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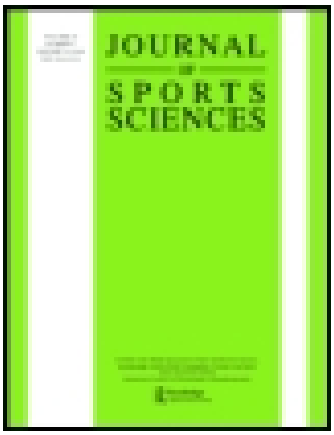

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The skinfold: Myth and reality

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The skinfold: myth and reality*

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Abstract

The interest in skinfolds, given the easy accessibility of the subcutaneous layer and its non-invasive nature, has led to a proliferation of 'skinfold' applications and formulae. To obtain data to investigate body composition methods, particularly the use of skinfolds, two separate cadaver dissection studies were undertaken, allowing for the analysis of data from 32 cadavers with more than 2500 data per cadaver. In addition, 40 elderly 'living' subjects of the same age range were compared with the cadaver population and no significant macro-morphological differences were found.

The available data have clearly demonstrated that skinfold compressibility is by no means constant. Adipose tissue patterning by assessment of skinfold thickness using calipers and incision confirms significant sex differences but emphasizes the neglected importance of skin thickness. It appears that the best adipose tissue predictors are different from those used in general. Also the problem of estimating body fat content by skinfold is compounded by the fact that two identical thicknesses of adipose tissue may contain significantly different concentrations of fat. Skinfolds are significantly related to external (subcutaneous) adipose tissue. However, the relation to internal tissue is less evident and the relation with intramuscular adiposity is unknown.

Introduction

In the literature, over 1000 articles can be found dealing directly or indirectly with skinfold measurements, both in applied and fundamental research. Altogether more than 100 equations to predict 'body fat' from skinfolds have been produced (Lohman, 1981; Marsboom and Clarys, 1982; Mattiaci and Clarys, 1982; Martin *et al.*, 1985). The number of studies using skinfolds and the number of skinfold formulae reflect the extent of sample specificity (Martin *et al.*, 1985), although many formulae are often used in applications of a non-specific nature. The interest in

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skinfolds, given the easy accessibility of the subcutaneous layer and given its non-invasive approach, has led to a proliferation of the commercialization and use of the skinfold caliper (Martin *et al.*, 1985).

Skinfold measurements and quantities derived from them are used in physiology, structural anatomy, endocrinology, kinanthropometry, nutrition, health and fitness, growth, sport and exercise sciences. They have specific applications in occupational biomechanics, human hydrodynamics, drug quantification, diabetes, coronary heart disease, hypertension, anorexia nervosa and in many epidemiological and human biology studies. The skinfold is a central factor in 'adipose tissue' patterning (Edwards, 1951; Garn, 1955, 1971; Mueller and Stallones, 1981; Mueller, 1985), in 'fat' distribution studies, in somatotyping (Heath and Carter, 1967 and others) and in the commercialized O-scale system (Ross and Ward, 1984) for monitoring adiposity and proportional weight.

'Body fat' is defined as the ether-extractable constituents (Keys and Brozek, 1953) and thus must be considered as a chemical component of the body. However, the term 'adipose tissue' includes not just lipid but also all the non-lipid constituents of cells, such as water and protein. As a result the interchangeable use of the terms 'adipose tissue' and 'fat' has led to many ambiguities and some serious errors, especially where anthropometric and dissection of biopsy data are combined (Alexander, 1964). These have been amplified elsewhere by Martin (1984) and by Clarys and Martin (1985).

The most common methods for estimating body fat are densitometry, whole-body potassium counting, body water measurement, anthropometry (e.g. skinfolds) and more recently computerized tomography. Anthropometry, however, relies for its validation on one or more of the other techniques and is therefore a doubly indirect method.

There is a series of problems to be addressed concerned with (i) validation and criteria, (ii) scientific and popular applications, and (iii) the term 'fat', since 'fat' has both a colloquial descriptive (anatomical) connotation and a specific chemical one. Nevertheless, a case can be made for the prediction of adipose tissue mass from caliper measurements since (i) it is based on dissection data, (ii) it eliminates the wide variability in water content of adipose tissue, and (iii) internal and external adipose tissue masses appear, on the basis of cadaver data, to be better related than internal and external fat (Martin, 1984; Clarys and Martin, 1985). These questions have been examined in a major research project which is known as 'The Brussels Cadaver Analysis Study' (CAS) and is referred to in previous reports (e.g. Clarys *et al.*, 1984; Martin *et al.*, 1984, 1985, 1986).

The Brussels Cadaver Analysis Study

In order to validate body composition methods, particularly the skinfold measurement, skinfold formulae, the choice of skinfold site and the relation among internal and subcutaneous adipose tissue deposits, two separate cadaver dissection studies were undertaken at the Vrije Universiteit Brussel in a joint venture with Simon Fraser University, Burnaby, Canada. The first Cadaver Analysis Study (CAS 1) on 25 corpses took place in 1979 and 1980; the second study (CAS 2) on seven cadavers took place in 1983. The subjects' age at death ranged from 55 to 94 years, except for one aged 16 and one aged 33 years. They were extensively measured and

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dissected regionally into skin, adipose tissue, skeletal muscle, bone, organs and viscera. The project generated more than 2500 data per cadaver, including anthropometry, densitometry, radiography and osteometry.

The purposes of the CAS were: (i) to extend existing quantitative data pertaining to tissues and organs in the adult human body, (ii) to obtain data which could be used to validate various *in vivo* methods for the estimation of human body composition, and (iii) to obtain data which could be used for the development of new anthropometric models for estimating body composition. This study was unique in that both extensive anthropometric and anatomical composition data were collected on the same subjects.

In the CAS 1 study, the body was divided into six major segments, i.e. the head and neck, trunk, two upper and two lower limbs, with each of the tissue masses being segregated according to these segments. A detailed account of this was given by Clarys *et al.* (1984) and a complete description of the methodology and selected data were presented in the theses of Drinkwater (1984) and Martin (1984). The objectives of the subsequent study (CAS 2) were to measure intact weights and volumes of the major segments (head, trunk and limbs) and to measure also the intact weights and volumes of the minor segments of the upper limbs (arm, forearm, hand) and of the lower limbs (thigh, leg, foot). The minor segments were further dissected and the distribution of tissues was measured within each. These data are given in the reports of Marfell-Jones (1984) and Clarys and Marfell-Jones (1986).

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Procedures

Facilities, equipment and personnel

Dissections were performed in a research laboratory adjacent to the Institute's mortuary in Brussels and away from the teaching laboratory. The facilities were air conditioned; temperature and humidity were continuously monitored using a chart recorder. Room temperature varied from 18 to 20° C while relative humidity varied between 50 and 60%. Underwater weighing of the cadavers was carried out in a large water-filled tank in the laboratory mortuary. Radiographic facilities were provided by the Department of Radiology of the Academic Teaching Hospital at Brussels.

Selection of cadavers

By means of a testament system, adult Belgians may donate their bodies for medical and scientific research purposes to the university of their choice. Cadavers for this study were thus selected from a population of cadavers received by both the Vrije Universiteit Brussel and the Université Libre de Bruxelles. Cadavers showing evidence of prolonged immobility prior to death, severe emaciation, extensive tissue deterioration, recent surgical intervention, or death from infectious disease were not used.

In all, 34 cadavers were dissected (CAS 1 and CAS 2). Prior to the main study, dissections were carried out on two cadavers in a pilot study to determine whether it was possible to complete a dissection in one day and to resolve any difficulties with respect to the handling and weighing of tissues. Data from these two cadavers are not reported. Of the other 25 subjects

dissected during the course of the CAS 1 study, 12 were embalmed (six males, six females) and 13 were unembalmed (six males, seven females). Cadavers ranged in age at death from 55 to 94 years. Descriptive data for these cadavers are shown in Tables 1, 2 and 3. During the course of the CAS 2 study a further seven embalmed cadavers (three females, four males) were measured and dissected. These cadavers ranged in age at death from 16 to 80 years; causes of death are listed as 'natural', age-associated heart failure, one suicide and one drug overdose or unknown.

Initially, the CAS dissections were performed on embalmed cadavers. Most of these subjects were readily to hand. After dissecting 12 cadavers, an increasing concern about the differential effects of embalming and the uneven distribution of embalming fluid leading to alterations in anthropometric measures and tissue weights prompted us to begin using unembalmed cadavers. These concerns about the effects of embalming are covered in the report of Clarys *et al.* (1984).

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Preparation and handling of the cadavers

Immediately upon receipt of a cadaver, date of birth, date of death or reported age were recorded. The cause of death was also noted. If the body was to be embalmed, approximately 6 litres of embalming fluid was infused via gravity feed into the left femoral or carotid artery from a height of about 2.5 m. This process took 4 to 12 h after which the cadavers remained at room temperature (20° C) in the mortuary for 24 to 48 h. At the end of this period the cadavers were again weighed, placed into body bags to minimize evaporative loss and refrigerated (4° C). Losses of embalming fluid occurred both during the embalming stage and later during handling and storage of the cadaver. The amount of embalming fluid assumed to be retained in the body was determined from the difference between the weight at receipt and the weight at dissection.

