*J. Physiol.* (1966), **182**, *pp.* 144–149
*With 3 text-figures*
*Printed in Great Britain*

# THE PATTERN OF GASTRIC EMPTYING: A NEW VIEW OF OLD RESULTS

BY ANTHONY HOPKINS*
*From the Department of Physiology,*
*Guy's Hospital Medical School, London, S.E.* 1

(*Received* 6 *May* 1965)

SUMMARY

1. Gastric emptying has until now been regarded as exponential in form, but this pattern does not account for all phases of a meal.

2. A pattern of emptying in which the square root of the volume of meal remaining declines linearly with time has been shown to account for the experimental results with less error.

## INTRODUCTION

At present it is thought that gastric emptying is an orderly process in which the volume of meal remaining in the stomach declines exponentially as time passes. This view is based on the results obtained with the serial test meal by Salamanca (1943) and Hunt & Spurrell (1951). The serial technique consists in withdrawing the gastric contents on different days at different intervals after taking standard liquid meals. The meals contain a marker which is not absorbed from the stomach, and this allows the volume of meal remaining to be calculated. With strict experimental discipline, the stomach is found to behave similarly from day to day. Thus the serial results can be synthesized into a description of the stomach's behaviour for a meal of that composition. When plotted against time the volume of meal remaining falls in a smooth curve, which until now has been regarded as exponential. If the logarithm of the volume of meal remaining is plotted against time on a linear scale the points are near to a straight line.

The exponential pattern of emptying does not, however, hold towards the end of the meal, when there is usually a phase of more rapid emptying. Out of 190 experiments on twenty-one subjects, Hunt (1949), using meals of 750 ml., noted that he was forced to discard fifteen results obtained near the end of the meal when the volume of meal remaining was less than 20 ml. Hunt & Macdonald (1954), using meals of 1250, 750 and 330 ml., found that

* Present address: National Hospital for Nervous Diseases, Queen Square, London, W.C. 1.

for the larger meals in every subject there was a final phase of rapid gastric emptying not consistent with extrapolation from the previous exponential pattern. This is seen in Fig. 1 which is reproduced from their paper. In Fig. 2 the square roots of the experimental volumes corresponding to those of Fig. 1 are shown plotted against time. The regression lines have been calculated, and account reasonably well for the duration of each meal, so that it is not necessary to postulate a change in the pattern of emptying towards the end of large meals.

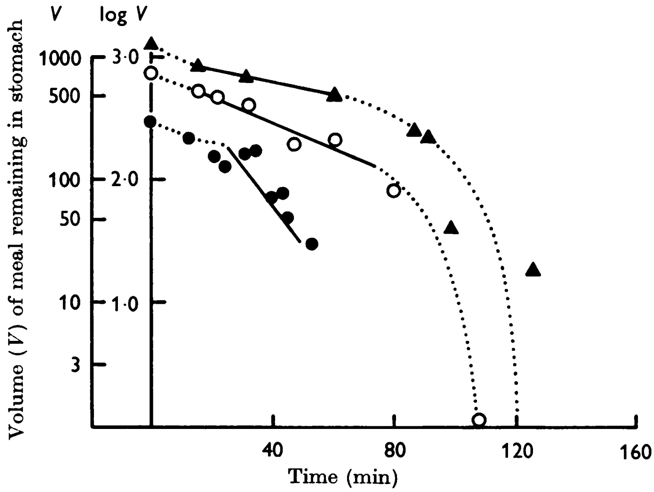


Fig. 1. Subject J.M. of Hunt & Macdonald (1954). The patterns of gastric emptying of meals of 1250 (▲), 750 (○) and 330 (●) ml. according to the exponential hypothesis.

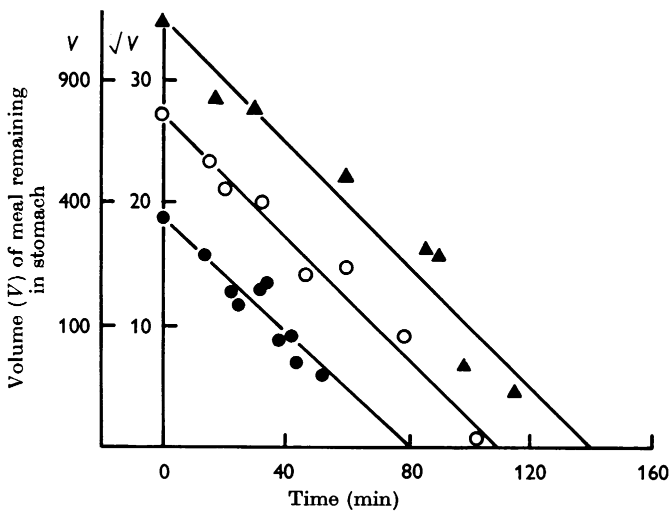


Fig. 2. Results of subject J.M. (see Fig. 1) according to the square-root hypothesis.

