA	42.7	−4.7	CT	L4-L5	497.7	−73.4	140.4	−25.3
Brochu [64]	CR	W71	58.0 ± 4.7	DXA	37.6	−4.0	CT	L4-L5	466	−44	186	−23
Purnell [65]	CR	M24	44.5	UWW	47	−15	CT	Umbil	436	−147	182	−92
Kim [66]	CR	M27	45.8 ± 8.8	DXA	31.1	−7.7	CT	L4-L5	269.5	−64.6	195.1	−65.7
Rossi [68]	CR	MW24	46.7 ± 14.3	DXA	35.3	−5.7	MRI	L3-L5	399.9	−54.4	174.8	−55.9
Ryan [72]	CR	W10	52 ± 6	DXA	40.4	−4.6	CT	L4-L5	469	−49	136	−37
Drummen [74]	CR	MW13	54.3 ± 13.1	ADP	38.8	−11.63	MRI	L5	360.5	−75.5	316.4	−114.4
	CR	MW12	57.9 ± 8.6	ADP	37.2	−10.78	MRI	L5	324.3	−69.5	306.1	−126.1
van Gemert [76]	CR	W97	60.5 ± 4.6	DXA	34	−3.7	MRI	L3-L5	312	−39	142	−17
Lovejoy [77]	CR	W10	NR	DXA	42.7	−3.9	CT	L4-L5	399.2	−39	150.5	−22
Coker [80]	CR	MW9	58 ± 6	DXA	34.4	−4.4	CT	L4-L5	343	−42	199	−29
Brinkley [81]	CR	W8	57.6 ± 4.8	DXA	38.5	−7.0	CT	L4-L5	544.3	−126.5	243.2	−63
Ryan [82]	CR	W40	61 ± 6	DXA	42.4	−5.7	CT	L4-L5	432	−52	141.8	−21.6
Yoshimura [83]	CR	MW38	40–75	UWW	25.0	−3.7	CT	L4-L5	284	−32	182	−31
Mean					36.2	−8.2			396	−87.2	166	−51.6

ADP air displacement plethysmography, *Abdom* abdoman, *BIA* bioimpedance, *CR* calorie restriction, *CT* computed tomography, *DXA* dual-energy X-ray absorptiometry, *EX* exercise, *L4-L5* between lumbar fourth and fifth vertebrae, *M* men, *MRI* magnetic resonance imaging, *MW* men and women, *NR* not reported, *Rib-Ilia* midway between the lower rib margin and the iliac crest, *SAT* subcutaneous adipose tissue, *UWW* underwater weighing, *Umbli* umbilicus, *VAT* visceral adipose tissue, *W* women.

Table 2 Age, number of subjects, total body fat, and visceral and abdominal subcutaneous adipose tissue areas in combination of low-calorie diet plus exercise intervention groups.

				Total fat mass (kg)					SAT area (cm^2)		VAT area (cm^2)	
Author [Reference #]	Group	Subject	Age (years)	Method	Baseline	ΔChange	Method	Level	Baseline	ΔChange	Baseline	ΔChange
Ross [28]	CR + EX	M20	42.1 ± 9.9	MRI	33.0	−9.2	MRI	L4-L5	338.4	−107.7	135.9	−46.3
	CR + EX	W38	36.9 ± 7.5	MRI	38.2	−8.5	MRI	L4-L5	425.3	−99.1	106.5	−27.8
Ryan [32]	CR + EX	W24	58 ± 5	DXA	40.6	−6.1	CT	L4-L5	493.3	−77.5	156.4	−27.7
van Rossum [34]	CR + EX	W54	60 ± 6	DXA	39.0	−5.2	CT	L4-L5	449.2	−50.3	154.7	−24.9
Lynch [36]	CR + EX	W40	62 ± 6	DXA	38.0	−6.0	CT	L4-L5	431	−75	156	−26
Janssen [38]	CR + EX	W11	37.5 ± 6.0	MRI	47.3	−9.9	MRI	L4-L5	356	−60	120	−39
	CR + EX	W14	34.8 ± 5.8	MRI	37.8	−8.6	MRI	L4-L5	307	−26	84	−19
Liao [41]	CR + EX	MW32	55.8 ± 1.8	UWW	19.9	−1.7	CT	Abdom	225.5	−29.3	86.3	−16.1
Okura [44]	CR + EX	W14	51.8 ± 5.0	DXA	25.8	−7.0	CT	L4-L5	280.1	−80.5	78.8	−23.6
	CR + EX	W15	51.9 ± 7.5	DXA	27.1	−8.7	CT	L4-L5	285.7	−106.2	147.1	−75.2
Park and Lee [46]	CR + EX	W21	42.2	BIA	24.9	−3.4	CT	L4-L5	268.3	−35.2	127	−33.1
	CR + EX	W19	57.6	BIA	24.3	−3.3	CT	L4-L5	282.5	−37.7	150.5	−13.2
Nicklas [50]	CR + EX	W57	60 ± 5	DXA	39	−6	CT	L4-L5	441	−57	162	−23
	CR + EX	W19	59 ± 6	DXA	45	−4	CT	L4-L5	552	−62	134	−13
Okura [51]	CR + EX	W22	51 ± 6	DXA	26.8	−6.6	CT	L4-L5	297	−64	128	−47
	CR + EX	W33	52 ± 6	DXA	27.3	−8.0	CT	L4-L5	287	−78	142	−54
Shadid and Jensen [52]	CR + EX	MW19	41 ± 9	DXA	35.8	−9.3	CT	L2-L3	259	−63	203	−80
Park [53]	CR + EX	MW78	37.3	BIA	27.7	−4.8	CT	L4-L5	299.4	−54	124.7	−29.9
Ryan and Nicklas [54]	CR + EX	W58	58 ± 6	DXA	40.2	−5.3	CT	L4-L5	470	−70.1	147.8	−26.2
Carr [55]	CR + EX	MW30	55.7 ± 9.9	UWW	20.0	−2.0	CT	Abdom	230.6	−30.1	87.2	−17.8
Stewart [56]	CR + EX	W26	64.3 ± 5.8	DXA	33.7	−3.4	MRI	Umbil	330.3	−27.3	109.6	−14.5
	CR + EX	M25	61.7 ± 6.4	DXA	28.7	−3.7	MRI	Umbil	236.2	−24.1	186.5	−40.6
Okura [57]	CR + EX	W71	21–66	BIA	27.2	−7.3	CT	L4-L5	289	−69	135	−52
	CR + EX	W70		BIA	22.7	−5.5	CT	L4-L5	246	−70	69	−21
Ryan [60]	CR + EX	W17	59 ± 4	DXA	39.1	−5.8	CT	L4-L5	452.3	−80.5	143.6	−26.3
Lee [62]	CR + EX	MW52	37.4 ± 11.6	DXA	24.9	−5.7	CT	L4-L5	237	−54.6	97.7	−28.3
Brochu [64]	CR + EX	W36	57.2 ± 5.0	DXA	39.5	−5.3	CT	L4-L5	467	−56	183	−23
	CR + EX	W21	57.6 ± 4.1	DXA	38.5	−5.6	CT	L4-L5	459	−65	180	−25
Goodpaster [67]	CR + EX	MW67	46.1 ± 6.5	DXA	60.4	−8.66	CT	L4-L5	718.00	−112.79	199.39	−28.73
	CR + EX	MW63	47.5 ± 6.2	DXA	59.2	−5.91	CT	L4-L5	717.56	−87.85	186.13	−22.9
Mouridsen [70]	CR + EX	W49	58.7 ± 5.0	DXA	33.8	−3.89	MRI	L3	290.8	−31.1	128.5	−23.5
Ipavec-Levasseur [71]	CR + EX	M18	44 ± 7	DXA	41.8	−8.1	MRI	L4	464	−63	204	−63
Ryan [72]	CR + EX	W15	54 ± 8	DXA	37.6	−5.4	CT	L4-L5	460	−55	144	−22
van Gemert [76]	CR + EX	W98	59.5 ± 4.9	DXA	34	−5.2	MRI	L3-L5	306	−49	143	−21
Brinkley [81]	CR + EX	W15	57.3 ± 5.7	DXA	39.5	−8.5	CT	L4-L5	614.4	−138.4	206.6	−57.6
	CR + EX	W98	59.4 ± 4.9	DXA	44.0	−11.7	CT	L4-L5	604.7	−121.1	273.3	−81.3
Ryan [82]	CR + EX	W37	60 ± 6	DXA	40.6	−5.8	CT	L4-L5	458.4	−68	145.8	−20.2
Yoshimura [83]	CR + EX	MW32	40–75	DXA	23.8	−4.2	CT	L4-L5	281	−40	183	−43
Mean					35.2	−6.1			384	−65.1	146	−33.6