Overview of measurement and dissection procedures

Before starting the anthropometric procedures, the cadaver was removed from the refrigerator, placed in a reinforced orthopaedic head harness and suspended for 12 to 16 h to allow it to warm to room temperature. From this point, the treatment of embalmed and fresh cadavers was essentially the same. The cadaver was marked, measured and photographed (Fig. 1), after which it was transported to the Radiography Department where soft tissue radiographs were taken at most limb skinfold sites. The body was then transported back to the dissection room where hydrostatic weight and skin-plus-subcutaneous adipose depths were measured by incision and direct measurement. Upon completion of the measurement battery, the body was placed in a body bag and put into cold storage to await dissection.

Further on in the study when working with unembalmed cadavers, all landmarking, anthropometry, radiography and other pre-dissection procedures were carried out as soon as possible upon receipt of the body prior to refrigeration. In this way, problems of fluid shifts in the limbs after the body had been suspended for a period of time and also problems relating to the measurement of stiff tissues, specifically skinfolds, were minimized.

On the morning of a dissection day the body was removed from cold storage and immediately weighed. Division lines were marked on the body and dissection begun. Skin, adipose tissue, skeletal muscle, bone, vital organs and viscera were then dissected out by segment and the

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Table 1. Description of male subjects, Brussels Cadaver Analysis Study (CAS 1), Vrije Universiteit Brussel (after Clarys *et al.*, 1984).

	Description of subjects			Gross tissue weights (kg)					
	Age	Cause of death	Supine length (cm)	Weight at dissection	Skin	Adipose	Muscle	Bone	Organs
Embalmed	73	Heart disease	157.1	52.8	2.5	17.3	17.3	7.4	8.4
	78	Heart disease	163.8	70.4	3.8	20.6	26.9	8.9	10.2
	78	Respiratory insuff.	168.0	71.5	4.7	17.8	26.3	11.7	10.9
	70	Natural	160.1	58.5	3.3	18.0	20.1	7.9	9.2
	83	Natural	168.5	51.7	3.3	12.1	17.9	9.8	8.6
	72	Carcinoma	166.8	65.1	3.7	16.9	25.7	9.6	9.1
Mean (±S.D.)	76 (5)		164.0 (4.6)	61.7 (8.6)	3.6 (0.7)	17.1 (2.8)	22.4 (4.4)	9.2 (1.6)	9.4 (1.0)
Unembalmed	65	Heart disease	167.1	54.8	3.2	9.7	23.3	8.8	9.7
	59	Heart disease	174.2	76.8	4.3	20.8	31.2	10.1	10.4
	81	Natural	177.9	61.0	2.7	17.0	21.8	8.7	10.8
	73	Heart disease	173.0	85.1	4.6	25.7	34.8	10.3	9.7
	73	Heart disease	164.6	57.7	2.9	25.3	15.8	7.3	6.3
	55	Suicide	187.6	88.9	5.5	20.8	40.4	11.1	11.1
Mean (±S.D.)	68 (10)		174.1 (8.2)	70.7 (14.8)	3.9 (1.1)	19.9 (5.9)	27.9 (9.2)	9.4	9.7 (1.8)
Total mean	72 (8)		169.1 (8.2)	66.2 (12.5)	3.7 (0.9)	18.5 (4.6)	25.1 (7.4)	9.3 (1.4)	9.5 (1.4)

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Table 2. Description of female subjects, Brussels Cadaver Analysis Study (CAS 1) Vrije Universiteit Brussel (after Clarys *et al.*, 1984).

	Description of subjects			Gross tissue weights (kg)					
	Age	Cause of death	Supine length (cm)	Weight at dissection	Skin	Adipose	Muscle	Bone	Organs
Embalmed	83	Carcinoma	149.2	61.6	4.1	25.3	16.9	7.0	8.3
	94	Heart disease	152.4	49.1	2.9	16.0	15.4	7.7	7.1
	79	Heart disease	158.0	48.3	3.2	14.4	16.0	7.4	7.4
	84	Unknown	158.7	75.4	3.7	35.6	18.6	8.0	9.5
	69	Carcinoma	169.6	62.9	3.9	18.0	20.3	10.0	10.8
	70	Accident	161.2	63.4	3.6	26.9	18.8	7.3	6.8
Mean (±S.D.)	80 (9)		158.2 (7.1)	60.1 (10.2)	3.6 (0.5)	22.7 (8.1)	17.6 (1.9)	7.9 (1.1)	8.3 (1.6)
Unembalmed	79	Heart disease	160.7	58.9	3.1	21.6	18.3	7.7	8.1
	83	Heart disease	173.3	74.2	3.3	40.1	14.3	8.8	7.7
	82	Renal insuff.	162.6	48.2	2.5	18.6	13.3	7.4	6.3
	77	Heart disease	152.2	71.6	3.5	28.0	23.4	7.6	9.1
	68	Natural	154.5	69.0	3.4	32.0	19.3	6.7	7.6
	86	Leukaemia	157.4	61.2	3.6	29.3	14.6	7.7	6.0
	82	Heart disease	164.4	68.8	3.1	29.3	21.7	7.3	7.5
Mean (±S.D.)	80 (6)		160.8 (7.1)	64.6 (9.0)	3.2 (0.3)	28.4 (7.0)	17.8 (3.9)	76.6 (0.6)	7.5 (1.1)
Total mean	80 (7)		159.6 (6.9)	62.5 (9.4)	3.4 (0.4)	25.8 (7.8)	17.8 (3.0)	7.7 (0.8)	7.9 (1.3)

Table 3. Descriptive data (mean ± S.D.) of subjects of the Brussels CAS Project.

Age (yrs)	Height (cm)	Weight (kg)	Skin (kg)	Adipose (kg)	Muscle (kg)	Bone (kg)	Organs (kg)
76 (±9)	164.1 (±8.9)	64.3 (±10.9)	3.5 (±0.7)	22.3 (±7.3)	21.3 (±6.6)	8.5 (±1.4)	8.7 (±1.6)

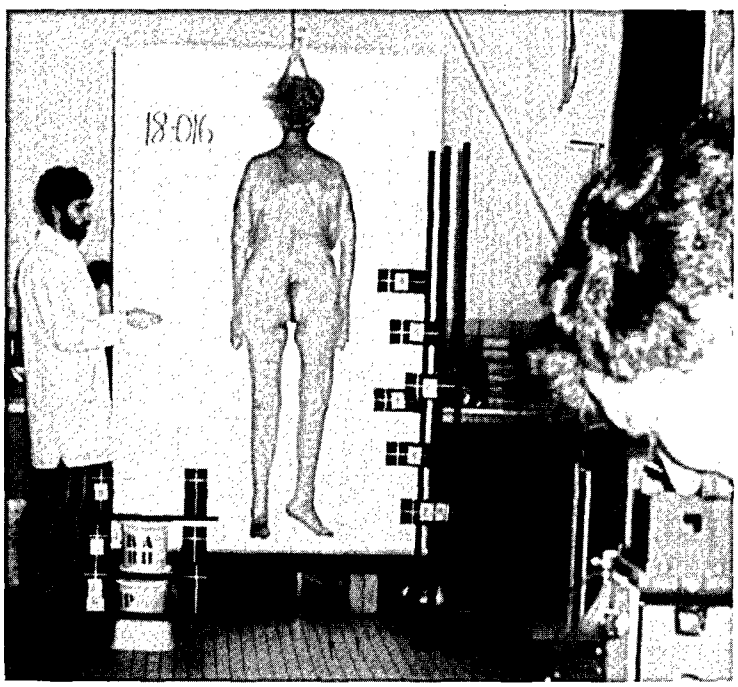

Fig. 1. The marked cadaver ready for photography, anthropometry and incisions.

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tissues placed into covered plastic buckets or Plexiglass containers where they were held until weighing; tissues were wrapped in gauze. The tissue was first weighed in air then under water. Tracings of the dissected skin were made on the first 20 cadavers. After removal of the skin and subcutaneous adipose tissue and before removal of muscle, a further series of girth and breadth measurements was obtained. The last and most arduous task of the dissection was the scraping of tissue from the bones, particularly the ribs, vertebrae, hands and feet. Skeletal remains were retained for the completion of osteometric measurements.

Anthropometric technique and protocol

As applications of the cadaver data to re-designing body composition methods were anticipated, the anthropometric techniques used were similar to those adopted by the

International Working Group on Kinanthropometry (IWGK). These have been specified in detail by Ross and Marfell-Jones (1983).

Adaptations and accommodations of normal anthropometric procedures are required for their employment on cadavers. There were marked changes in protocol in some measures and minor changes in others. Details of the anthropometric adaptations are contained in the theses of Drinkwater (1984) and Martin (1984).

Instrument calibration

Spreading calipers and tapes were calibrated against the anthropometer. The skinfold calipers were calibrated by clamping one arm on a laboratory stand, then hanging laboratory calibration weights from the tip (near the jaw) of the other arm until the jaws just opened. The pressure was determined to be 9.8 g mm^{-2}. The balances used for weighing tissues were regularly checked against laboratory reference weights. This was carried out three or four times each dissection day during the procedure for weighing of tissues.

Photography

While the cadaver remained suspended, it was photographed from the front, the back and each side (anterior, posterior and lateral views) against an illuminated, moveable light box placed about 1 m behind the body. Four 500 W flood lamps, two to each side, were placed about 2 m to the front and side of the body at an angle of about 45°. Vertical markers (50 cm between marks) and horizontal markers (40 cm between marks) were placed at the midline of the cadaver and 30 cm in front of and behind the body. These markers enabled measurements to be obtained from the photographs if necessary (Fig. 1).

