COMPARATIVE DIGESTIBILITY OF WHOLEMEAL AND WHITE BREADS AND THE EFFECT OF THE DEGREE OF FINENESS OF GRINDING ON THE FORMER

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The first satisfactory experiments on the relative digestibility of wholemeal and white breads were carried out by Rubner (1883), whose results are current in physiological text-books throughout the world. His inquiry was undertaken at the instigation of the British Bread Reform League, who supplied the wholemeal flour. The white flours were ordinary straight run (70% extraction). A further series of experiments was begun at Minnesota in 1900 at a time when there was propaganda in favour of 'wholemeal Graham' bread (Woods & Merrill, 1900; Snyder, 1901, 1905). A further inquiry instigated by public clamour for eating 'standard' bread was made at Cambridge (Newman, Robinson, Halnan & Neville, 1912). Because of restrictions in food supplies imposed by the last war, Rubner (1916) returned to the subject and made some further experiments to determine how wheat could be utilized most economically. A War Food Committee of the Royal Society (1918) also organized some experiments with the same object.

The results of these early experiments are set out in Table 1. The values are expressed as the digestibility of the bread alone. In Rubner's experiments and in a later experiment by Martin & Robison (1922) the diet consisted entirely of bread. In the American experiments by Woods & Merrill and Snyder, digestion coefficients obtained in earlier experiments were used in computing the faecal matter produced by constituents of the ration other than bread; these constituents often formed as much as half the ration. In the other experiments these constituents were assumed to be completely digestible; they formed about 40% of the total nitrogen and about 50% of the total energy in the Royal Society experiments and about 25% of the nitrogen and 37% of the energy in the experiments of Newman *et al.* Only in Martin & Robison's experiments, the Royal Society experiments and those of Newman *et al.* at the two lower extractions were the feeding periods of more than 4 days' duration.

The aims of the experiments described below were:

(1) To provide further information on the relative availability of the constituents of white and wholemeal breads.

(2) To find whether the fineness to which wholemeal flour is ground affects the digestibility of the bread.

Such information as we have on the effect of grinding cereals on their digestibility is chiefly from agricultural sources. Except for poultry (Maslieff & Denissoff, 1936; Fritz, 1935), grinding increases the digestibility of oats, barley and maize for one-stomached animals (Hansson, 1931; Woodman, Evans & Kitchin, 1932). Information on the effect

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Table 1. *Percentage digestibility of total energy (E) and total nitrogen (N) in breads made from wheat flours of different degrees of extraction**

Percentage extraction ...	100		95–92		88		85	
	E	*N*	*E*	*N*	*E*	*N*	*E*	*N*
1. Rubner (1883)	93†	70	—	—	—	—	—	—
2. Rubner (1916)	—	—	88·9	78·9	—	—	—	—
3. Woods & Merrill (1900)	88	77	—	—	—	—	94	86·7
4. Snyder (1901)	83·9	77·6	—	—	—	—	88·9	80·4
5. Snyder (1905): (1)	83·9	63·0	—	—	—	—	89·7	76·1
(2)	84·7	77·3	—	—	—	—	87·6	79·6
6. Newman *et al.* (1912)	—	—	91·4	76·7	92·1	80·4	—	—
7. Martin & Robison (1922)	—	79·2	—	—	—	—	—	—
8. Royal Society (1918)	—	—	—	—	89·2	78·4	—	—

Percentage extraction ...	80		78		70		Patent flours	
	E	*N*	*E*	*N*	*E*	*N*	*E*	*N*
1. Rubner (1883)	—	—	—	—	97†	75	—	—
2. Rubner (1916)	—	—	—	—	95·4	87·7	—	—
3. Woods & Merrill (1900)	—	—	—	—	94·2	86·4	—	—
4. Snyder (1901)	—	—	—	—	93·2	85·3	—	—
5. Snyder (1905): (1)	—	—	—	—	97·1	84·9	—	—
(2)	—	—	—	—	96·2	90·9	—	—
6. Newman *et al.* (1912)	95·8	85·9	—	—	—	—	97·3	89·3
7. Martin & Robison (1922)	—	—	—	—	—	—	—	—
8. Royal Society (1918)	—	—	93·0	82·5	—	—	—	—

* Extraction is the percentage of the total grain recovered in the flour after milling.
† 'Carbohydrate.'