ADP air displacement plethysmography, *Abdom* abdoman, *BIA* bioimpedance, *CR* calorie restriction, *CT* computed tomography, *DXA* dual-energy X-ray absorptiometry, *EX* exercise, *L4-L5* between lumbar fourth and fifth vertebrae, *M* men, *MRI* magnetic resonance imaging, *MW* men and women, *NR* not reported, *Rib-Ilia* midway between the lower rib margin and the iliac crest, *SAT* subcutaneous adipose tissue, *UWW* underwater weighing, *Umbli* umbilicus, *VAT* visceral adipose tissue, *W* women.

Table 3 Age, number of subjects, total body fat, and visceral and abdominal subcutaneous adipose tissue areas in exercise intervention groups.

Author [Reference #]	Group	Subject	Age (yr)	Total fat mass (kg)					SAT area (cm^2)		VAT area (cm^2)	
				Method	Baseline	ΔChange	Method	Level	Baseline	ΔChange	Baseline	ΔChange
Despres [22]	EX	W13	38.8 ± 5.3	UWW	42.6	−4.6	CT	L4-L5	546.5	−60	124.7	−3.4
Schwartz [23]	EX	M13	28.2 ± 2.4	UWW	19.7	−1.6	CT	Umbil	218.7	−20.8	66.3	−11.5
	EX	M15	67.5 ± 5.8	UWW	19.8	−2.4	CT	Umbil	172.8	−34.9	144.5	−35.5
Bouchard [26]	EX	M14	21	UWW	20.8	−4.9	CT	L4-L5	246	−67	81	−29
Treuth [27]	EX	W14	67 ± 4	UWW	25.8	−0.4	CT	L4-L5	299.2	−17.4	143.9	−13.9
Pare [37]	EX	M45	45.4 ± 6.2	UWW	29.4	−2.8	CT	L4-L5	328	−33	186	−37
Miyatake [40]	EX	M31	46.2 ± 6.8	ADP	24.1	−2.8	CT	Umbil	147.1	−20.1	110.8	−22.5
Park [45]	EX	W10	42.2 ± 1.9	BIA	26.9	−7.4	CT	L4	602	−23	195	−83
	EX	W10	43.4 ± 1.0	BIA	27.9	−8.9	CT	L4	646	−62	201	−93
Irwin [48]	EX	W87	61.0	DXA	38.5	−1.4	CT	L4-L5	389.1	−21.2	147.6	−8.5
O'Leary [59]	EX	MW16	63 ± 4	UWW	38.8	−3.4	CT	L4	351.4	−46.6	175.6	−39.4
Sigal [61]	EX	MW64	53.5 ± 7.3	BIA	37.6	−1.9	CT	L4-L5	416	−27	246	−22
	EX	MW60	53.9 ± 6.6	BIA	39.2	−1.6	CT	L4-L5	448	−17	257	−13
	EX	MW64	54.7 ± 7.5	BIA	36.5	−1.3	CT	L4-L5	412	−18	228	−10
Kim [63]	EX	M24	49.4 ± 9.6	DXA	26.7	−2.7	CT	L4-L5	234.6	−40.5	197.1	−31.4
Heydari [69]	EX	M25	28.4 ± 4.8	DXA	29.8	−2.0	CT	L4-L5	288	−13	69	−12
Zhang [73]	EX	W15	21.5 ± 1.7	DXA	25.7	−2.8	CT	L4-L5	248.4	−35	69	−9.1
	EX	W15	20.9 ± 1.4	DXA	26.1	−2.8	CT	L4-L5	219.9	−28.3	69.4	−9.2
Hintze [75]	EX	W25	NR	DXA	35.3	−3.5	CT	L4-L5	446.1	−37.4	158.4	−13.9
Schmitz [78]	EX	W71	36 ± 5	DXA	34.8	−1.1	CT	L2-L3	269	−5.2	71.8	−2.1
Irving [79]	EX	W11	51 ± 9	ADP	43.1	−1.3	CT	L4-L5	486	−11	153	−7
	EX	W9		ADP	41.0	−2.8	CT	L4-L5	513	−46	173	−25
Coker [80]	EX	MW9	55 ± 6	DXA	34.8	−4.5	CT	L4-L5	422	−52	236	−71
Henriquez [84]	EX	W18	58	DXA	34.4	−2.8	CT	L3	323.7	−19.1	160.4	−29.4
Mean					31.4	−3.0			361	−31.5	153	−26.3

ADP air displacement plethysmography, *Abdom* abdoman, *BIA* bioimpedance, *CR* calorie restriction, *CT* computed tomography, *DXA* dual-energy X-ray absorptiometry, *EX* exercise, *L4-L5* between lumbar fourth and fifth vertebrae, *M* men, *MRI* magnetic resonance imaging, *MW* men and women, *NR* not reported, *Rib-Ilia* midway between the lower rib margin and the iliac crest, *SAT* subcutaneous adipose tissue, *UWW*, underwater weighing, *Umbli* umbilicus, *VAT* visceral adipose tissue, *W* women.

exercise ($n = 4$) [27, 61, 75, 78], combined resistance and aerobic exercise ($n = 2$) [45, 61], and interval exercise ($n = 2$) [69, 73]. Regarding the time of the aerobic exercise session, many studies used 45–60 min at a moderate intensity (e.g. 50–60% heart rate reserve).