Measurement of projected lengths

After the photography was completed the body was lowered onto a hydraulic cart and arranged in a supine position such that the head was oriented in the Frankfort plane. An instrument support was placed under the head and firmly pushed against it. The anthropometer was then placed in the support and projected lengths were measured from the vertex. This technique is similar to that used by Dempster (1955) and Clauser *et al.* (1969) in their studies. Recumbent length was measured from the vertex to the balls of the left and right heels.

Radiography

Before transporting the body to the Department of Radiology of the academic hospital, selected skinfold sites were marked with straight pins. These pins also served to mark the position of sites for measurement of girths when, during the dissection phase of the study, girths were again measured after the removal of skin and subcutaneous adipose tissue. Soft tissue radiographs were made at the triceps, biceps and anterior forearm skinfold sites of both upper limbs and at the medial thigh and medial calf skinfold sites of both lower limbs (Fig. 2). Anterior–posterior radiographs were also made of both knees and of the right elbow. A perforated metal reference bar, placed at the midline of each limb, was included in the image to enable measurements to be

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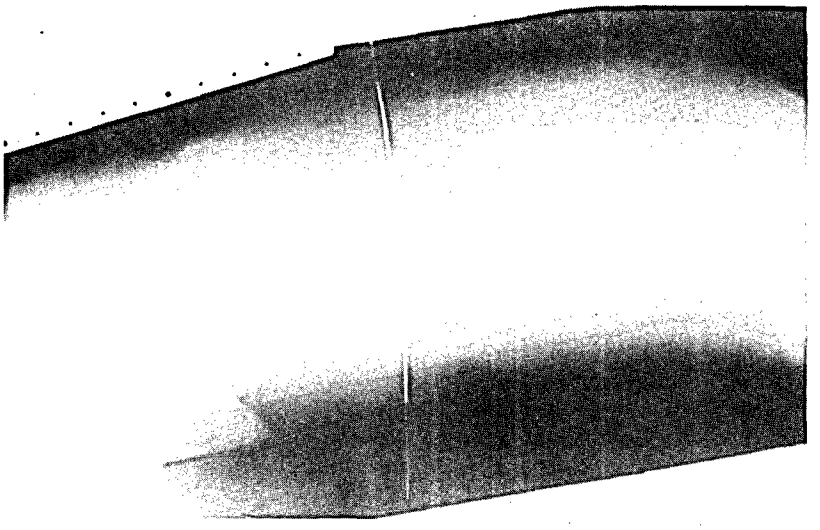

Fig. 2. Soft tissue radiography with pin indicating the skinfold site.

obtained from the radiographs. Computerized axial tomographic scans were made of one cadaver with scanning every 2 cm of the whole body.

Hydrostatic weighing of the intact cadaver

When the radiographic procedures were completed, the body was transported back to the laboratory where body volume was measured by hydrostatic weighing. The cadaver was placed supine on a metal frame, then lowered into a tank of water at 19° C and suspended from a Toledo spring autopsy scale. Steel cross-shaped weights of known hydrostatic weight were used to prevent flotation. Care was taken to ensure that no part of the cadaver or frame touched the tank and that the cadaver was completely submerged. A single reading was taken when needle oscillations on the scale ceased. Weight was recorded before immersion and after immersion (after blotting the cadaver dry) to determine the amount of water, if any, entering the body. No substantial increases in weight (greater than 500 g) were noted.

Measurement of skin-plus-subcutaneous adipose tissue depths

To measure skin-plus-subcutaneous adipose tissue depths, the body was once more placed in the head harness and re-suspended (Fig. 1). Incisions were made through the skin and subcutaneous adipose tissue to the level of the muscle fascia (fascia generalis) at all skinfold sites. Depths of the skin-plus-subcutaneous adipose tissue layer were measured to the nearest millimetre using a small metal ruler positioned at the centre of the incision. This method of measuring skin-plus-subcutaneous adipose tissue depths had been reported by other investigators (Alexander, 1964; Lee and Ng, 1965).

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Dissection procedures

Immediately prior to dissection the subject was re-weighed. Since the tissues from the limbs, trunk and head were to be kept apart from one another, the dissection was begun by marking the division lines between head, limbs and trunk. The segments were not equivalent to those of Clauser *et al.* (1969) and Dempster (1955) in that the heads of the humeri and femora were included with their associated limbs (Fig. 3). The dissection of the skin and subcutaneous adipose tissue was performed according to the normal anatomical procedures as described in Grant (1967). This was followed by the separation of skeletal muscle and major organs (brain, heart, lungs, liver, kidneys and spleen). The remaining soft tissues, that is those of the gastrointestinal tract, major vessels, the spinal cord and internal and external genitalia, were retained as a unit which we refer to as undifferentiated tissues. Vascular, nervous and connective tissues were retained with the gross tissues in which they were found.

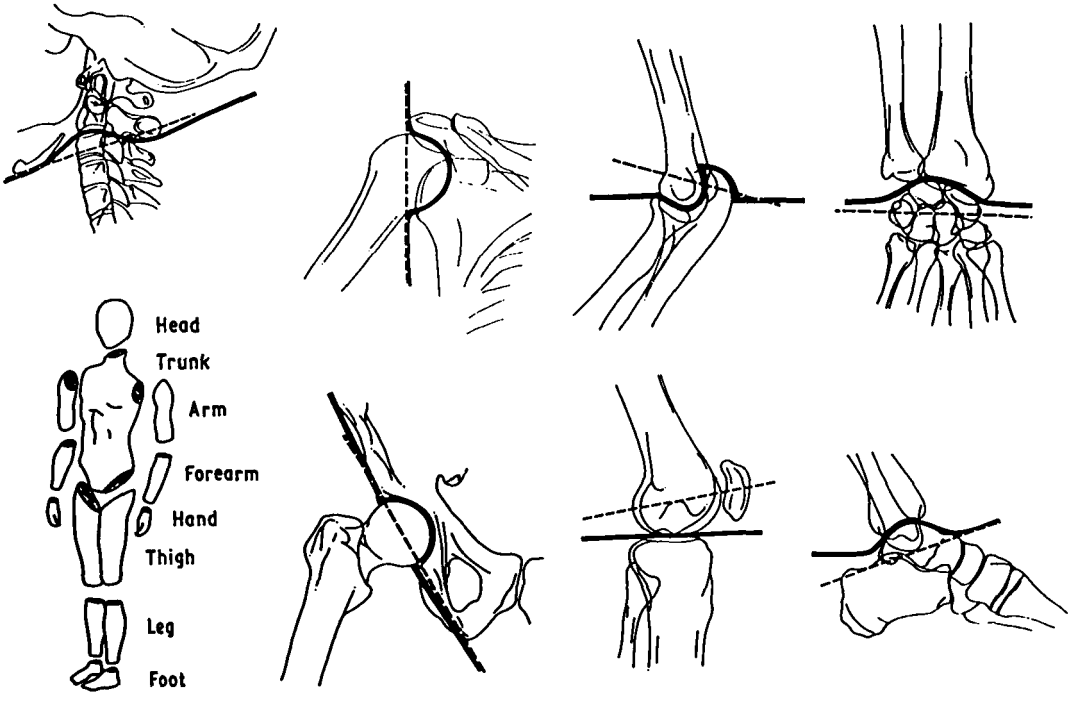

Fig. 3. The cutting plane for limb segmentations.

After the removal of the major masses of soft tissue the individual bones were separated at their articulations and scraped to leave their surfaces free of muscle and adipose tissue. Ligaments were included with muscle and the cartilage of any articular surface was retained with the bone. Any fluid separating from the tissues during the dissection was collected. Evaporative loss from the fresh tissues was reduced by the use of plastic covers over tissues not being processed. All dissected tissues, including scrapings, were stored in airtight plastic buckets

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according to the segment from which they originated. The buckets were fitted with stainless steel strainers to collect any fluid that might separate. All bones were stored in Plexiglass boxes containing moist sponges to reduce evaporative weight loss.

All the collected tissues and fluids were weighed to 0.1 g. The bones were weighed separately except for those of the hands, feet and spinal column, which were weighed as anatomical units. All tissues were then weighed under water to 0.01 g for determination of density. The dissection and weighing were completed within one day to minimize evaporative losses. This required a team of 10 to 12 people working for 10 to 15 h, depending on the size and ease of dissection of the cadaver.

Removal of skin and subcutaneous adipose tissue

The skin was first removed, followed by the subcutaneous adipose tissue. All tissues were removed by segment and placed immediately into airtight plastic buckets to retard evaporative losses. The buckets containing stainless steel strainers to allow collection of fluids draining from the prosected tissues.

Measurement of surface areas

After removal and just prior to weighing, the skin was scraped free of any adhering fascia and adipose tissue. After weighing, the thickness of a double fold of skin at all skinfold sites was measured using a Harpender caliper. The skin was then stretched out on large sheets of non-absorptive paper and the outline of all pieces for each of the six segments carefully traced. This technique provided a record of the skin surface area which was later determined by planimetry. To ensure that no appreciable size changes had occurred, areas marked on the intact and then the dissected skin were measured.

Girths and breadths after removal of skin and subcutaneous adipose tissue

After removal of skin and subcutaneous adipose tissue and prior to dismemberment, girth and breadth measurements were taken at selected sites where surface anthropometric measurements had also been obtained. These sites were marked by pins pushed through the skin and adipose tissues.