Description of flours used

1. Rubner (1883). Wholemeal was obtained from the British Bread Reform League, Manchester. 70% extraction was mixed Girka and Minnesota wheat.
2. Rubner (1916). Wholemeal was 'Volkormehl'. 70% extraction was the 'best obtainable'.
3. Woods & Merrill (1900) not stated.
4. Snyder (1901). Flours prepared from hard Scotch Fife spring wheat.
5. Snyder (1905). (1) Flours prepared from Oregon white winter wheat. (2) Flours prepared from hard winter Weissenberg wheat.
6. Newman *et al.* (1912). Wholemeal flours prepared from home-grown wheat. Patents flour from a blend of home-grown and foreign wheat.
7. Martin & Robison (1922). Mixed grist, Allinson's wholemeal flour.
8. Royal Society (1918). Mixed grist.

Table 2

Type of flour	% extraction	% digestibility of protein	% digestibility of carbohydrate
'Graham wholemeal'	100	77·3	87·4
'Entire wheat'	85	79·6	90·5
White	70	90·9	97·7
White flour mixed with finely ground bran	86	85·9	93·4

of the degree of fineness of flour on the digestibility of bread for human subjects is very meagre. Table 2 gives values obtained by Snyder (1905) for three breads made from flours of 100, 85 and 70% extraction and for a bread from a flour of 86% extraction made by mixing white flour with finely ground bran, which formed 14% of the mixture. Snyder concluded from these experiments that grinding the bran finely increased its digestibility.

METHOD OF EXPERIMENT

The conventional method of determining the coefficients of digestibility of the constituents of a foodstuff was used. This is arrived at by subtracting the output in the faeces from the intake and expressing the result as the percentage of the latter. This procedure does not determine the true digestibility as some material is contributed to the faeces by the various secretions into the gut.

In the estimations of the total energy, fat and carbohydrates of the food which is digested, this is of smaller moment, but the utilization of nitrogen is considerably underestimated as the intestinal contribution to the faeces is rich in nitrogen. The amount of this endogenous nitrogen varies with the individual and with the amount and nature of the food ingested.

The bacteria in the faeces, which amount to 10–30% of the dry weight, introduce another complication. They contain upwards of 10% nitrogen on a dry weight basis and it is uncertain how much of this bacterial nitrogen is derived from the food and how much from the intestinal secretions.

Further, the proportion of nitrogen in the foodstuff under investigation seriously influences the apparent digestibility. If small, the endogenous contribution of the nitrogen to the faeces is proportionately high. This is well illustrated by some experiments of Snyder (1905) who determined the apparent digestibility on the same person and under the same conditions of the nitrogen in wholemeal flours ground from Oregon white winter wheat containing 9% protein and hard winter Weissenberg wheat containing 16·8% protein. The coefficients were 66 and 78 respectively.

To avoid fallacies from individual capacity to digest it is important to have a suitable statistical lay-out. There were six subjects and three treatments, white bread, wholemeal bread made from medium ground flour, and wholemeal bread made from fine ground flour. Three experiments were carried out on each of the six subjects, one with each of the three treatments. There were thus six possible orders in which the three treatments might be distributed over the three experimental periods for each subject. One of these orders was assigned to each subject at random. With this lay-out the effects of periods, persons and treatments could be separated by the ordinary analysis of variance.

The feeding periods consisted of a preliminary period of 3 days (in period A it was 3½ days), an experimental period of 7 days, and an end period of 1–4 days. On the morning of the first day of the experimental period before breakfast 1·5 g. of carmine was taken in a gelatin capsule. The collection of the faeces began when the red colour first appeared in the faeces, the red portion only being retained. On the morning after the last day of the experimental feeding period another carmine capsule was taken and the collection of the faeces was discontinued when the red colour first appeared in the faeces, the red portion being rejected. The subjects remained on the experimental rations till the marker appeared in the faeces. Between the experimental periods there was an interval of about a week during which the subjects took their normal diet. The subjects were weighed at the beginning of the preliminary period and at the end of the experimental period.

The faeces were collected in large glass jars. Collections for a whole feeding period were combined. They were preserved by covering with $N/5$ H_2SO_4. The samples of faeces were weighed at the end of the periods, and thoroughly mixed. They were dried at 110° C.

and the analyses were made on the dry samples. The faeces were analysed for total nitrogen by the Kjeldahl method, for total energy by the bomb calorimeter, for ether extract by soxhlet extraction and for crude fibre by the method described in *Methods of Analysis of the Association of Official Agricultural Chemists* (Washington), 4th ed., p. 340.

A few faeces samples were analysed for total nitrogen before drying and the results were in good agreement with those obtained from the dried samples. The breads were analysed in the same way as the faeces, except that the ether extract was determined by a method specially suitable for cereal products described in *Methods of Analysis of the Association of Official Agricultural Chemists*, 4th ed. p. 229.

To find out whether the length of the 4-day preliminary period was adequate, daily analyses of the faeces excreted by the subject J.C.D.H. were carried out throughout the whole feeding periods. No big changes in the amount of nitrogen and dry matter excreted were found after the end of the preliminary period.