Based on group mean ages, many studies targeted middle-aged men and women, and relatively few studies targeted young or older men and women. In order to assess body composition (i.e. total body fat), 36 studies used dual-energy X-ray absorptiometry, 20 studies used densitometry (i.e. underwater weighing and air displacement plethysmography), 2 studies used MRI, and 7 studies used bioelectrical impedance. To acquire abdominal cross-sectional images, CT was used for 53 of the 65 studies, while the other 12 studies used MRI.

The study period for weight loss was 34 studies within 6 months (62 experimental groups: CR = 28, CR + EX = 21, EX = 13) [20, 24–30, 33, 38, 43, 44, 46, 47, 51–53, 57–59, 61–63, 66, 68–71, 73, 76, 79–81, 83], 20 studies from 6 months to less than 12 months (30 experimental groups: CR = 10, CR + EX = 14, EX = 6) [21, 23, 32, 34–36, 41, 45, 50, 54, 56, 60, 64, 65, 72, 74, 75, 77, 82, 84], and 11 studies from 12 months or longer (15 experimental groups: CR = 7, CR + EX = 3, EX = 5) [22, 31, 37, 39, 40, 42, 48, 49, 55, 67, 78].

Changes in total body fat versus changes in VAT and abdominal SAT areas

The relationships between changes in total body fat and changes in VAT and abdominal SAT areas for CR, CR + EX and EX are illustrated in Fig. 2. There appeared to be a close relationship between changes in total body fat and changes in abdominal SAT area, whereas, the relationship

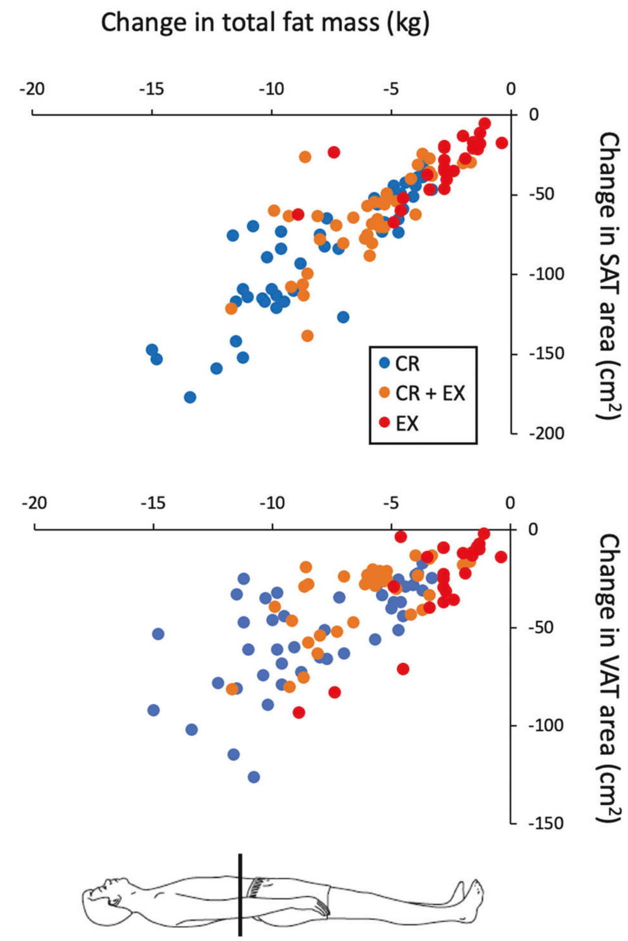

Fig. 2 Relationships between changes in total body fat and abdominal subcutaneous adiposetissue (SAT) area or visceral adipose tissue (VAT) area. CR, calorie restriction; CR+EX, calorie restriction combined with exercise; EX, exercise.

between total body fat and changes in VAT area did not appear as strong.

Absolute changes in VAT and abdominal SAT areas

Figure 3 compares changes in VAT and abdominal SAT areas with CR, CR + EX, and EX. After the interventions, reductions in total body fat were higher with CR (mean change; −8.2 kg), followed by CR + EX (−6.1 kg), and then EX (−3.0 kg). Baseline values of abdominal SAT area were 396, 384, and 361 cm^2 in CR, CR + EX, and EX, respectively. Similarly, baseline values of the VAT area were, respectively 166, 146, and 153 cm^2 for the three intervention groups. Decreases in abdominal SAT area were consistent with changes in total body fat (CR = −87.2 cm^2; CR + EX = –65.1 cm^2; EX = −31.5 cm^2) in the three intervention groups. Changes in abdominal SAT area, for a 1 kg reduction in total body fat, were −10.6 cm^2 for CR, −10.6 cm^2 for CR + EX, and −10.5 cm^2 for EX. In the EX, the decrease in the VAT area (−26.3 cm^2) was a similar amount as the decrease in abdominal SAT area. However, for the other two intervention groups, the decrease in VAT area was approximately half of that found for abdominal SAT reductions (CR = −51.6 cm^2; CR + EX = −33.6 cm^2). Changes in VAT area, for a 1 kg reduction in total body fat, were −6.3 cm^2 for CR, −5.5 cm^2 for CR + EX, and −8.8 cm^2 for EX.