Weights

The bundles of tissues were weighed in air to the nearest 0.1 g and were then weighed under water (at 19° C) to the nearest 0.01 g for density determination. All fluids recovered in the specific tissue buckets were also weighed and allocated to the corresponding tissue weight and volume.

Direct bone measurements

One of the final tasks of the study was to make a series of direct measurements on bones of the

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limbs. This was carried out after the rest of the study was completed and was made on bones which had been previously frozen.

Postmortem versus living subjects

The 34 cadavers used in this study were examined and weighed on receipt and those showing severe emaciation, physical abnormality or deterioration were not used. The cadavers in our sample were Belgians ranging in age at death from 16 to 94 years, but with 32 cadavers older than 50 years. An immediate question that can be raised concerns the validity of applying the relationship found in such a sample to the living.

Todd and Lindala (1928) used preservative to restore the tissue to "normal' appearance in 50 white male cadavers in the course of investigating postmortem changes in tissue thickness. They found that the amount of preservative used markedly affected circumferential measurements. In his study, Dempster (1955) used seven unpreserved cadavers and one embalmed cadaver. He made no distinction between the two conditions in measuring or reporting. In a personal communication to Clauser *et al.* (1969), Dempster wrote:

> 'Preserved specimens, which look natural, have in all probability, a weight and volume similar to that which they had at death.'

Fujikawa (1963) used four preserved and one fresh cadaver. He observed:

> '. . . little influence of the injected formalin–alcohol on the ratio of weight of each part to the body weight and little individual difference in the physique'

and also made no differentiation between the cadaver types.

Clauser *et al.* (1969) used 13 embalmed cadavers. They injected a solution (approximately 3 gallons or 13.6 litres) containing equal proportions of phenol, glycerine and alcohol by gravity flow through the subclavian and femoral arteries. They observed that:

> 'the preservative is not retained in the quantities injected for any appreciable time . . . the tissue appearing only to retain the amount needed to replace body fluids lost through the skin immediately post-mortem.'

This finding answers the question raised by Todd and Lindala (1928) concerning the importance of the amount of preservative injected. Clauser *et al.* (1969) concluded that:

> 'cadavers, if properly treated, will be closely comparable, in mass distribution and density, to living subjects . . . [and] . . . use of preserved specimens is not believed to have introduced a significant bias in the results obtained.'

If there are changes in circumferences and segment composition, these changes should be detectable by anthropometry. The relationships should not change to any marked extent, only the absolute values. It is a major assumption of this study, therefore, that the relationship between anthropometric variables and segment composition in cadavers is similar to their relationship in the living.

In addition to the work and statements of the above authors on the matter, we have measured

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in vivo 18 elderly male and 22 elderly female subjects ranging in age from 55 to 92 years. Using a selection of anthropometric measurements employed also in the cadaver sample and determining the somatotype of both the cadaver group and the 'living' subjects according to the Heath and Carter (1967) technique as adapted by Ducquet (1980), an overall comparison of the physique of postmortem and living Belgian subjects of a similar age group was attempted (Figs 4, 5). Apart from a few single measurements it appears that both embalmed and unembalmed cadavers can be used to approximate these relations in the living; in other words, the use of embalmed cadavers, as opposed to fresh cadavers, will not appreciably affect the predictive ability and validity of the models and conclusions generated. Although there were no significant differences between the groups investigated, the fresh cadavers showed more overall similarities.

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Skinfold caliper prediction of fat

As subcutaneous adipose tissue is easily accessible and as it contains a large fraction of the total fat content of the body, the application of skinfold calipers appears most reasonable. It has been pointed out that '. . . only the subcutaneous 'fat' can be estimated by . . . methods as simple as skinfold measurements . . .' (Bonnet and Rocour-Brumioul, 1981), whereas a significant amount of body 'fat' is located within the abdomen, within muscle and elsewhere (Anderson *et al.*, 1982; Clarys *et al.*, 1984; Fanelli and Kuczmarski, 1984; Martin *et al.*, 1985).

The measurement of subcutaneous 'fat' with skinfold calipers is a routine laboratory and field method of assessing body composition and nutritional status (Becque *et al.*, 1986). Häger (1981) stated that '. . . two important assumptions must be made in the calculation of body fat from skinfold measurements: (1) subcutaneous fat constitutes a constant proportion of total body fat over all ranges of body weight, and (2) the sites of measurement are representative of all subcutaneous fat. These assumptions are unlikely to be true . . .'

What is really being measured is the thickness of a double fold of skin and compressed subcutaneous adipose tissue. To infer from this the mass of fat in the body, requires another series of assumptions whose validity has never been seriously challenged. Therefore these assumptions need close scrutiny, and the evidence available to test their validity needs to be reviewed, keeping in mind that 'fat' is the ether-extractable or chemical constituent of the anatomical 'adipose tissue' mass.

The transformation from caliper reading to total body fat can be divided into a number of steps (Martin *et al.*, 1985). The thickness of a compressed double layer of skin and subcutaneous adipose tissue should be representative of the uncompressed double layer of adipose tissue. This should indicate total subcutaneous adiposity. Adiposity must be converted to fat and, finally, the internal fat must somehow be included. These steps are illustrated in Fig. 6 which also shows the assumptions implicit at each step.

Compressibility

The decline in caliper reading after the initial application of the caliper to the skinfold is familiar to all users of skinfold calipers. This dynamic aspect of caliper use has been documented but

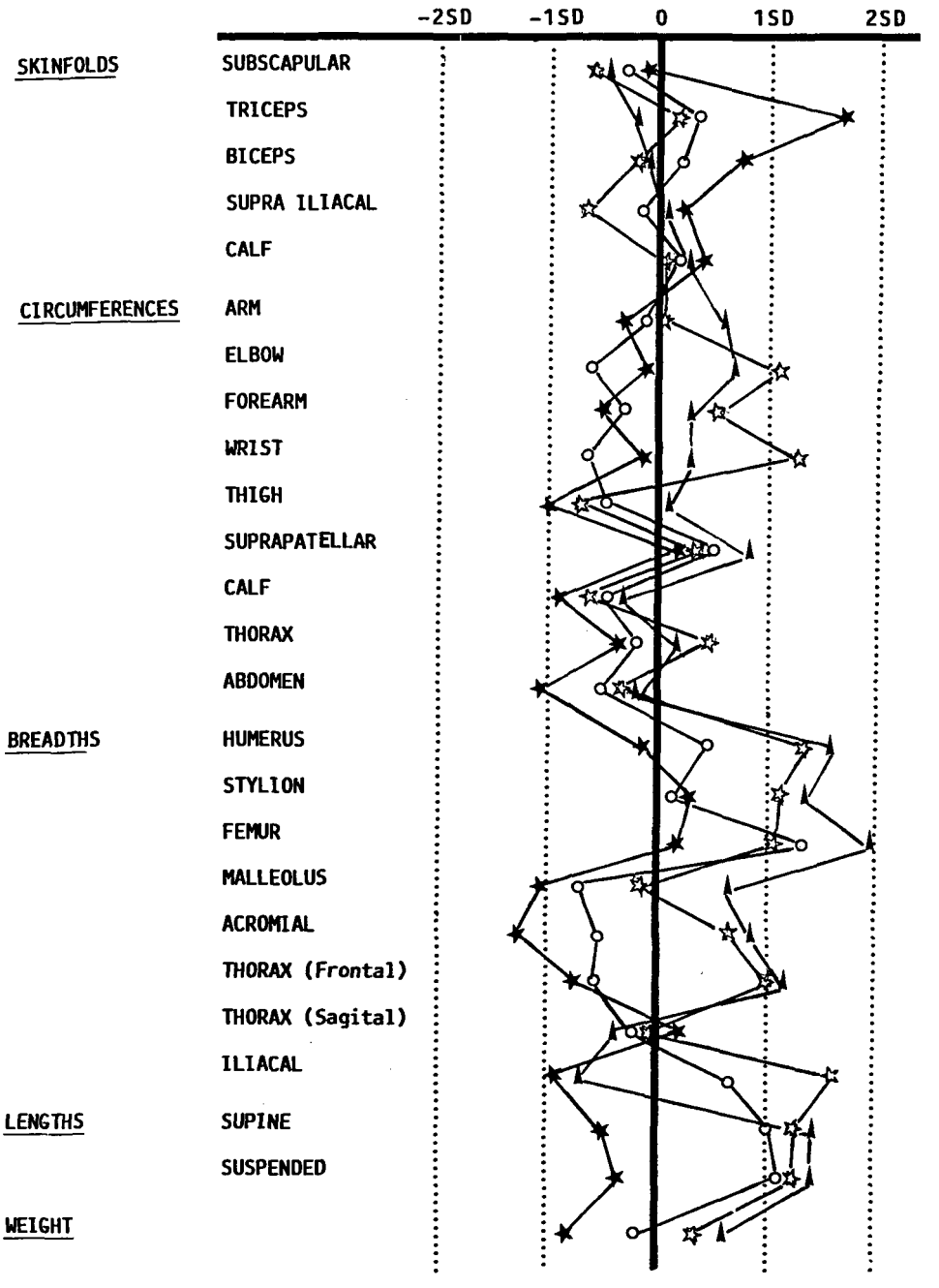

Fig. 4. Normalized anthropometric comparison between the living (zero axis) and the dead (within the same age group): ☆, embalmed female; ▲, unembalmed female; ★, embalmed male; ○, unembalmed male.