The flours from which the breads were made were kindly supplied by the Research Association of British Flour Millers who also carried out the sieving tests and gave recipes for the baking of the breads. All flours were derived from the same grist. The wholemeal flours were reconstituted, 100% extraction flours, and the two specimens differed only in the degree to which the offals were ground before reconstitution. The results of the sieving tests on the flours are given in Table 3.

Table 3. *Sieving tests on the flours*

No. of silk	24g.g.	32g.g.	1s.	5s.	10s.	14s.	Through 14s.
Corresponding size of aperture (mm.)	0·860	0·605	0·390	0·270	0·135	0·095	0·095
	Percentage on the above silks						
Medium wholemeal flour	1·4	3·5	6·4	4·2	5·8	14·7	62·5
Fine wholemeal flour	Trace	Trace	0·1	2·2	10·8	13·4	73·5

The breads were baked three times weekly by Messrs Matthew and Son, Cambridge. In the baking 1 oz. of yeast and $1\frac{1}{3}$ oz. salt were added to 6 lb. of flour. The loaves were weighed after they had cooled; samples having the correct proportion of crust were cut from each batch and the dry weights determined by finding the loss in weight on heating at 105° C. for 4 hr. In order to obtain representative material for estimation of the calorific value, nitrogen, ether extract and fibre content of the three breads, the various dried samples which were obtained in the determinations of the dry weights of the different batches were ground and mixed. The values found expressed on a dry weight basis, are given in Table 4.

Table 4. *Composition of breads (on dry-matter basis)*

	kg.cal. per g.	% N (Kjeldahl)	% ether extract	% crude fibre
White	4·365	2·70	2·21	0·159
Medium wholemeal	4·450	2·91	3·23	2·07
Fine wholemeal	4·415	2·92	3·41	2·18

The rations were so arranged that the constituents other than bread were reduced to a minimum. The quantities taken were 37 g. margarine, 72 g. marmalade, $\frac{1}{2}$ pint milk and $\frac{1}{2}$ pint beer daily. Tea and coffee were taken ad lib., and saccharine was taken by some of the subjects. The margarine was bought on the open market. The marmalade was kindly given by Messrs Chivers; it was a jelly variety, and contained only 0·24%

insoluble matter and 0·38% pectic acid expressed as calcium pectate. The milk was obtained from Onyett's Dairy, Cambridge. The beer was a bottled pale ale from the Greene King Brewery, Cambridge. Each subject had 50 mg. ascorbic acid daily. The bread was given ad lib. except that the subjects were encouraged to keep to a constant intake in the individual periods so far as they could do so without discomfort or hunger. Details of the bread intake are given in Table 5. 2–2½ lb. of bread were consumed daily by each subject. The energy of the bread was 74% of the total energy intake, and the bread nitrogen 90% of the total nitrogen of the ration.

EXPERIMENTAL RESULTS

Table 5 gives the amount of bread consumed and the intake of energy, crude protein, ether extract, crude fibre and total carbohydrate energy derived therefrom. The table also gives the total nutrients derived from foods other than bread, and also values for the faecal excretions. The energy of the carbohydrate is calculated by subtracting the energy of the fat and protein (N × 6·25)* from the total energy using conventional factors, namely, 5·65 kg.cal./g. for protein and 9·4 kg.cal./g. for the fat. It is thus only an approximate estimate. Table 6 gives the digestibility coefficients of the total energy, crude protein, ether extract, fibre and the total carbohydrate energy of the bread. Table 7 gives the digestibility coefficients of the total energy, crude protein and ether extract of the whole rations.

Analyses of variance were made of the faecal weight before drying per gram dry matter bread intake, the time taken to pass the marker, the changes in body weight, the intake of bread (fresh and dry weights), and of the digestibility of the total energy, crude protein, ether extract, crude fibre and the total carbohydrate energy of the breads. These are given in Table 8.

Condition of subjects

The subjects were all healthy young males. J.S.D.B., J.C.D.H., E.I.McD., T.F.M. and K.C.S. were research workers and G.W.F. a laboratory assistant. With the exception of J.S.D.B. all led fairly active lives considering their occupation; K.C.S. and E.I.McD. had a swim daily. The condition of the subjects was in general very satisfactory throughout the experiment, and all completed the feeding periods. However, during the feeding periods with fine wholemeal bread four of the subjects had a slight tendency to colic. T.F.M. also had slight colic and a severe headache during the white-bread period.

In general the fine wholemeal bread was less palatable than the coarser wholemeal and the white bread. Since both the brown breads were baked with only 1% of yeast they did not rise very well, and the fine wholemeal bread was rather more 'soggy' than the medium wholemeal bread. The palatability of the medium wholemeal bread and the white bread appeared to be about the same; some subjects expressed a preference for one and some for the other.