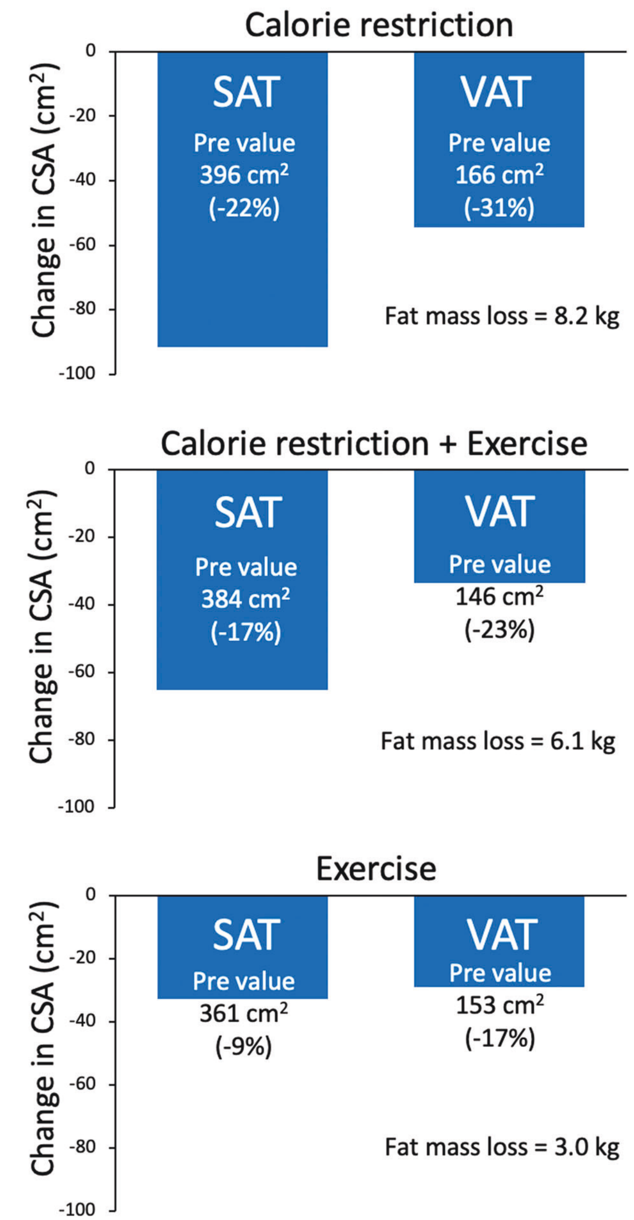

Fig. 3 Changes in abdominal subcutaneous adipose tissue (SAT) area and visceral adiposetissue (VAT) area following treatments of calorie restriction, calorie restriction combined withexercise, and exercise alone. Each bar represents the mean values of baseline and relative changes in subcutaneous and visceral adipose tissue areas.

Discussion

The current paper reviewed the associations between changes in anatomical regions specific to VAT and abdominal SAT, and the change in total body fat achieved through common negative energy balance treatments (CR, CR + EX, and EX). This systematic review included 65 studies involving a total of 3151 adult participants. Of the studies examined, the majority were conducted in overweight and obese populations, predominantly with middle-aged and older men and women. Our findings demonstrated that (1) baseline values of abdominal SAT and VAT areas were comparable across the three treatments; (2) the change in total body fat was associated with changes in both VAT and abdominal SAT areas, but the relationship between total body fat and the SAT area appeared stronger; (3) the reduction in abdominal SAT area for a loss of 1 kg of total body fat was about 10 cm^2, which was similar among the three treatments; and (4) the change in VAT area was a similar level as the change in abdominal SAT area in the exercise, whereas in the calorie restriction with and without exercise, the change in VAT area was approximately half of the reduction found for abdominal SAT area.

Study significance and implications

About two decades ago, Ross and Janssen [15] examined the relationship between exercise-induced weight loss and the specific reduction in VAT and SAT. The authors reported that although exercise with or without weight loss is associated with reductions in VAT and SAT, there was insufficient evidence to determine whether a preferential reduction occurred in abdominal adipose tissue (VAT and/or SAT) provided by exercise-induced weight loss. In 2017, Merlotti et al. [17] compared VAT and SAT loss, comparing three weight reduction strategies (1: diet and exercise, 2: weight-loss promoting agents, and 3: bariatric surgery). They reported that decreases in SAT were greater than VAT when compared using absolute values of adipose tissue (i.e. area, volume or mass). Although relative changes in VAT were always larger than relative changes in SAT. However, in that study they could not separate the effect of the two strategies since calorie restriction and exercise were one category together. Furthermore, these previous reviews included a couple of methodological concerns as it relates to comparing the change in abdominal adipose tissue as mentioned above (i.e. studies used different number of images and/or used body weight change for the intervention effect). In the current review, the intervention effect was assessed by changes in total body fat, as opposed to total body weight change, and we have used studies that measured abdominal SAT and VAT areas.

Possible underlying causes of the changes in VAT area versus abdominal SAT area

When compared based on the loss of total body fat, the decrease in VAT in the exercise group tended to be different from that in the other two groups. A possible reason for this difference in VAT and abdominal SAT reduction could be the difference in lipolytic effect, as it relates to hormonal sensitivity between exercise and calorie restriction [22, 23, 27, 37, 40, 45, 59, 63, 73]. There is evidence that visceral adipocytes are more sensitive to catecholamine stimulation than abdominal subcutaneous adipocytes, with a greater lipolytic capacity and lesser antilipolytic action of insulin [85, 86]. However, these findings are in vitro results and the effect of negative energy balance during treatments on VAT/SAT is not fully understood. We hypothesized that differences specific to the catabolic processes, along with the metabolic environment that utilizes those energy sources, are likely to be involved. The possibilities we consider are listed below.

Change in resting energy expenditure

To achieve energy imbalance for weight loss, energy expenditure must exceed energy intake. Calorie restriction creates a negative energy balance through a reduction in energy intake. However, in time this also precedes a likely decrease in resting energy expenditure (~10%) [24, 72, 87]. Exercise produces a negative energy balance by utilizing energy in order to sustain the exercise bout. However, resting energy expenditure is generally maintained (due to maintenance of lean body mass). Calorie restriction combined with exercise reduces resting energy expenditure to a similar extent as calorie restriction alone [87]. Resting energy expenditure is the largest contributing factor to daily energy expenditure and reflects the summated heat production (metabolic rate times mass) of individual organs and tissues. In particular, skeletal muscle, liver, kidneys, and the brain all contribute ~70% of the resting energy expenditure [88]. It should be noted that the liver, despite weighing ~1.7 (women) −2.0 (men) kg, accounts for ~20% of resting energy expenditure, with a similar contribution found for skeletal muscle [25 (women) −35 (men) kg] [88]. Calorie restriction leads to decreased secretion of thyroid hormone [89], and may affect the reduction of organ/tissue's metabolic rate including the liver [90]. For example, the liver plays a key role in lipid metabolism (e.g. lipid circulation through lipoprotein synthesis, fatty acid oxidation and ketone production from fatty acids). If metabolically active organs such as the liver are susceptible to calorie restriction, they may be involved in changes in visceral fat. In exercise-induced weight loss, a level of resting energy expenditure is maintained during the intervention. In addition, energy is consumed commensurate with intensity and duration of the exercise, and resting energy expenditure can remain elevated for many hours after an exercise bout [91].