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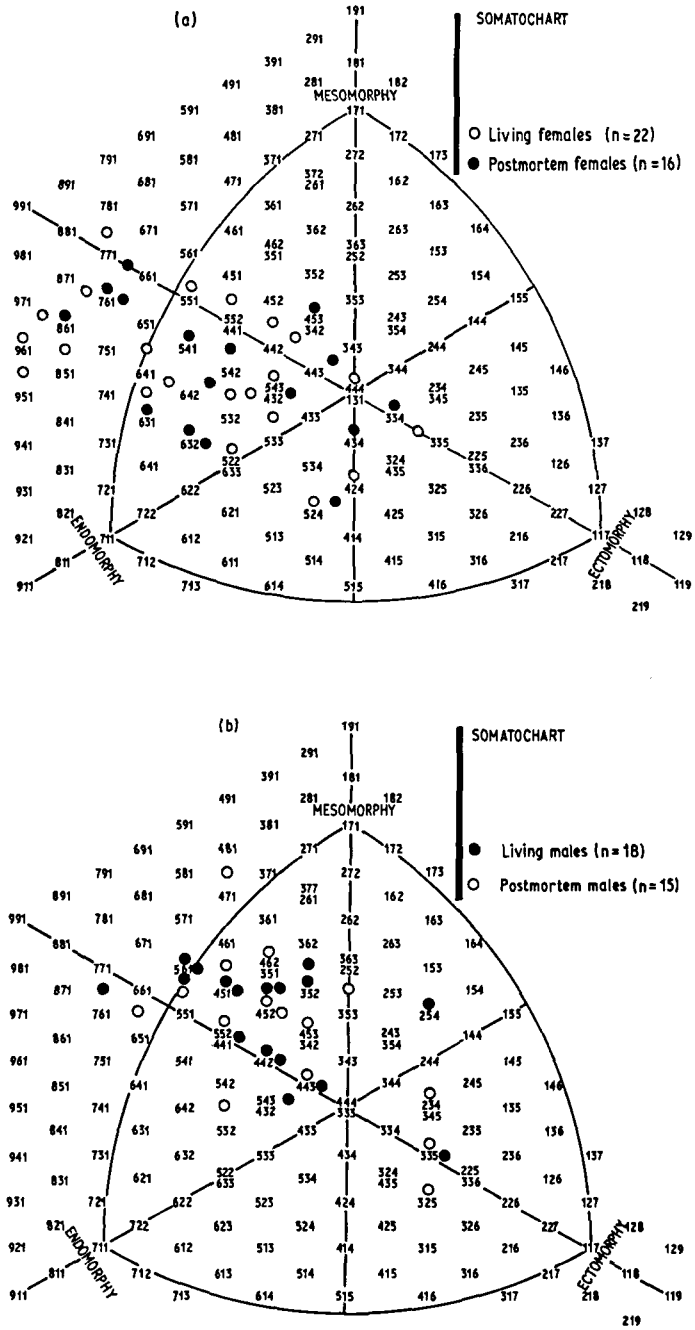

Fig. 5. Somatochart of living and postmortem females (a) and postmortem males (b).

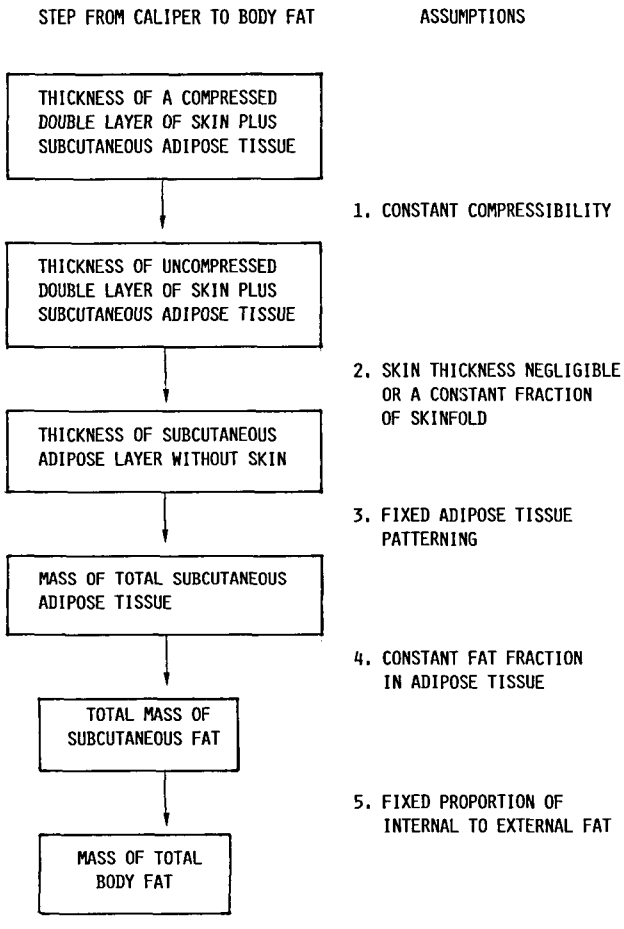

Fig. 6. Steps and assumptions from caliper to body fat. Reproduced from Martin *et al.* (1985) courtesy of the *International Journal of Obesity*.

given little investigative attention (Fletcher, 1962; Orpin and Scott, 1964; Booth *et al.*, 1966). Brans and co-workers (1974) measured the dynamic compressibility of subcutaneous adipose in neonates, and showed an exponential decrease in caliper reading over the first minute.

Most workers adopt some strategy to standardize the reading in spite of its dynamic characteristics. Some wait 'for all needle movements to cease before taking the reading' (Booth *et al.*, 1966), while others record after 'an initial rapid phase of the movement' (Orpin and Scott, 1964), or read after 2 s of applied pressure (Ross and Ward, 1984). None of these authors provided direct evidence to support their procedures. Recently, a clearer recommendation was made by Becque and co-workers (1986) who advised that skinfolds should be read within 4 s of applying the caliper.

In addition to the dynamic compressibility there is also a static one (Fig. 7). Even after

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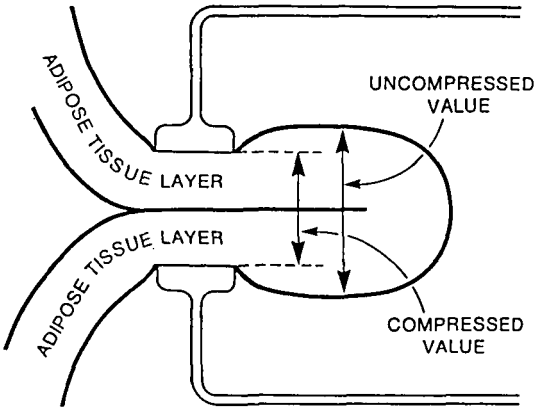

Fig. 7. Skinfold compressibility after Martin *et al.* (1985) courtesy of the *International Journal of Obesity*.

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standardizing the timing of the caliper reading, similar thicknesses of adipose tissue may yield different caliper values due to different degrees of tissue compressibility. Various researchers have studied the extent to which skinfold calipers compress tissue in relation to some uncompressed standard such as that obtained by radiography and ultrasound (Edwards, 1951; Hammond, 1955; Garn and Gorman, 1956; Brozek and Mori, 1958; Jones, 1970; Ward, 1979). Compressibility has generally been defined as:

$$100 \times \frac{(\text{uncompressed value} - \text{compressed value})}{\text{uncompressed value}}$$

allowing for the fact that the compressed value, a double layer, must be halved for comparison with the reference value, a single layer. Mean compressibilities for different samples in the literature already cited ranged from 16 to 51%, with the variability being attributed to sex, age, site and level of tissue hydration. Significant additional variability will also be introduced by the use of different methods for obtaining the reference value.

Since the Brussels CAS data include both skinfold thicknesses and the direct measurement, after incision, of the thickness of the subcutaneous adipose tissue layer, skinfold compressibility could be calculated directly at each site. In accordance with previous practice, compressibility is defined as:

$$100 \times \frac{(\text{incised depth} - \tfrac{1}{2}\,\text{caliper reading})}{\text{incised depth}}$$

Table 4 shows the corresponding values, for both males and females, at all right side sites. The mean compressibility over all sites for each subject ranged from 38.2 to 69.3% with a mean of 52.6%. When all 14 sites were combined there was no significant effect of sex. Differences were observed at different sites, with the front thigh and medial calf showing the lowest compressibilities (33.6 and 34.4%) and the supraspinale and biceps the highest (64.9 and

Table 4. Skinfold compressibilities (%) for six male plus seven female cadavers at 14 sites on the right side.