There was a fairly steady rise in the intake of fresh bread from period A to C. The average consumption per day was 908 g. in period A, 950 g. in period B and 979 g. in period C. The period differences were significant ($P = 0·05$). The personal differences in intake were naturally significant, since each subject fixed his own intake according to

* Throughout this paper for simplicity the factor 6·25 has been used to convert nitrogen values to protein in both breads and faeces although in the case of wheat the factor 5·7 is usually employed.

Table 5. *Total food intake per 24 hr.*

Subject	Period	Fresh weight g.	Dry weight g.	Crude protein g.	Ether extract g.	Crude fibre g.	Total energy kg.cal.	Carbohydrate energy kg.cal.
				White bread				
J.S.D.B.	A	861	525	88·7	11·6	0·83	2290	1679
G.W.F.	C	1050	658	111·0	14·5	1·04	2854	2091
J.C.D.H.	C.	939	583	98·6	12·9	0·93	2536	1858
E.I.McD.	A	950	579	97·9	12·8	0·92	2526	1855
T.F.M.	B	885	553	93·5	12·2	0·88	2405	1762
K.C.S.	B	1002	626	105·9	13·8	0·99	2720	1992
Average		948	587	99·3	13·0	0·93	2555	1873
				Medium wholemeal bread				
J.S.D.B.	C	1019	584	106·3	18·9	12·1	2600	1822
G.W.F.	A	995	570	103·7	18·4	11·8	2536	1778
J.C.D.H.	B	914	544	99·3	17·6	11·3	2423	1698
E.I.McD.	B	1000	596	109·3	19·3	12·4	2656	1861
T.F.M.	A	857	512	93·4	16·5	10·6	2278	1596
K.C.S.	C	1009	579	105·1	18·7	12·0	2579	1807
Average		966	564	102·8	18·2	11·7	2512	1760
				Fine wholemeal bread				
J.S.D.B.	B	872	513	93·9	17·5	11·2	2266	1572
G.W.F.	B	1025	609	111·1	20·8	13·3	2690	1867
J.C.D.H.	A	875	517	94·7	17·6	11·3	2284	1584
E.I.McD.	C	1007	592	108·0	20·2	12·9	2615	1814
T.F.M.	C	849	499	91·3	17·0	10·9	2201	1528
K.C.S.	A	955	565	103·2	19·3	12·3	2492	1730
Average		931	549	100·2	18·7	12·0	2425	1683
Intake other than bread in all cases		709	148	11·0	42·6	0·00	853	—

Excretion of faeces per 24 hr.

Subject	Period	Fresh weight g.	Dry weight g.	Crude protein g.	Ether extract g.	Crude fibre g.	Total energy kg.cal.	Carbohydrate energy kg.cal.
				White bread				
J.S.D.B.	A	35	13·2	5·24	2·4	0·26	73	21
G.W.F.	C	46	18·7	8·9	3·0	0·20	100	22
J.C.D.H.	C	81	22·4	11·64	3·0	0·33	116	22
E.I.McD.	A	53	15·4	7·56	2·5	0·30	89	23
T.F.M.	B	85	20·2	9·65	3·0	0·35	109	26
K.C.S.	B	71	20·3	10·03	2·4	0·45	110	31
Average		62	18·4	8·84	2·7	0·32	99	24
				Medium wholemeal bread				
J.S.D.B.	C	277	66·1	11·81	4·9	10·0	306	193
G.W.F.	A	233	64·7	10·8	5·6	11·8	305	192
J.C.D.H.	B	261	66·4	16·7	4·1	9·4	315	181
E.I.McD.	B	286	71·4	13·73	5·5	10·7	333	203
T.F.M.	A	299	65·3	12·33	4·7	11·1	314	200
K.C.S.	C	339	79·7	22·68	4·7	10·0	377	206
Average		283	68·8	14·67	4·9	10·5	325	196
				Fine wholemeal bread				
J.S.D.B.	B	197	57·3	10·51	3·3	8·2	256	165
G.W.F.	B	242	70·5	12·08	5·2	11·6	325	207
J.C.D.H.	A	232	70·0	16·85	4·5	9·6	324	187
E.I.McD.	C	272	74·4	16·78	4·9	11·4	349	208
T.F.M.	C	221	62·4	13·67	4·2	9·2	287	171
K.C.S.	A	226	76·6	17·98	4·7	11·5	362	216
Average		232	68·5	14·65	4·5	10·3	317	192

(Values taken for margarine, etc., are those given by McCance & Widdowson (1940).)

appetite. The intakes of bread were significantly different between the different treatments as well as between the different periods. The intake of the white bread was highest, averaging 587 g. per day (dry weight) while that of the medium wholemeal was 564 g. and that of the fine wholemeal 549 g.