Factors for releasing hormones and myokines by exercise

Exercise acutely raises circulating levels of interleukin-6, which is involved in glucose and lipid metabolism. A recent study investigated the hypothesis as to whether or not exercise-induced change in VAT mass is regulated by interleukin-6 signaling in middle-aged men and women with abdominal obesity [92]. The authors reported that VAT decreased following a 12 week of aerobic exercise training, but no change in VAT was observed following the same training in the presence of interleukin-6 blockade. Thus, it seems as though interleukin-6 is playing an important mechanistic role as it relates to exercise-induced VAT loss. An animal study reported that higher expressions of interleukin-6 receptors are observed in VAT (mesentery) than in SAT [93]. In addition, acute elevations of circulating hormones (e.g. growth hormone, catecholamine, testosterone) occur during and/or after exercise [94]. Although VAT and SAT are known to be differentially affected by several hormones [95, 96], and these responses may influence the exercise-induced change in VAT, the direct causal relationship that exercise-induced preferentially reduces VAT area is unknown. Further research is needed to understand those relationships for providing a better strategy of reducing VAT.

Other considerations and future tasks

First, the amount of body fat lost in the exercise intervention was substantially less compared with the other two interventions. It is unclear whether greater reductions in body fat within the exercise group would have led to similar reductions in abdominal SAT observed in the other two groups (as opposed to similar reductions between abdominal SAT and VAT). It is possible that both abdominal SAT and VAT are reduced similarly to a point, followed by a more specific loss in abdominal SAT as the amount of total body fat loss increases. Second, when comparing changes in VAT and abdominal SAT associated with weight loss between men and women, the absolute change in VAT tends to be higher in men than in women [24, 25, 28–30, 33, 43, 56]. One factor may be higher baseline values in men prior to the intervention [24, 43, 57]. For the exercise groups used in this review, the proportion of men seems high when compared to the other two intervention groups (i.e. men to women ratio is more even than CR or CR + EX). It is possible that this is causing a more prominent decrease in VAT seen in the exercise group. In the current review, however, baseline values of VAT and abdominal SAT were similar in the three intervention groups, and it was considered unlikely that differences in the proportion of men and women affected the results. Jenssen and Ross support the idea that absolute reductions in VAT and SAT areas were not different between men and women following calorie restriction with and without exercise [97]. Third, VAT and abdominal SAT areas were mainly measured at the L4-L5 intervertebral space in this review, but not all (Table 1). The pattern of VAT area by measurement image location varied in individuals and the peak of the VAT area was located between 1 and 4 cm above the L4-L5 intervertebral space in women, and most frequently 5–8 cm above L4-L5 in men [98]. It is possible that differences in VAT distribution pattern changes before and after weight loss may affect results in each intervention. Fourth, methods for assessing body composition in the selected articles were not universally measured using a single method. It has been reported that results vary depending on methods used to assess body composition, and different instrumentation and mathematical functions further compound the variability of the results [99]. However, since this review used the change in total body fat, it is presumed that the influence of different assessment methods is minimal. Lastly, due to the insufficient number of articles in this review, we could not compare and discuss the types of exercise (i.e. aerobic, resistance, interval) separately on changes in VAT and abdominal SAT. Although there are reviews observing the association between aerobic/resistance exercise and visceral fat loss [12, 13], differences in the effects of exercise type on both VAT and abdominal SAT reduction needs to be determined in future research.

Conclusions

The data analyzed from the collected studies suggest that absolute changes in VAT and abdominal SAT area differ between interventions for both exercise and calorie restriction, with and without exercise. It seems that these results were derived since the change in total body fat was used as a reference, as well as abdominal adipose tissue area. However, specific physiological factors that promote the reduction in VAT by way of exercise remain unresolved.

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TA. Reviewed and critically revised the manuscript: JSS, ZWB, VW, RWS, YY and JPL. All authors approved the final version of the manuscript.

Compliance with ethical standards

Conflict of interest The authors declare no competing interests.