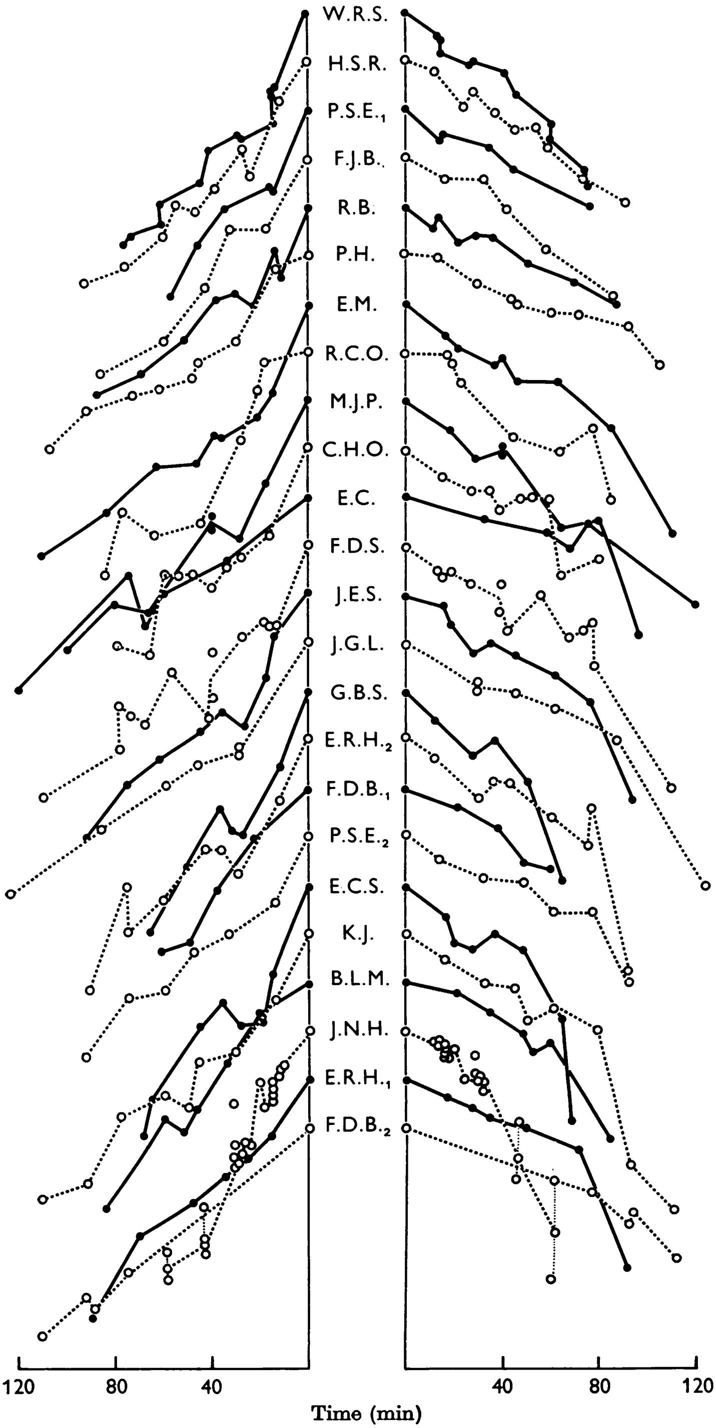


Fig. 3. For legend see opposite page.

TABLE 1. Comparison of $t$ values of regression lines for exponential and square root hypotheses of gastric emptying, from data of Hunt & Spurrell (1951)