Table 6. *Digestibility of breads (assuming other constituents of diet completely digested). Digestibility coefficients*

Persons	Total energy %	Crude protein %	Ether extract %	Crude fibre %	Total carbohydrate %
			White bread		
J.S.D.B.	96·8	94·1	79·3	68·6	98·7
G.W.F.	96·5	92·0	79·4	80·4	99·0
J.C.D.H.	95·4	88·2	76·7	64·5	98·8
E.I.McD.	96·5	92·3	80·6	67·0	98·8
T.F.M.	95·5	89·7	75·2	59·8	98·5
K.C.S.	96·0	90·5	82·3	54·2	98·5
Mean (6 persons)	96·1	91·1	80·6	65·8	98·7
			Medium wholemeal bread		
J.S.D.B.	88·2	88·9	74·3	17·7	89·4
G.W.F.	88·0	89·6	69·7	0·0	89·2
J.C.D.H.	87·0	83·1	76·6	16·4	89·3
E.I.McD.	87·5	87·4	71·2	13·5	89·1
T.F.M.	86·2	86·8	71·4	−4·7	87·5
K.C.S.	85·4	78·5	74·9	16·4	88·6
Mean (6 persons)	87·1	85·7	73·0	9·7	88·9
			Fine wholemeal bread		
J.S.D.B.	88·7	88·8	80·9	22·2	89·5
G.W.F.	87·9	89·1	74·7	12·3	88·9
J.C.D.H.	85·8	82·2	74·7	15·5	88·2
E.I.McD.	86·7	84·5	75·7	12·2	88·5
T.F.M.	87·0	85·0	75·4	15·4	88·8
K.C.S.	86·0	82·5	75·5	−6·5	87·5
Mean (6 persons)	86·9	85·3	76·2	14·0	88·6

The body weights of the subjects on the whole decreased during the feeding periods. This may have been partly due to changes in the intestinal fill, since the subjects were weighed on the first day of the preliminary periods. The average weight loss in period A was 0·20 kg. in period B 0·83 kg. and in period C 1·63 kg. Thus the weight loss increased

Table 7. *Digestibility of whole rations*

Persons	Total energy %	Crude protein %	Ether extract %	Total energy %	Crude protein %	Ether extract %	Total energy %	Crude protein %	Ether extract %
	White bread			Medium wholemeal bread			Fine wholemeal bread		
J.S.D.B.	97·7	94·7	95·5	91·2	89·8	92·0	91·8	90·1	94·4
G.W.F.	97·3	92·7	94·7	91·0	90·5	90·8	90·9	90·1	91·7
J.C.D.H.	96·6	89·3	94·5	90·4	86·0	93·1	89·7	84·0	92·5
E.I.McD.	97·4	92·9	95·5	90·6	88·6	90·9	90·0	85·8	93·1
T.F.M.	96·7	90·7	94·4	91·2	86·5	91·9	90·7	95·3	90·9
K.C.S.	96·9	91·4	95·6	89·1	80·4	92·3	89·3	84·2	91·9
Mean (6 persons)	97·1	92·0	95·0	90·6	87·0	91·8	90·4	88·2	92·7

in succeeding feeding periods although the energy intake increased. These differences in weight losses between different periods were significant ($P < 0{\cdot}05$). The weight loss on the white bread averaged 0·58 kg., on the medium wholemeal, 0·65 kg., and on the fine wholemeal 1·43 kg. The difference in weight losses on the different diets were not significant.

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Table 8. *Analyses of variance*