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References

1. Wong Y, Beydoun MA, Liang L, Caballero B, Kumanyika SK. Will all Americans become overweight or obese? estimating the progression and cost of the US obesity epidemic. Obesity. 2008;16:2323–30.
2. Fox CS, Massaro JM, Hoffmann U, Pou KM, Maurovich-Horvat P, Liu CY, et al. Abdominal visceral and subcutaneous adipose tissue compartments: association with metabolic risk factors in the Framingham Heart Study. Circulation. 2007;116:39–48.
3. Neeland IJ, Ayers CR, Rohatgi AK, Turer AT, Berry JD, Das SR, et al. Associations of visceral and abdominal subcutaneous adipose tissue with markers of cardiac and metabolic risk in obese adults. Obesity. 2013;21:E439–E447.
4. Ross R, Janiszewski PM. Is weight loss the optimal target for obesity-related cardiovascular disease risk reduction? Can J Cardiol. 2008;24:25D–31D.
5. Borges JH, Carter SJ, Bryan DR, Hunter GR. Exercise training and/or diet on reduction of intra-abdominal adipose tissue and risk factors for cardiovascular disease. Eur J Clin Nutr. 2019; 73:1063–8.
6. Arner P. Differences in lipolysis between human subcutaneous and omental adipose tissue. Ann Med. 1995;27:435–8.
7. Ibrahim MM. Subcutaneous and visceral adipose tissue: structure and functional differences. Obes Rev. 2010;11:11–18.
8. Ross R, Shaw KD, Martel Y, de Guise J, Avruch L. Adipose tissue distribution measured by magnetic resonance imaging in obese women. Am J Clin Nutr. 1993;57:470–5.
9. Petersen MC, Shulman GI. Mechanisms of insulin action and insulin resistance. Physiol Rev. 2018;98:2133–223.
10. Smith SR, Zachwieja JJ. Visceral adipose tissue: a critical review of intervention strategies. Int J Obes. 1999;23:329–35.
11. Kay SJ, Fiatarone, Singh MA. The influence of physical activity on abdominal fat: a systematic review of the literature. Obes Rev. 2006;7:183–200.
12. Ismail I, Keating SE, Baker MK, Johnson NA. A systematic review and meta-analysis of the effect of aerobic vs. resistance exercise training on visceral fat. Obes Rev. 2012;13:68–91.
13. Ohkawara K, Tanaka S, Miyachi M, Oshikawa-Takata K, Tabata I. A dose-response relation between aerobic exercise and visceral fat reduction: systematic reciew of clinical trials. Int J Obes. 2007;31:1786–97.
14. RJHM Verheggen, MFH Maessen, Green DJ, ARMM Hermus, MTE Hopman, DHT Thijssen. A systematic review and meta-analysis on the effects of exercise training versus hypocaloric diet: distinct effects on body weight and visceral adipose tissue. Obes Rev. 2016;17:664–90.
15. Ross R, Janssen I. Is abdominal fat preferentially reduced in response to exercise-induced weight loss? Med Sci Sports Exerc. 1999;31:S568–S572.
16. Chaston TB, Dixon JB. Factors associated with percent change in visceral versus subcutaneous abdominal fat during weight loss: findings from a systematic review. Int J Obes. 2008;32:619–28.
17. Merlotti C, Ceriani V, Morabito A, Pontiroli AE. Subcutaneous fat loss is greater than visceral fat loss with diet and exercise, weight-loss promoting drugs and bariatric surgery: a critical review and meta-analysis. Int J Obes. 2017;41:672–82.
18. Moher D, Liberati A, Tetzlaff J, Altman DG. The PRISMA Group. Preferred reporting items for systematic reviews and meta-analyses: The PRISMA statement. Int J Surg. 2010;8:336–41.
19. Letts L, Wilkins S, Law M, Stewart D, Bosch J, Westmorland M. Guidelines for critical review form: quantitative studies (version 2.0). Qualitative Review Form Guidelines. Hamilton, ON: McMaster University; 2007.
20. Weits T, van der Beek EJ, Wedel M, Hubben MWA, Koppeschaar HPF. Fat patterning during weight reduction: a multimode investigation. Neth J Med. 1989;35:174–84.
21. Stallone DD, Stunkard AJ, Wadden TA, Foster GD, Boorstein J, Arger P. Weight loss and body fat distribution: a feasibility study using computed tomography. Int J Obes. 1991;15:775–80.
22. Despres JP, Pouliot MC, Moorjani S, Nadeau A, Tremblay A, Lupien PJ, et al. Loss of abdominal fat and metabolic response to exercise training in obese women. Am J Physiol. 1991;261: E159–E167.
23. Schwartz RS, Shuman WP, Larson V, Cain KC, Fellingham GW, Beard JC, et al. The effect of intensive endurance exercise training on body fat distribution in young and older men. Metabolism. 1991;40:545–51.
24. Leenen R, van der Kooy K, Deurenberg P, Seidell JC, Weststrate JA, Schouten FJ, et al. Visceral fat accumulation in obese subjects: relation to energy expenditure and response to weight loss. Am J Physiol. 1992;263:E913–E919.
25. Leenen R, van der Kooy K, Seidell JC, Deurenberg P, Koppeschaar HPF. Visceral fat accumulation in relation to sex hormones in obese men and women undergoing weight loss therapy. J Clin Endocribol Metab. 1994;78:1515–20.
26. Bouchard C, Tremblay A, Despres JP, Theriault G, Nadeau A, Lupien PJ, et al. The response to exercise with constant energy intake in identical twins. Obes Res. 1994;2:400–10.
27. Treuth MS, Hunter GR, Kekes-Szabo T, Weinsier RL, Goran MI, Breland L. Reduction in intra-abdominal adipose tissue after strength training in older women. J Appl Physiol. 1995; 78:1425–31.
28. Ross R, Rissanen J, Hudson R. Sensitivity associated with the identification of visceral adipose tissue levels using waist circumference in men and women: effects of weight loss. Int J Obes. 1996;20:533–8.
29. Goodpaster BH, Kelley DE, Wing RR, Meier A, Thaete FL. Effects of weight loss on regional fat distribution and insulin sensitivity in obesity. Daibetes. 1999;48:839–47.
30. Kockx M, Leenen R, Seidell J, Princen HMG, Kooistra T. Relationship between visceral fat and PAI-1 in overweight men and women before and after weight loss. Thromb Haemost. 1999; 82:1490–6.
31. Tchernof A, Starling RD, Turner A, Shuldiner AR, Walston JD, Silver K, et al. Impaired capacity to lose visceral adipose tissue during weight reduction in obese postmenopausal women with the Trp64Arg beta3-adrenoceptor gene variant. Diabetes. 2000;49:1709–13.
32. Ryan AS, Nicklas BJ, Berman DM, Dennis KE. Dietary restriction and walking reduce fat deposition in the midthigh in obese older women. Am J Clin Nutr. 2000;72:708–13.
33. Doucet E, St-Pierre S, Almeras N, Mauriege P, Despres JP, Richard D, et al. Fasting insulin levels influence plasma leptin levels independently from the contribution of adiposity: evidence from both a cross-sectional and an intervention study. J Clin Endocrinol Metab. 2000;85:4231–7.
34. van Rossum EFC, Nicklas BJ, Dennis KE, Berman DM, Goldberg AP. Leptin responses to weight loss in postmenopausal women:

relationship to sex-hormone bibding globulin and visceral obesity. Obes Res. 2000;8:29–35.
35. Yip I, Go VLW, Hershman JH, Wang HJ, Elashoff R, DeShields S, et al. Insulin-leptin-visceral fat relation during weight loss. Pancreas. 2001;23:197–203.
36. Lynch NA, Nicklas BJ, Berman DM, Dennis KE, Goldberg AP. Reductions in visceral fat during weight loss and walking are associated with improvements in VO2max. J Appl Physiol. 2001;90:99–104.
37. Pare A, Dumont M, Lemieux I, Brochu M, Almeras N, Lemieux S, et al. Is the relationship between adipose tissue and waist girth altered by weight loss in obese men? Obes Res. 2001; 9:526–34.
38. Janssen I, Fortier A, Hudson R, Ross R. Effects of an energy-restrictive diet with or without exercise on abdominal fat, intermuscular fat, and metabolic risk factors in obese women. Diabetes Care. 2002;25:431–8.
39. Tchernof A, Nolan A, Sites CK, Ades PA, Poehlman ET. Weight loss reduces C-reactive protein levels in obese postmenopausal women. Circulation. 2002;105:564–9.
40. Miyatake N, Nishikawa H, Morishita A, Kunitomi M, Wada J, Suzuki H, et al. Daily walking reduces visceral adipose tissue areas and improves insulin resistance in Japanese obese subjects. Diabetes Res Clin Pr. 2002;58:101–7.
41. Liao D, Asberry PJ, Shofer JB, Callahan H, Matthys C, Boyko EJ, et al. Improvement of BMI, body composition, and body fat distribution with lifestyle modification in Japanese Americans with impaired glucose tolerance. Diabetes Care. 2002;25:1504–10.
42. Gower BA, Weinsier RL, Jordan JM, Hunter GR, Desmond R. Effects of weight loss on changes in insulin sensitivity and lipid concentrations in premenopausal African American and white women. Am J Clin Nutr. 2002;76:923–7.
43. Doucet E, St-Pierre S, Almeras N, Imbeault P, Mauriege P, Pascot A, et al. Reduction of visceral adipose tissue during weight loss. Eur J Clin Nutr. 2002;56:297–304.
44. Okura T, Tanaka K, Nakanishi T, Lee DJ, Nakata Y, Wee SW, et al. Effects of obesity phenotype on coronary heart disease risk factors in response to weight loss. Obes Res. 2002;10:757–66.
45. Park SK, Park JH, Kwon YC, Kim HS, Yoon MS, Park HT. The effect of combined aerobic and resistance exercise training on abdominal fat in obese middle-aged women. J Physiol Anthropol. 2003;22:129–35.
46. Park HS, Lee KU. Postmenopausal women lose less visceral adipose tissue during a weight reduction program. Menopause. 2003;10:222–7.
47. Laaksonen DE, Kainulainen S, Rissanen A, Niskanen L. Relationships between changes in abdominal fat distribution and insulin sensitivity during a very low calorie diet in abdominally obese men and women. Nutr Metab Cardiovasc Dis. 2003; 13:349–56.
48. Irwin MI, Yasui Y, Ulrich CM, Bowen D, Rudolph RE, Schwartz RS, et al. Effect of exercise on total and intra-abdominal body fat in postmenopausal women. JAMA. 2003;289:323–30.
49. Brochu M, Tchernof A, Turner AN, Ades PA, Poehlman E. Is there a threshold of visceral fat loss that improves the metabolic profile in obese postmenopausal women? Metabolism. 2003; 52:599–604.
50. Nicklas BJ, Dennis KE, Berman DM, Sorkin J, Ryan AS, Goldberg AP. Lifestyle intervention of hypocaloric dieting and walking reduces abdominal obesity and improves coronary heart disease risk factors in obese, postmenopausal, African-American and Caucasian women. J Gerontol A Biol Sci Med Sci. 2003; 58:181–9.
51. Okura T, Nakata Y, Tanaka K. Effects of exercise intensity on physical fitness and risk factors for coronary heart disease. Obes Res. 2003;11:1131–9.
52. Shadid S, Jensen M. Effects of pioglitazone versus diet and exercise on metabolic health and fat distribution in upper body obesity. Diabetes Care. 2003;26:3148–52.
53. Park HS, Sim SJ, Park JY. Effect of weight reduction on metabolic syndrome in Korean obese patients. J Korean Med Sci. 2004;19:202–8.
54. Ryan AS, Nicklas BJ. Reductions in plasma cytokine levels with weight loss improve insulin postmenopausal women. Diabetes Care. 2004;27:1699–705.
55. Carr DB, Utzschneider KM, Boyko EJ, Asberry PJ, Hull RL, Kodama K, et al. A reduced-fat diet and aerobic exercise in Japanese American with impaired glucose tolerance decreases intra-abdominal fat and improves sensitivity but not b-cell function. Diabetes. 2005;54:340–7.
56. Stewart KJ, Bacher AC, Hees PS, Tayback M, Ouyang P, Jan de Beur S. Exercise effects on bone mineral density Relationships to changes in fitness and fatness. Am J Prev Med. 2005;28:453–60.
57. Okura T, Nakata Y, Lee DJ, Ohkawara K, Tanaka K. Effects of aerobic exercise and obesity phenotype on abdominal fat reduction in response to weight loss. Int J Obes. 2005;29:1259–66.
58. Alvarez GE, Davy BM, Ballard TP, Beske SD, Davy KP. Weight loss increases cardiovagal baroreflex function in obese young and older men. Am J Physiol Endocrinol Metab. 2005;289: E665–E669.
59. O'Leary VB, Marchetti CM, Krishnan RK, Stetzer BP, Gonzalez F, Kirwan JP. Exercise-induced reversal of insulin resistance in obese elderly is associated with reduced visceral fat. J Appl Physiol. 2006;100:1584–9.
60. Ryan AS, Nicklas BJ, Berman DM. Aerobic exercise is necessary to improve glucose utilization with moderate weight loss in women. Obesity. 2006;14:1064–72.
61. Sigal RJ, Kenny GP, Boule NG, Wells GA, Prud'homme D, Fortier M, et al. Effects of aerobic training, resistance training, or both on glycemic control in type 2 diabetes. Ann Intern Med. 2007;147:357–69.
62. Lee JW, Lee HR, Shim JY, Im JA, Lee DC. Abdominal visceral fat reduction is associated with favorable changes of serum retinol binding protein-4 in nondiabetic subjects. Endocr J. 2008; 55:811–8.
63. Kim MK, Tomita T, Kim MJ, Sasai H, Maeda S, Tanaka K. Aerobic exercise training reduces epicardial fat in obese men. J Appl Physiol. 2008;106:5–11.
64. Brochu M, Malita MF, Messier V, Doucet E, Strychar I, Lavoie JM, et al. Resistance training does not contribute to improving the metabolic profile after a 6-month weight loss program in overweight and obese postmenopausal women. J Clin Endocrinol Metab. 2009;94:3226–33.
65. Purnell JQ, Kahn SE, Samuels MH, Brandon D, Loriaux DL, Brunzell JD. Enhanced cortisol production rates, free cortisol, and 11b-HSD-1 expression correlate with visceral fat and insulin resistance in men: effect of weight loss. Am J Physiol Endcrinol Metab. 2009;296:E351–E357.
66. Kim MK, Tanaka K, Kim MJ, Matuso T, Endo T, Tomita T, et al. Comparison of epicardial, abdominal and regional fat compartments in response to weight loss. Nutr Metab Cardiovasc Dis. 2009;19:760–6.
67. Goodpaster BH, Delany JP, Otto AD, Kuller L, Vockley J, South-Paul JE, et al. Effects of diet and physical activity interventions on weight loss and cardiometabolic risk factors in severely obese adults. JAMA. 2010;304:1795–802.
68. Rossi AP, Fantin F, Zamboni GA, Mazzali G, Zoico E, Bambace C, et al. Effect of moderate weight loss on hepatic, pancreatic and visceral lipids in obese subjects. Nutr Diabetes. 2012;2:e32.
69. Heydari M, Freund J, Boutcher SH. The effect of high-intensity intermittent exercise on body composition of overweight young males. J Obes. 2012;2012:480467.