| Subject | $t\sqrt{V}$ | $t$ log | Difference in $t$ | No. of observations |
|---|---|---|---|---|
| | Results more favourable to exponential hypothesis | | | |
| W.R.S. | 11·759 | 18·641 | 6·882 | 13 |
| H.S.R. | 9·931 | 14·806 | 4·875 | 10 |
| P.S.E.$_1$ | 6·736 | 10·039 | 3·303 | 6 |
| F.J.B. | 9·214 | 10·119 | 0·905 | 6 |
| R.B. | 8·523 | 9·361 | 0·838 | 9 |
| P.H. | 9·340 | 10·029 | 0·689 | 9 |
| E.M. | 8·209 | 8·653 | 0·440 | 9 |
| | Results more favourable to square root hypothesis | | | |
| R.C.S. | 6·334 | 5·640 | 0·694 | 8 |
| M.J.P. | 8·293 | 7·477 | 0·816 | 8 |
| C.H.O. | 6·049 | 4·799 | 1·250 | 10 |
| E.C. | 5·367 | 4·101 | 1·266 | 6 |
| F.D.S. | 8·561 | 6·576 | 1·985 | 14 |
| J.E.S. | 8·961 | 6·703 | 2·258 | 9 |
| J.G.L. | 8·712 | 6·420 | 2·292 | 7 |
| G.B.S. | 7·808 | 5·296 | 2·512 | 7 |
| E.R.H.$_2$ | 6·820 | 3·813 | 3·007 | 9 |
| F.D.B.$_1$ | 9·733 | 6·118 | 3·615 | 5 |
| P.S.E.$_2$ | 9·872 | 6·511 | 3·361 | 7 |
| E.C.S. | 7·448 | 4·087 | 3·361 | 8 |
| K.J. | 10·852 | 6·253 | 4·599 | 9 |
| B.L.M. | 12·868 | 5·418 | 7·450 | 7 |
| J.N.H. | 20·291 | 12·464 | 7·827 | 26 |
| E.R.H.$_1$ | 13·525 | 4·900 | 8·625 | 7 |
| F.D.B.$_2$ | 20·350 | 7·520 | 12·830 | 5 |

TABLE 2. Comparison of $t$ values of regression lines for exponential and square root hypotheses of gastric emptying, from data of Hunt & Macdonald (1954). Gradients of square root regression lines

| Subject | | Gradient | $t\sqrt{V}$ | $t$ log | Difference in $t$ | No. of observations |
|---|---|---|---|---|---|---|
| | | Results more favourable to exponential hypothesis | | | | |
| M.B.R.M. | 750 | −0·3593 | 7·960 | 14·329 | 6·369 | 5 |
| R.B. | 1250 | −0·3214 | 9·129 | 13·176 | 4·047 | 7 |
| R.E.O. | 750 | −0·2872 | 5·929 | 5·967 | 0·038 | 8 |
| | | Results more favourable to square root hypothesis | | | | |
| R.E.O. | 330 | −0·7622 | 6·398 | 5·893 | 0·505 | 5 |
| R.G. | 330 | −0·4359 | 4·905 | 3·071 | 1·834 | 5 |
| M.B.R.M. | 330 | −0·5678 | 6·423 | 4·191 | 2·232 | 6 |
| R.G. | 750 | −0·3587 | 9·875 | 7·616 | 2·259 | 6 |
| J.M. | 330 | −0·2417 | 10·146 | 7·868 | 2·278 | 10 |
| R.E.O. | 1250 | −0·3462 | 6·837 | 4·206 | 2·631 | 5 |
| M.B.R.M. | 1250 | −0·3256 | 8·712 | 4·800 | 3·912 | 7 |
| J.M. | 1250 | −0·2508 | 9·746 | 4·870 | 4·876 | 8 |
| J.M. | 750 | −0·2448 | 14·485 | 6·435 | 8·050 | 8 |

Legend to Fig. 3

Fig. 3. The data of Hunt & Spurrell (1951), plotted according to the square root hypothesis on the left, and to the logarithmic hypothesis on the right. The order of subjects is as in Table 1. Open and closed circles are used for alternate subjects. Each subject is displaced 5 units on the ordinate from his neighbour. The original volume of meal was 750 ml. in each case. On the left at a point 27·4 units ($\sqrt{750} = 27·4$) below the origin of each curve represents zero volume for that curve. 10 units above this point represent 100 ml., and 20 units 400 ml. On the right a point 28·7 units (log. 750 = 2·87) below the origin of each curve represents zero volume for that curve. Ten units above this point thus represent 10 ml., and 20 units 100 ml.

As the relation between the square root of the volume of meal remaining in the stomach and time appeared to have some advantage over the exponential or logarithmic relation in this particular experiment, it seemed worth while to re-examine the original results on which the exponential hypothesis was formulated.