Between	Sum of squares	Degrees of freedom	Mean square	Mean square / Mean square error
	Intake of fresh bread (g. in 7 days)			
Persons	2,429,187	5	485,837	**8·08**
Treatments	122,121	2	61,061	1·02
Periods	718,840	2	359,420	**5·97**
Error	481,255	8	60,157	
Total	3,751,403	17		
	Intake of bread dry matter (g. in 7 days)			
Persons	906,770	5	181,354	**8·18**
Treatments	211,376	2	105,688	**4·77**
Periods	232,351	2	116,176	**5·24**
Error	177,371	8	22,171	
Total	1,527,868	17		
	Changes in body weight (kg. in whole period)			
Persons	6·97	5	1·39	3·09
Treatments	2·68	2	1·34	2·98
Periods	6·19	2	3·09	**6·87**
Error	3·58	8	0·45	
Total	19·42	17		
	Time taken to pass marker (hr.)			
Persons	1,166·41	5	233·28	3·34
Treatments	1,019·70	2	509·85	**7·30**
Periods	688·37	2	344·19	**4·93**
Error	558·76	8	69·84	
Total	3,433·24	17		
	Fresh weight faeces/g. dry matter bread intake g.			
Persons	0·021207	5	0·004241	2·98
Treatments	0·526934	2	0·263467	**184·89**
Periods	0·003121	2	0·001560	1·09
Error	0·011399	8	0·001425	
Total	0·562661	17		
	Digestibility of total energy of bread (%)			
Persons	11·47	5	2·29	**9·16**
Treatments	333·21	2	166·61	**666·44**
Periods	1·45	2	0·73	2·92
Error	1·97	8	0·25	
Total	348·10	17		
	Digestibility of crude protein of bread (%)			
Persons	119·08	5	23·82	**8·57**
Treatments	125·57	2	62·79	**22·59**
Periods	13·88	2	6·94	2·50
Error	22·21	8	2·78	
Total	280·74	17		
	Digestibility of ether extract of bread (%)			
Persons	39·40	5	7·88	1·29
Treatments	104·57	2	52·28	**8·53**
Periods	7·86	2	3·93	0·64
Error	49·03	8	6·13	
Total	200·86	17		
	Digestibility of crude fibre of bread (%)			
Persons	314·57	5	62·91	1·13
Treatments	11,629·01	2	5,814·51	**105·03**
Periods	240·51	2	120·26	2·17
Error	442·89	8	55·36	
Total	12,626·98	17		
	Digestibility of total carbohydrate of bread (%)			
Persons	2·43	5	0·49	**3·27**
Treatments	400·90	2	200·45	**1,336·33**
Periods	1·44	2	0·72	**4·80**
Error	1·21	8	0·15	
Total	405·98	17		

Significant variance ratios are given in black type.

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The stools on the wholemeal bread were well formed and of a 'bran-like' appearance. It was particularly noticeable that the faeces on the medium wholemeal bread diet were more bulky than those excreted on the fine wholemeal. Analysis of variance of the weights of fresh faeces excreted per g. dry matter bread intake, corrected for the amount of $N/5$ H_2SO_4 added, showed a significant difference between treatments ($P<0{\cdot}001$). Further examination of the data showed a significant difference ($P<0{\cdot}01$) between the fine and medium wholemeal breads. The volume of faeces on the white bread diet was of course much smaller. There were no significant differences between persons or periods. The wholemeal bread rations contained about as much indigestible matter as the human organism can tolerate with comfort. It was calculated that 3·5–4 lb. of carrots per day or 4·5 lb. of cabbage would produce the same quantity of dry matter in the faeces.

In the white bread periods there were a few days on which some of the subjects did not defaecate, while in the wholemeal periods the subjects usually defaecated twice a day. The average time taken to pass the marker was 40 hr. on the white bread, 23·5 hr. on the medium wholemeal, and 24 hr. on the fine wholemeal; the times on the white bread ration were significantly different ($P<0{\cdot}01$) from those on the wholemeal bread rations. The average of the time taken to pass the marker in the different periods was 36 hr. in period A, 30 hr. in period B and 21 hr. in period C; these differences between periods were significant ($P<0{\cdot}05$), and are thus inversely correlated with the bread intakes. The differences between persons were not significant, but the subject J.S.D.B. took twice as long as the other subjects to pass his markers. This subject took less exercise than the others, but was occasionally on night duty. He tended to give slightly higher digestion coefficients and his food intake was lower than most of the other subjects.

Digestibility

The details of the coefficients of apparent digestibility of the breads are given in Table 6, and are summarized below.

Total energy. The average digestibility was 96·1 in white bread, 86·9 in fine wholemeal and 87·1 in medium wholemeal. The digestibility of the white bread was significantly higher than that of the wholemeal breads ($P<0{\cdot}001$). The difference between the coefficients of fine and medium wholemeal breads was not significant. The standard deviation of individual observations was 0·5. Period differences were not significant.

Crude protein. The average digestibility was 91·1 in the white bread, 85·3 in the fine wholemeal and 85·7 in the medium wholemeal. The digestibility of the white bread was significantly higher than that of the wholemeal breads ($P<0{\cdot}001$). The difference between fine and medium wholemeal breads was not significant. Personal differences were significant; period differences were not. The standard deviation of individual observations was 1·7.

Ether extract. The average digestibility was 80·6 in the white bread, 76·2 in the fine wholemeal, and 73·0 in the medium wholemeal. The digestibility of the white bread was significantly higher than that of the wholemeal breads ($P<0{\cdot}01$). The difference between fine and medium wholemeal breads was not significant. Neither personal nor period differences were significant. The standard deviation of individual observations was 0·8.