	Males plus females ($n=13$)	
Site	Mean	S.D.
Subscapular	58.3	11.7
Triceps	48.7	14.7
Biceps	63.8	11.3
Forearm	54.0	11.6
Pectoral	48.0	15.1
Chest	63.4	14.0
Waist	55.9	16.0
Sup-spinale	64.9	9.0
Abdominal	61.3	10.2
Front thigh	33.6	17.0
Med. thigh	50.7	13.0
Rear thigh	45.7	17.2
Patellar	53.9	15.3
Medial calf	34.4	11.6
Overall, all subjects, all sites	52.6	16.2

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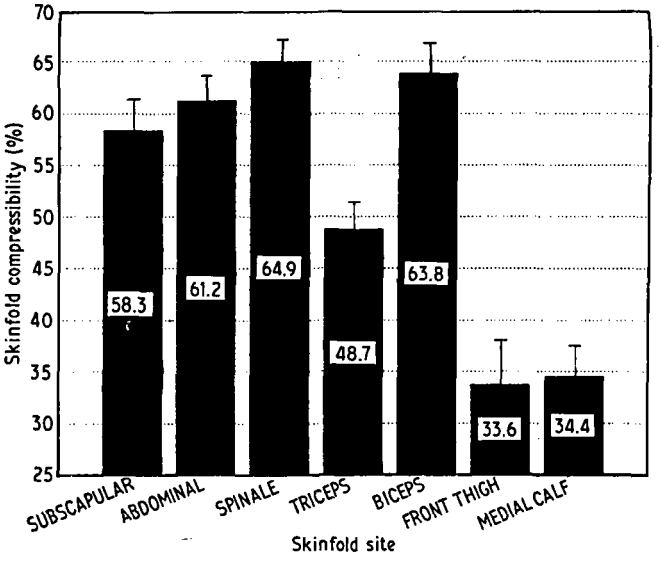

Fig. 8. Compressibility means for seven common skinfold sites.

63.8%). Emphasis is placed on the fact that these sites are commonly selected for prediction of adipose tissue.

Means for all 13 subjects are shown graphically in Fig. 8. The available data clearly demonstrate that skinfold compressibility is by no means constant. This has important implications and the Brussels study included several examples, including two male cadavers with almost identical (dissected) adiposities of 27.1 and 27.8%, whose skinfold caliper readings at the seven commonly used sites show wide differences in compressibility (Fig. 9a). The sums of these seven skinfolds are 116.3 mm for subject No. 20 and 58.9 mm for subject No. 23. This would mean a predicted adiposity value for No. 20 some 97% higher than for No. 23. The apparent contradiction is easily resolved by examining the directly measured adipose tissue thicknesses and compressibilities. Fig. 9b shows the same information as Fig. 9a except that the directly measured (incision) thicknesses are used. The differences are greatly reduced – the sum of seven thicknesses for No. 20 is now only 19% greater than for No. 23, compared to a difference of 97% when caliper readings are used. This remaining difference will be discussed in relation to internal adipose tissue differences. Thus the large error that would arise in the prediction of adipose tissue for these two subjects is a direct reflection of different compressibilities (38.2% compared to 69.3%; Fig. 9a).

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Skin thickness and skin patterning

All skinfold measurements contain a double layer of skin of unknown thickness. If this is very small in comparison to the skinfold measurement then its influence may be negligible. Data on skin thickness are sparse. In an autopsy study on 35 Chinese subjects, Lee (1957) found that forearm skin thickness ranged from 0.82 to 1.82 mm. At the same site Sheppard and Meema (1967), using radiography, reported a mean thickness of 1.43 mm in male and 1.34 mm in female Caucasians. Bliznak and Staple (1975), using a similar procedure, found that males had a thicker skin than females and that for each sex, skin thickness decreased with age. In a much more comprehensive study of 35 cadavers, Lee and Ng (1965) measured skin thickness directly at nine typical skinfold sites. The mean values at each site ranged from 0.96 mm (biceps) to 3.41 mm (subscapular) with somewhat lower values in females. Their technique, which utilized a plastic ruler inserted in the incised skin, only gave readings to the nearest 0.5 mm, a value larger than some of the thicknesses they were measuring.

The Brussels study provides the most comprehensive data on skin thickness to date; the use of a Harpenden skinfold caliper on a double layer of skin enabled measurement to 0.1 mm at all skinfold sites. No correction was made for any compressibility due to the caliper pressure as this was observed to be negligible. The mean data for 14 sites on the right side are shown in Table 5. The site with the thinnest skin was the biceps and the thickest the subscapular, both in male and female. This confirmed previous work concerning significant sex differences. On the other hand, the effect of the variability of skin thickness on skinfold values has never been seriously assessed. Since the doubled skin thickness is generally of the order of a few millimetres, it would appear that the effect of skin would be most marked at those sites and in those subjects with little adipose tissue. Skin thickness expressed as a percentage of skinfold reading is given in Table 6. The site where the effect of skin thickness was most marked was the subscapular, where skin

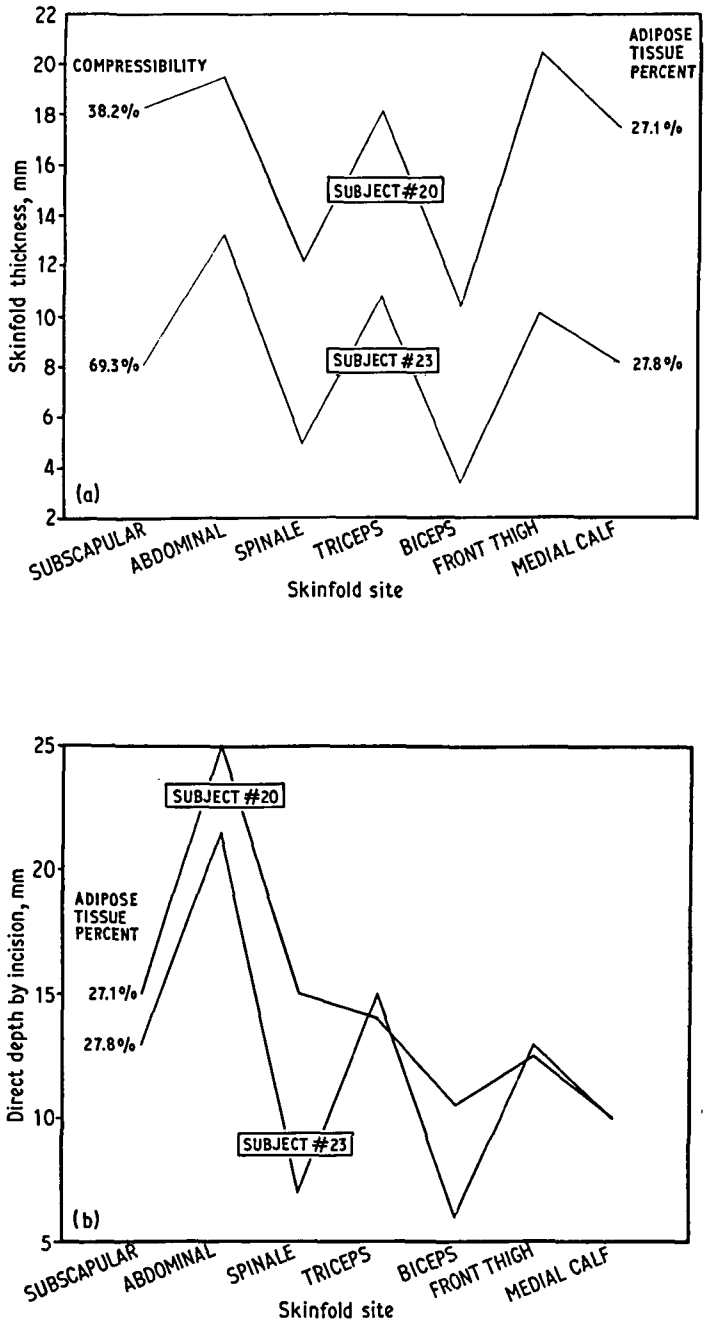

Fig. 9. (a) Extremely different compressibilities with similar adiposities (adipose tissue patterning by caliper. (b) Similar adiposities (adipose tissue patterning by incision).

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Table 5. Skin thickness (mm) means (±S.D.) for 13 subjects (six male plus seven female cadavers) at 14 right side sites, ranked.

Site (right side)	Males ($n=6$)	Females ($n=7$)	Males + females ($n=13$)	Rank		
				Males + females	Males only	Females only
Subscapular	2.07 (±0.38)	1.74 (±0.33)	1.87 (±0.38)	1	1	1
Waist	1.58 (±0.28)	1.32 (±0.24)	1.44 (±0.28)	2	2	3
Pectoral	1.23 (±0.28)	1.33 (±0.38)	1.28 (±0.32)	3	7	2
Abdominal	1.49 (±0.30)	1.04 (±0.21)	1.25 (±0.34)	4	3	5
Triceps	1.28 (±0.42)	1.10 (±0.34)	1.18 (±0.37)	5	5	4
Rear thigh	1.21 (±0.30)	1.04 (±0.28)	1.12 (±0.29)	6	9	5
Front thigh	1.21 (±0.33)	1.02 (±0.09)	1.11 (±0.24)	7	10	7
Patellar	1.22 (±0.37)	0.99 (±0.21)	1.10 (±0.30)	8	8	8
Sup-spinale	1.27 (±0.36)	0.92 (±0.06)	1.10 (±0.28)	8	6	9
Chest	1.39 (±0.24)	0.82 (±0.20)	1.10 (±0.37)	8	4	10
Medial thigh	0.91 (±0.22)	0.79 (±0.14)	0.84 (±0.18)	11	11	11
Medial calf	0.89 (±0.25)	0.79 (±0.11)	0.84 (±0.18)	12	12	11
Forearm	0.77 (±0.23)	0.60 (±0.09)	0.68 (±0.18)	13	13	13
Biceps	0.77 (±0.20)	0.49 (±0.12)	0.62 (±0.21)	14	14	14
Overall mean	1.22 (±0.43)	1.00 (±0.37)	1.10 (±0.37)			

Table 6. Skin thickness as a percentage of skinfold reading (subcutaneous tissue + double layer of skin): overall means for each site, ranked.