70. Mouridsen MR, Bendsen NT, Astrup A, Haugaard SB, Binici Z, Sajadieh A. Modest weight loss in moderately overweight postmenopausal women improves heart rate variability. Eur J Prev Cardiol. 2012;20:671–7.
71. Ipavec-Levasseur S, Croci I, Choquette S, Byrne NM, Cowin G, O'Moore-Sullivan TM, et al. Effect of 1-h moderate intensity aerobic exercise on intramyocellular lipids of obese men before and after a lifestyle intervention. Appl Physiol Nutr Metab. 2015;40:1262–8.
72. Ryan AS. Improvements in insulin sensitivity after aerobic exercise and weight loss in older women with a history of gestational diabetes and type 2 diabetes mellitus. Endoc Res. 2016; 41:132–41.
73. Zhang H, Tong TK, Qiu W, Zhang X, Zhou S, Liu Y, et al. Comparable effects of high-intensity interval training and prolonged continuous exercise training on abdominal visceral fat reduction in obese young women. J Diabetes Res. 2017;2017:5071740.
74. Drummen M, Dorenbos E, Vreugdenhil ACE, Raben A, Fogelholm M, Westerterp-Plantenga MS, et al. Long-term effects of increased protein intake after weight loss on intrahepatic lipid content and implications for insulin sensitivity: a PREVIEW study. Am J Physiol Endocrinol Metab. 2018;315:E885–E891.
75. Hintze LJ, Messier V, Lavoie ME, Brochu M, Lavoie JM, Prud-homme D, et al. A one-year resistance training program following weight loss has no significant impact on body composition and energy expenditure in postmenopausal women living with overweight and obesity. Physiol Behav. 2018;189:99–106.
76. van Gemert WA, Peeters PH, May AM, Doornbos AJH, Elias SG, van der Palen J, et al. Effect of diet with or without exercise on abdominal fat in postmenopausal women - a randomized trial. BMC Pub Health. 2019;19:174.
77. Lovejoy JC, Bray GA, Bourgeois MO, Macchiavelli R, Rood JC, Greeson C, et al. Exogenous androgens influence body composition and regional body fat distribution in obese postmenopausal women – A clinical research center study. J Clin Endocrinol Metab. 1996;81:2198–203.
78. Schmitz KH, Hannan PJ, Stovitz SD, Bryan CJ, Warren M, Jensen MD. Strensth training and adiposity in premenopausal women: Strong, Healthy, and Empowered study. Am J Clin Nutr. 2007;86:566–72.
79. Irving BA, Davis CK, Brock DW, Weltman JY, Swift D, Barrett EJ, et al. Effect of exercise training intensity on abdominal visceral fat and body composition. Med Sci Sports Exerc. 2008;40:1863–72.
80. Coker RH, Williams RH, Yeo SE, Kortebein PM, Bodenner DL, Kern PA, et al. The impact of exercise training compared to caloric restriction on hepatic and peripheral insulin resistance in obesity. J Clin Endocrinol Metab. 2009;94:4258–66.
81. Brinkley TE, Ding J, Carr JJ, Nicklas BJ. Pericardial fat loss in postmenopausal women under conditions of equal energy deficit. Med Sci Sports Exerc. 2011;43:808–14.
82. Ryan AS, Ge S, Blumentbal JB, Serra MC, Prior SJ, Goldberg AP. Aerobic exercise and weight loss reduce vascular markers of inflammation and improve insulin sensitivity in obese women. J Am Geriatr Soc. 2014;62:607–14.
83. Yoshimura E, Kumahara H, Tobina T, Matsuda T, Watabe K, Motono S, et al. Aerobic exercise attenuates the loss of skeletal muscle during energy restriction in adults with visceral adiposity. Obes Facts. 2014;7:26–35.
84. Henriquez S, Monsalves-Alvarez M, Jimenez T, Barrera G, Hirsch S, de la Maza MP, et al. Effects of two training modalities on body fat and insulin resistance in postmenopausal women. J Strength Cond Res. 2017;31:2955–64.
85. Bolinder J, Kager L, Ostman J, Arner P. Differences at the receptor and postreceptor levels between human omental and subcutaneous adipose tissue in the action of insulin on lipolysis. Diabetes. 1983;32:117–23.
86. Hellmer J, Marcus C, Sonnenfeld T, Arner P. Mechanisms for differences in lipolysis between human subcutaneous and omental fat cells. J Clin Endocrinol Metab. 1992;75:15–20.
87. Martin CK, Heilbronn LK, de Jonge L, DeLany JP, Volaufova J, Anton SD, et al. Effect of calorie restriction on resting metabolic rate and spontaneous physical activity. Obesity. 2007;15:2964–73.
88. Hwaung P, Bosy-Westphal A, Muller MJ, Geisler C, Heo M, Thomas DM, et al. Obesity tissue: Composition, energy expenditure, and energy content in adult humans. Obesity. 2019; 27:1472–81.
89. Cavallo E, Armellini F, Zamboni M, Vicentini R, Milani MP, Bosello O. Resting metabolic rate, body composition and thyroid hormones. Horm Metab Res. 1990;22:632–5.
90. Muller MJ, Enderle J, Pourhassan M, Braun W, Eggeling B, Lagerpusch M, et al. Metabolic adaptation to caloric restriction and subsequent refeeding: the Minnesota Starvation Experiment revisited. Am J Clin Nutr. 2015;102:807–19.
91. Tremblay A, Despres JP, Bouchard C. The effects of exercise-training on energy balance and adipose tissue morphology and metabolism. Sports Med. 1985;2:223–33.
92. Wedell-Neergaard AS, Lehrskov LL, Christensen RH, Legaard GE, Dorph E, Larsen MK, et al. Exercise-induced changes in visceral adipose tissue mass are regulated by IL-6 signaling: a randomized controlled trial. Cell Metab. 2019;29:844–55.
93. Ji P, Drackley JK, Khan MJ, Loor JJ. Inflammation- and lipid metabolism-related gene network expression in visceral and subcutaneous adipose depots of Holstein cows. J Dly Sci. 2014;97:3441–8.
94. Powers SK, Howley ET. Exercise Physiology: Theory and Application to Fitness and Performance. Seventh Edition. New York: McGraw Hill; 2009. pp.72–105.
95. Zouhal H, Lemoine-Morel S, Mathieu ME, Casazza GA, Jabbour G. Catecholamines and obesity: effects of exercise and training. Sports Med. 2013;43:591–600.
96. Abete N, Garg A. Heterogeneity in adipose tissue metabolism: causes, implications and management of regional adiposity. Prog Lipid Res. 1995;34:53–70.
97. Janssen I, Ross R. Effects of sex on the change in visceral, subcutaneous adipose tissue and skeletal muscle in response to weight loss. Int J Obes. 1999;23:1035–46.
98. Demerath EW, Sun SS, Rogers N, Lee M, Reed D, Choh AC, et al. Anatomical patterning of visceral adipose tissue: race, sex, and age variation. Obesity. 2007;15:2984–93.
99. Fogelholm M, van Marken Lichtenbelt W. Comparison of body composition methods: a literature analysis. Eur J Clin Nutr. 1997;51:495–503.