Crude fibre. The average digestibility was 65·8 in white bread, 14·0 in the fine wholemeal and 9·7 in the medium wholemeal. The digestibility of the white bread was significantly higher than that of the wholemeal breads ($P<0{\cdot}001$). The difference in digestibility between fine and coarse wholemeal bread was not significant, nor were personal or period differences. The standard deviation of individual observations was 7·4.

Total carbohydrate. The average digestibility was 98·7 in white bread, 88·6 in the fine wholemeal and 88·9 in the medium wholemeal. The digestibility of the white bread was significantly higher than that of the wholemeal breads ($P<0·001$). The difference between fine and medium wholemeal breads was not significant. Personal differences were nearly significant at ($P=0·05$). Period differences were just significant ($P<0·05$); the digestibility was somewhat lower in period A than in the other two periods. The standard deviation of the individual observations was 0·4.

Personal differences were only significant in the digestibility coefficients for total nitrogen and total energy. When the energy of the total nitrogen and ether extract was subtracted the coefficients of digestion of the remaining energy (total carbohydrate) showed scarcely significant personal differences. Thus personal differences were very largely confined to the apparent digestibility of total nitrogen, and the differences found in the digestion coefficients of the total energy were chiefly due to the protein fraction of the energy. It is possible that these differences represent variation in the excretion of endogenous nitrogen by the different subjects.

Period differences were only significant in the digestibility of total carbohydrate, and the significance only just passed the $P=0·05$ probability level. The mean digestibility coefficients were 91·6 for period A, 92·3 for period B and 92·2 for period C.

It is clear from the figures given above that the fine and medium wholemeal breads were equally well digested. The digestibility coefficients of all constituents of the white were significantly higher than those of the constituents of the wholemeal breads. The figures for the total energy and total nitrogen are accurate; those for the ether extract and crude fibre are less reliable. The ether extract of the breads was a small proportion of the total ether extract of the rations, and since all the ether extract of the faeces was debited to the bread the figures for the coefficients of digestibility are rather low for all the breads. The digestibility of the total ether extract of the rations was, however, high (Table 7). The estimation of the ether extract of the white bread was not very reliable owing to the small quantity present. The digestibility coefficients of crude fibre are more variable than those of the other constituents. The greater utilization of the fibre of the white bread is in accordance with the observations of Rubner who showed that the cell membranes of the endosperm were of different composition from bran and more readily attacked by bacteria in the gut. Since there was a 10% difference between the digestibility of the total carbohydrate energy of the white and wholemeal bread, it is probable that but little of the pentosans or of the cellulose was digested.

The average digestibility of the nitrogen of white and of wholemeal breads was higher than previously found by other workers. We obtained digestibility coefficients of about 85·5 and 91·1 for the nitrogen of wholemeal and white bread, while other workers have given values of about 77 and 87 for these breads respectively. The high coefficients obtained in our experiments were probably due to the fact that our breads were unusually rich in nitrogen.

The difference in the average digestibility of the total energy in the white and wholemeal breads was 9·1%. This is in agreement with the figures obtained from the short period experiments of the earlier workers, given in Table 1. The figures of Newman *et al.* and of the Royal Society also show a decrease in digestibility as extraction is raised. The greater loss of the energy of the wholemeal bread is largely accounted for by the undigested cell envelopes and woody fibre in the bran.

The difference in average digestibility of the nitrogen of white and wholemeal breads was 5·6%; this is about half what one would expect from the results of the previous experiments given in Table 1. A factor which decreases the digestibility of the nitrogen of wholemeal bread is the large amount of 'indigestible matter'. It is well known that such 'indigestible matter' increases the endogenous faecal nitrogen (Mendel & Fine, 1912; Mitchell, 1924; Hutchinson & Morris, 1936). This endogenous faecal nitrogen is also naturally a smaller fraction of the nitrogen intake if the bread is rich in nitrogen. The white and wholemeal bread used in our experiments contained 2·70 and 2·91% nitrogen respectively on a dry-matter basis, an exceptionally high percentage. However, this fact does not explain the whole of the discrepancy between our results and those of previous workers. For example, Snyder (1905) in the experiment quoted on p. 2 using wholemeal and straight run white flours containing 2·94 and 2·68% of nitrogen respectively, obtained a difference in digestibility of 13·6%. In our experiment the bread nitrogen was 90% of the total intake of nitrogen, a considerably greater proportion than in any of the other experiments quoted in Table 1 except those of Rubner, and Martin & Robison. Thus we measured the digestibility of bread less complicated by other factors, while most other workers measured it when the bread was part of a more or less normal ration, debiting to the bread alone any associative effects on digestibility between the bread and the other constituents of the ration. In 1895 Atwater pointed out that our knowledge of these associative effects was incomplete; it is still incomplete.