			Rank		
Site	Mean	S.D.	Males + females	Males only	Females only
Subscapular	28.1	(8.8)	1	1	1
Waist	21.0	(9.8)	2	5	3
Supraspinale	20.4	(12.3)	3	2	5
Patellar	18.3	(9.3)	4	7	4
Biceps	17.9	(12.5)	5	3	10
Pectoral	17.9	(6.2)	6	10	2
Rear thigh	17.9	(11.6)	7	4	8
Forearm	16.4	(7.5)	8	6	6
Chest	15.6	(8.8)	9	8	7
Triceps	13.2	(5.5)	10	11	8
Abdominal	12.9	(6.9)	11	12	11
Medial calf	12.7	(6.9)	12	9	12
Front thigh	11.5	(8.1)	13	13	13
Medial thigh	8.2	(4.8)	14	14	14
Overall mean	16.5	(9.9)			

thickness accounted for 28.1% of the skinfold reading (34.0% for males, 23.9% for females). It can be seen that two of the most commonly used sites for predicting body fat, the subscapular and triceps, have quite different proportions of skin.

In summary, while the contribution of skin to total skinfold thickness is generally not large, it may lead to significant error, especially in lean males. Normalized as a percentage of total adipose tissue free mass (ATFM) it can be noted that skin can have an important contribution (Fig. 10). Sites where skin thickness is small relative to skinfold might prove better predictors of adiposity. Consequently, on the basis of skin thickness, the subscapular skinfold should be a poorer predictor than the skinfold at arm and leg sites.

Adipose tissue patterning or topography

'Fat patterning' refers to differences in the anatomical placement of adipose tissue (Mueller, 1985). For reasons mentioned earlier, the term 'fat' should be replaced by 'adipose tissue'. The patterning of subcutaneous adipose tissue is known to exhibit very large variations between individuals (Edwards, 1951; Garn, 1955, 1971; Mueller and Stallones, 1981).

Garn (1955) used *z*-score pattern profiles of selected and representative subcutaneous areas. Vague (1983) used the adipo–muscular ratio, which is the ratio of adipose tissue to muscle areas on the upper (arm) and lower (trochanter) limbs. Feldman *et al.* (1969) used various *ad hoc* skinfold ratios. Others have examined normal variation in statistical 'components' (Mueller and Reid, 1979; Mueller and Wohlleb, 1981) or 'clusters' (Bailey *et al.*, 1982) of adipose patterns.

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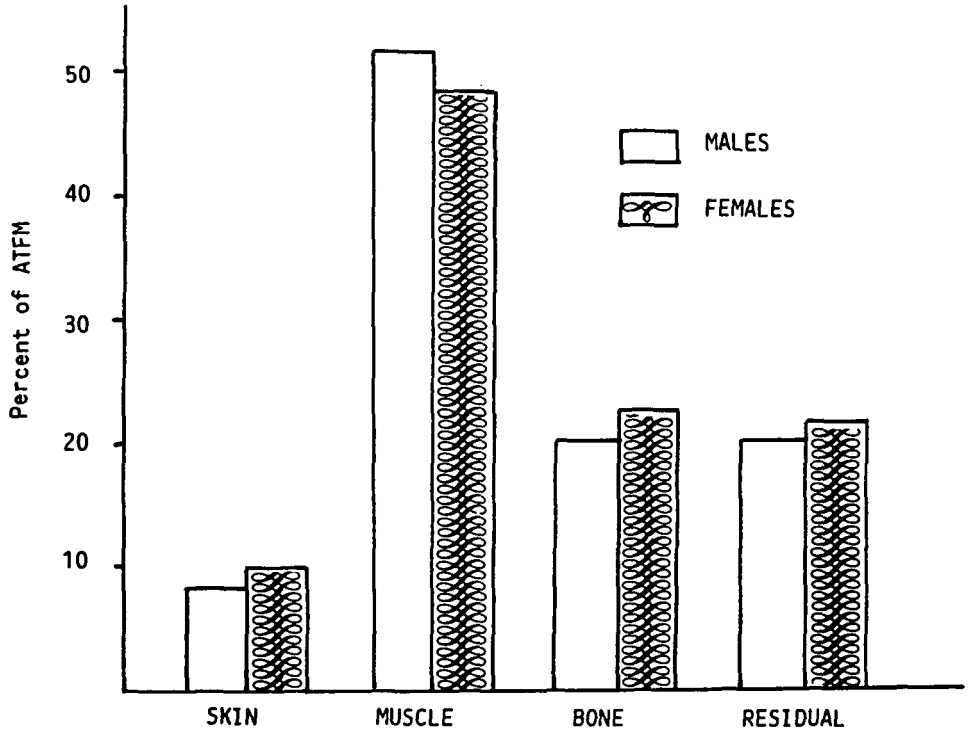

Fig. 10. Masses of skin, muscle, bone and residual as percentage of adipose tissue mass (ATFM).

The most widely used field method, skinfolds, often cannot be performed in the morbidly obese; hence ratios of diameters of the body outline or circumferences have been proposed as a method of overcoming this problem (Ashwell *et al.*, 1978, 1982, 1985). The relationship between the various methods and their reliability needs to be examined (Mueller, 1985). The multivariate approaches may require as few as two skinfolds (Mueller and Stallones, 1981; Mueller, 1985). The critical concerns are, firstly, the number of skinfold readings that are required to be representative of the adipose tissue pattern, and, secondly, the choice of the best sites.

To provide an overall impression of adipose tissue distribution, adipose tissue mass per segment as a percentage of total adipose tissue mass is shown in Fig. 11. Fig. 12a shows the skinfolds at seven commonly chosen sites for seven female cadavers and Fig. 12b shows the incision values at the same sites. Both patterning approaches indicate wide differences in subcutaneous adipose tissue topography.

To assess the value of various sites as predictors of subcutaneous adiposity, correlations between the caliper and incision thicknesses with the dissected subcutaneous adipose tissue mass have been determined (Table 7). An unexpected finding is the high correlation for lower limb sites. Of the six best sites all but one were on the lower limb. The triceps, a highly favoured site for 'fat' prediction and sometimes considered to be the best single indicator of adipose tissue,

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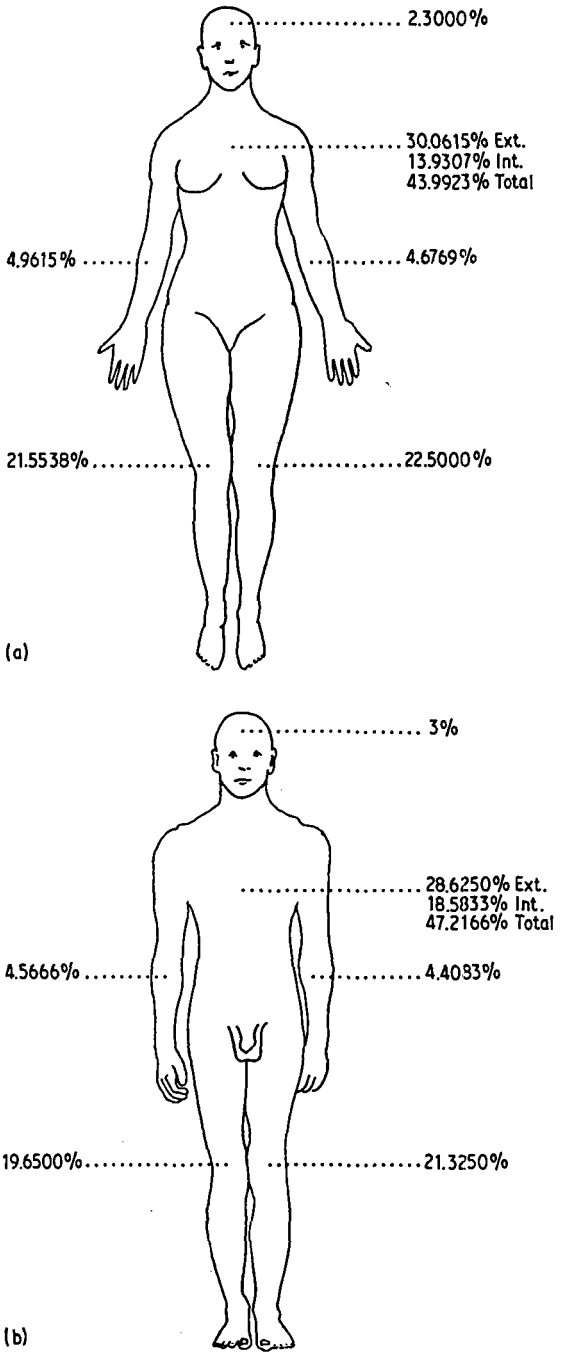

Fig. 11. Adipose tissue per segment as percentage of total adiposity in (a) female and (b) male.