## METHODS

Professors Hunt and Spurrell have kindly allowed me access to the laboratory notebooks on which their work was founded (Hunt, 1949; Hunt & Spurrell, 1951). The square root of the volume of meal remaining has been plotted against the time of aspiration. Regression lines have been calculated for each of the original twenty-four series of meals on twenty-one subjects for both the logarithmic and the square-root relations with time. The fifteen experiments in which the volume remaining was less than 20 ml. which, Hunt (1949) remarks that he discarded, have in all cases been included. The success of a linear regression in describing a set of observations is related to the residual variance not accounted for by regression, but owing to the different units used in calculating the variances it is not possible to compare directly the residual variance of the logarithmic and square-root regressions. It is necessary to remove the units. One way of doing this is to divide the gradient by the standard error of the gradient

$$\text{gradient}\Big/\sqrt{\frac{\text{residual variance}}{(n-2)(\Sigma x^2 - n\bar{x}^2)}},$$

where $n$ is the number of observations and $x$ is the independent variable (time). It may be shown that this expression reduces to

$$\frac{r\sqrt{(n-2)}}{\sqrt{(1-r^2)}},$$

where $r$ is the correlation coefficient. This expression may be entered in the tables of Student's $t$ to test the significance of the correlation coefficient. The smaller the residual variance, the higher will be the value of the correlation coefficient and of $t$. Thus a regression line which accounts better for a set of observations transformed in some way will have a higher value of $t$.

## RESULTS

Table 1 is based on the results of Hunt & Spurrell (1951) for twenty-four serial meals. The value of Student's $t$ is higher for the square-root regression lines than for the logarithmic regression lines in seventeen pairs out of twenty-four. Testing this difference by $\chi^2$, the result is favourable for the square-root relation at the 5 % level of significance; $\chi^2$ is 4·17.

The results of Hunt & Macdonald (1954) have been similarly examined, plus one further subject, R.G., studied, but not published by them. These authors investigated the effect of varying the volume of the meal on gastric emptying, and Figs. 1 and 2 show results on one subject according to the exponential and the square-root hypotheses. Values of Student's $t$ have been calculated for twelve series of meals of all four subjects studied and the results tabulated in Table 2. It may be seen that the values of $t$ are higher for the square-root relation in nine out of twelve series of meals. If these twelve pairs are added to the earlier twenty-four pairs, then the value of $t$ for the square-root regression lines is higher in twenty-six out of thirty-six pairs. This result is favourable for the square-root relation at the 1 % level of significance; $\chi^2$ is 7·11.

In Fig. 3 the experimental results are shown so that a visual comparison can be drawn between the two methods of transforming them. The order of the curves is as they are entered in Table 1, so that the first seven curves are those in which the logarithmic method gives the better fit; in the remaining seventeen the square-root method is more successful.

## DISCUSSION

The results suggest that the square-root pattern is a more satisfactory description of gastric emptying than the hitherto accepted exponential pattern.

Figure 2 demonstrates an additional strength of the square-root relation. With the exponential relation the meals of low original volume have a steeper gradient, or shorter half life than the meals of larger original volume. A volume of, for example, 300 ml. is treated in a different way depending on the original volume of the meal of which it forms part. It cannot be that a distended duodenum slows down the larger meals because, according to the exponential relation, the largest meal has a very rapid final phase of emptying. Also, if two meals are given in rapid succession, the second empties more quickly than the first (Hunt & Macdonald, 1954). Therefore, it is of particular interest to note than the three regression lines in Fig. 2 are parallel, indicating that, according to the square-root relation, there is a constant pattern of gastric activity regardless of the original volume of the meal, and regardless of the volume already distending the duodenum. For example, 300 ml. is reduced to 100 ml. in about 30 min whether the original volume of the meal was 1250, 750 or 330 ml. A similar approximate parallelism of regression lines is seen in the remaining three subjects studied by Hunt & Macdonald when the results are plotted according to the square root relation (Table 2).

It is interesting to note than the radius of a cylinder varies with the square root of the volume, and that by the Law of Laplace the circumferential tension is proportional to the radius, so that there might conceivably be a physical basis for the square root pattern of gastric emptying.

I am indebted to Professors J. N. Hunt and W. R. Spurrell, and to Dr I. Macdonald for their generosity in allowing me access to their results, and to Professor Hunt for his encouragement in the preparation of this paper.

## REFERENCES

HUNT, J. N. (1949). A critical study of some aspects of gastric function in man. Ph.D. Thesis, University of London.

HUNT, J. N. & MACDONALD, I. (1954). The influence of volume on gastric emptying. *J. Physiol.* **126**, 459–474.

HUNT, J. N. & SPURRELL, W. R. (1951). The pattern of emptying of the human stomach. *J. Physiol.* **113**, 157–168.

DE SALAMANCA, F. E. (1943). La fisiologia gástrica humana segum los datos de mi procedimiento de exploración functional. *Rev. clin. espãn.* **8**, 94–104.