The nitrogen digested averaged 2·46 g./100 g. white bread (dry weight) consumed and 2·49 g./100 g. wholemeal. In 100 g.cal. digested 20·8 g.cal. were derived from protein in the white bread and 22·9 g.cal. in the wholemeal. If therefore appetite were controlled by the amount of energy absorbed from the diet, about 10% more protein would be assimilated from wholemeal bread than from white bread since 10% more would be eaten to give the same quantity of available energy. This, however, was clearly not the case in our experimental periods of 10 days, for the gross energy intake of the white bread averaged 2555 kg.cal. per 24 hr., that of the medium wholemeal bread 2512 kg.cal. and that of the fine wholemeal bread 2425 kg.cal. We therefore assimilated about the same amount of nitrogen from the white and wholemeal breads but about 10% less energy from the wholemeal bread.

SUMMARY AND CONCLUSIONS

1. Loaves were baked from three types of wheaten flour made from the same grist; a straight run white flour of 73% extraction, a finely ground wholemeal (100% extraction) and a medium ground wholemeal (100% extraction). Bread from each was consumed by six persons for periods of 11–12 days. The daily consumption was 530–630 g. dry weight of bread and, in addition, 37 g. margarine, 284 c.c. milk, 72 g. marmalade jelly and 284 c.c. of mild ale.

2. The total energy, nitrogen and fibre of the food consumed and of the faeces excreted over a period of 7 days were determined. Assuming that the foods other than bread were wholly digestible, the average percentage absorption of energy, nitrogen and fibre from the white bread was 96·1, 91·1, and 65·8 respectively; from the fine wholemeal

bread it was 86·9, 85·3 and 14 respectively and from the coarser ground wholemeal 87·1, 85·7 and 9·7 respectively.

3. The nitrogen intake per 100 g. of the wholemeal bread eaten was 2·91; of the white bread 2·70 g. This advantage was, however, neutralized by the greater amount of nitrogen lost in the faeces when wholemeal was taken, so that the average net gain of nitrogen to the body was 2·46 and 2·49 respectively per 100 g. dry weight of bread consumed.

4. The loss of 9% more of the energy of the bread in the faeces from wholemeal than from white bread is largely accounted for by the undigested cell envelopes and woody fibre in the bran. The greater utilization of the fibre of the white bread is in accordance with the observations of Rubner who showed that the cell membranes of the endosperm were of different composition from those of the bran cells and were more readily attacked by bacteria in the gut.

5. The range of individual variations in the utilization of the energy of the breads were: for white bread 95·4–96·8% and for wholemeal 85·4–88·7%. In the utilization of nitrogen these were: for white bread 88·2–94·1%, and for wholemeal 78·5–89·6%. The same subjects showed the better utilization of both energy and nitrogen.

6. The fineness of grinding of the wholemeal within the range used made no significant difference to the utilization of either energy or nitrogen.

Our experiments show that with the sample of wheat which we used, the net amount of nitrogen available to the body from 1 lb. of white flour (73% extraction) was the same as from 1 lb. of wholemeal although the latter contained 8% more nitrogen than the former. The energy derived from the same weight of the white flour was about 10% greater, and we were unable to eat more of the wholemeal bread to compensate for this. This is a matter of some interest in considering the diets of heavy workers under wartime restrictions. Whether, however, it is advisable to divert a quarter of the weight of the wheat berry to the feeding of animals depends on the supplies of wheat available. There is no evidence that pigs and poultry can make any better use of the offals than human beings can.

There are other facts with an important bearing upon the question of how much of the wheat berry should be reserved for human consumption apart from the digestibility of its various constituents with which our experiments have been solely concerned. The first is that the bulk of the water soluble vitamins is contained in the germ and outer layers of the berry, most of which are removed in the production of white flour (Copping & Roscoe, 1937). To what extent this is a serious detriment to consumers of white bread depends on the extent to which these vitamins are supplied by the other articles of the diet.

The second is that the composition of the proteins in the portion discarded in the production of white flour is not the same as that of gliadin and glutenin (gluten), the predominant proteins in the white flour, so that the proteins of the offals may exert a supplementary nutritive effect on the gluten and increase the biological value of the mixture out of all proportion to the amount added. The experiments of Osborne & Mendel (1919) indicated that the improvement in biological value gained by this admixture was of the order of 20%, and in recent experiments Chick (1942) has also shown, that the biological value of the nitrogen of the specimen of whole grain used in our experiments was about 20% greater than that of the white flour extracted from it; thus 10 g. nitrogen of this whole wheat is worth 12 g. nitrogen of the 73% extraction flour made from it. The extent to which it is necessary to retain the whole or some part of the offals to supply proteins to satisfy human needs depends on the amount and nature of the proteins in the remainder of the diet.

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