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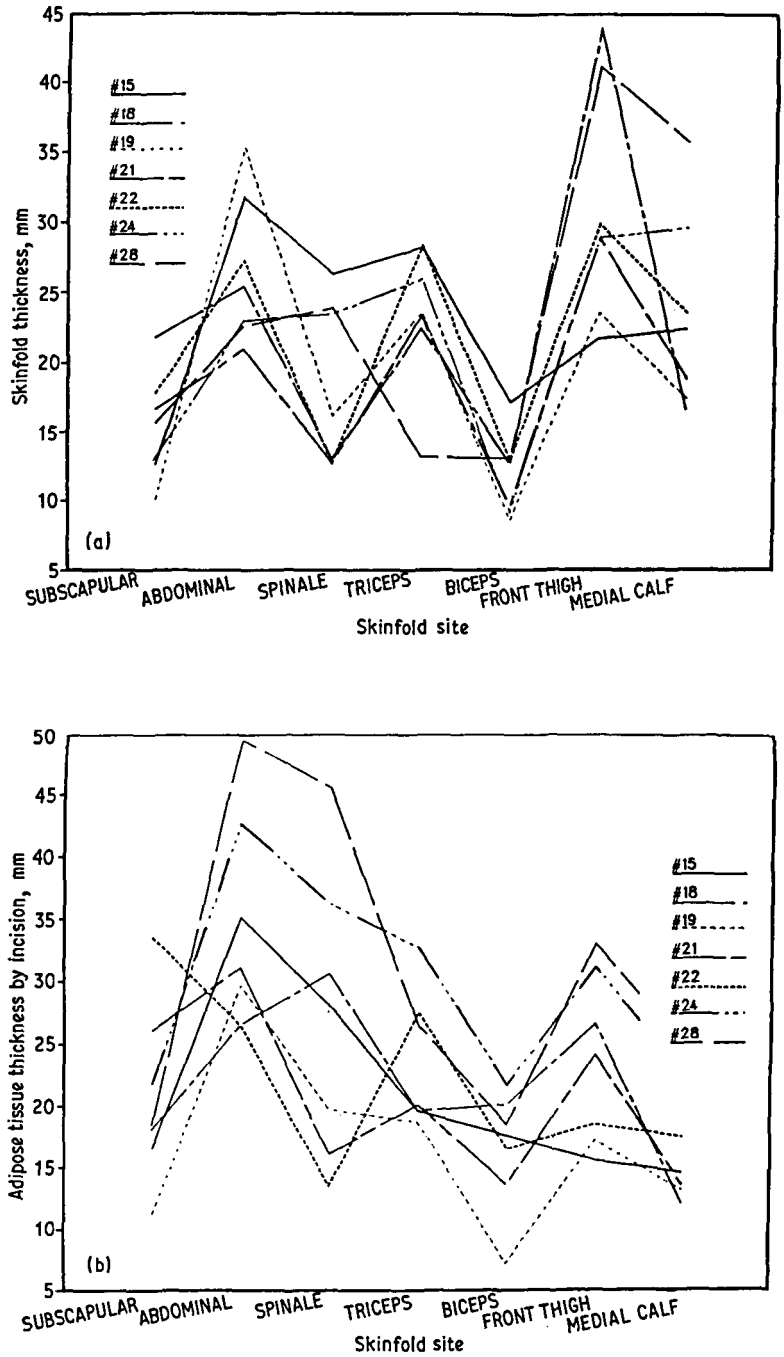

Fig. 12. Adipose tissue patterning (a) by caliper and (b) by incision.

Table 7. Correlation coefficients of caliper reading and incised depth with total subcutaneous adipose tissue mass (after Martin *et al.*, 1985).

Site (right side)	Caliper reading		Incised depth	
	Uncorrected	Corrected for skin thickness	Uncorrected	Corrected for skin thickness
Front thigh	0.89	0.88	0.87	0.87
Sup-patellar	0.85	0.86	0.91	0.91
Medial calf	0.84	0.85	0.82	0.82
Rear thigh	0.82	0.84	0.75	0.76
Forearm	0.80	0.83	0.74	0.74
Medial thigh	0.76	0.79	0.83	0.83
Chest	0.64	0.70	0.68	0.68
Supraspinale	0.61	0.62	0.73	0.73
Biceps	0.58	0.61	0.78	0.79
Subscapular	0.54	0.67	0.62	0.63
Triceps	0.39[a]	0.43[a]	0.73	0.74
Abdominal	0.34[a]	0.49[a]	0.75	0.75
Waist	0.31[a]	0.33[a]	0.62	0.62
Pectoral	0.23[a]	0.24[a]	0.09[a]	0.08[a]

[a] Denotes not significant at the 5% level of probability.

ranked a poor eleventh. As would be expected, correction for skin thickness for both caliper and incision values improved the correlations in 17 out of the 28 values, but it must be noted that most of the improvements were marginal.

In a later analysis of 15 different sites of the 'CAS 2' cadavers, the best predictors were front thigh, medial calf, rear thigh and supra-spinale, confirming in part the calculated findings of Martin (1984). This suggests that the commonsense approach of selecting sites from all important storage levels – e.g. segments, and especially the legs – is well founded.

Chemical fat in anatomical adipose tissue

Even if the mass of subcutaneous adipose tissue was known exactly, the prediction of subcutaneous fat mass requires some assumption concerning the fat content of adipose tissue. Reported values range from 5.2 to 94.1% (Martin, 1984), but they are generally in the range 60–85%. Besides, the fat content of adipose tissue increases with increasing adiposity. This has been demonstrated cross-sectionally (Pawan and Clode, 1960; Thomas, 1962), although the relationship has not been quantified. The Brussels study included no chemical analysis for fat, but six samples of adipose tissue from each of six subjects were desiccated to constant weight under vacuum and the water contents were determined. These limited data support the previous findings of decreasing water content and increasing fat content as adiposity levels increase. The correlation coefficient between water content and adiposity was −0.94. Although it was recognized that more data are needed to quantify this trend accurately, these results indicate

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that over the range of adiposity in our sample the water content of adipose tissue would be expected to vary from about 14 to 34% (Martin *et al.*, 1985). Due to the inverse relationship between water and fat content this would roughly correspond to a similar range (about 20%) in fat content.

Thus the problem of estimating body fat content by skinfold caliper is compounded by the fact that two identical thicknesses of adipose tissue may contain significantly different concentrations of fat.

The number of adipose tissue compartments

There is very good evidence that people with a 'centralized' adipose tissue distribution (high waist to hip ratio (WHR) – 'apples') are most at risk from diabetes, coronary heart disease, hypertension and stroke compared with those people with a peripheral adipose tissue distribution (low WHR – 'pears') (Ashwell, 1985). It is assumed that 'apples', or people with a high WHR ratio, have the greater proportion of intra-abdominal adipose tissue.

In general, research in body composition deals with a two-compartment adipose tissue distribution, the subcutaneous or external and the intra-abdominal (better referred to as internal) adipose tissue.

From evidence based on cadaver studies it is assumed that, both in male and female subjects, the excess of adipose tissue is piled up subcutaneously, inter-muscular and internally, mostly in the trunk. The amount of intra-muscular fat in the obese should not be underestimated and should therefore be considered as a third compartment. However, in both our cadaver analysis studies the intramuscular amount has been allocated to the internal adipose tissue.

Skinfold calipers are only able to estimate subcutaneous adiposity; in order to estimate total body fat some assumption must be made about the relation between internal and subcutaneous fat. If internal fat stores are proportional to subcutaneous fat, this relationship provides a rationale for the use of skinfold calipers. An alternative is that internal fat may be negligible compared with subcutaneous fat, again providing some justification for the use of calipers. Unfortunately, there are no direct data, even in a single subject, on the amounts of internal and external fat.

The Brussels studies provide comprehensive data on the relation of internal to subcutaneous adipose tissue masses. Fig. 13 shows the mass of dissectible internal adipose tissue mass, with linear regression lines drawn for males and females. There were high correlations between a number of (but not all) skinfold sites and subcutaneous adipose tissue (Table 7), but the correlation between skinfolds and internal adipose tissue was non-significant. However, skinfolds were significantly correlated with the total amount of adipose tissue (internal plus external), indicating a dominance of subcutaneous adiposity, even though intra-muscular adiposity has not been allocated to it (Marsboom and Clarys, 1982). Obviously, and referring to our previous statements, little can be said about the proportion of internal to external fat.

Skinfold prediction formulae and other implications

The sample specificity of skinfold prediction formulae is in part a result of wide variations in

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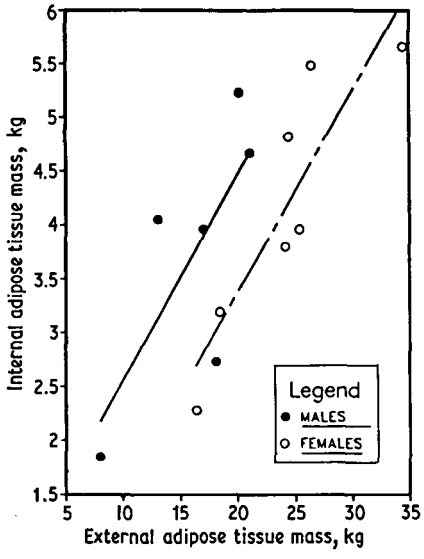

Fig. 13. The relationship between internal + intramuscular and external adiposity ($n = 13$). Reproduced from Martin *et al.* (1985) courtesy of the *International Journal of Obesity*.

compressibility, internal to subcutaneous adiposity ratios and adipose tissue composition. In addition, all prediction equations must be calibrated by another technique whose errors will compound those inherent in caliper use. Densitometry, the commonest criterion, requires that the density of the fat-free portion of the body is constant, an assumption that may be violated far more frequently than is commonly thought (Martin, 1984; Clarys and Martin, 1985; Martin *et al.*, 1986). In view of this uncertainty, it seems unreasonable to introduce further error by transforming anthropometric values into percent body fat.

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