Lacrimal scintigraphy.
I. Compartmental analysis of data

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SUMMARY Linear compartmental analysis was applied to lacrimal scintigraphy data from asymptomatic and obstructed lacrimal systems. Failure to achieve satisfactory results in most of the asymptomatic systems studied suggests that variable tear flow is a feature of normal lacrimal drainage which precludes linear analysis. However, in cases where the analysis was successful the results were consistent with the occurrence of reflux between the conjunctival and lacrimal sacs, and between the lacrimal sac and nasolacrimal duct. Further support for the existence of reflux between compartments was provided by the analysis of obstructed systems, particularly those with obstruction at the upper end of the nasolacrimal duct. In such cases there was rapid equilibrium of the tracer between the conjunctival and lacrimal sacs, which in the absence of tear flow could be explained by reflux between these 2 compartments.

Because of its physiological character lacrimal scintigraphy (LS) has been considered a suitable technique for studying the dynamics of lacrimal drainage.1 Carlton et al.2 introduced the concept of quantitation by measuring the transit time of the tracer to the lacrimal sac and nasolacrimal duct, and in a later study3 used the 'region of interest' technique to plot the activity—time function curves of the various compartments of the lacrimal drainage system (LDS) using a computer. Similar studies were carried out by other investigators,4,5 who also measured the T½ values for the conjunctival sac. The analysis of lacrimal scintigraphy data was extended by Hurwitz et al.6 to include the transit times (tmax) and T½ values for the various compartments of the LDS, while Sørensen and Jensen7 used a simple compartmental model of the conjunctival sac to estimate the fractional turnover rate of tears to measure the tear flow. The results to date have shown that, although the more elaborate analysis has thrown further light on the physiology of lacrimal drainage, it would appear to have contributed little to the clinical value of LS, since in the majority of patients with obstructive epiphora an accurate diagnosis of the cause can be made by examining the serial images in conjunction with the dynamic curves alone.8

However, in a study of asymptomatic lacrimal systems9 the authors found that in a significant number of these systems the nasolacrimal duct offered a physiological obstruction to tear flow, which suggested that LS had no role in the clinical evaluation of tear passage through the nasolacrimal duct to the nose. These observations would therefore imply that, because the lacrimal drainage system does not empty at a constant rate, it would be difficult to analyse LS data and establish quantitative criteria on the basis of a linear flow, as has been done in the other studies.

The present paper describes an attempt to analyse LS data by means of a multicompartiment model to explore in more detail the dynamics of lacrimal drainage. By introducing this more complicated model instead of the simple model used by Sørensen and Jensen it was our intention to determine whether reflux can occur between various compartments and whether there is any need to postulate a variable flow as other workers had done10 in their experiments. The analysis was applied to systems with no obstruction and to systems with an obstruction at differing levels.
Material and methods

The initial aim was to perform compartmental analysis on a group of asymptomatic systems to obtain normal values of the various parameters associated with lacrimal drainage, so that these could be compared with estimates in obstructed systems. However, for reasons which are given later, this proved not to be a practical proposition. Indeed, out of the 20 asymptomatic systems selected for study compartmental analysis could be performed satisfactorily in only 2. Nine systems within this group were also studied with a view to determining the exponential components of tracer disappearance from the conjunctival sac. Twelve other symptomatic systems with a demonstrable obstruction at the lower end of the nasolacrimal duct, proved equally difficult to analyse. In fact only 2 of these could be analysed. However, analysis was performed satisfactorily in 10 systems in which an obstruction was present at the upper end of the nasolacrimal duct—that is, where only two compartments, representing the conjunctival and lacrimal sacs, needed analysis. Also analysed were 11 systems with complete canicular obstruction—that is, where only one compartment, the conjunctival sac, was present. Thus altogether 25 systems were studied by multicompartiment analysis.

Data were acquired with an Ohio Nuclear Series 100 gamma camera linked to a Varian V76 computer. Subjects were positioned upright with the cornea at a distance of 85 mm from the hole of the 2.5 mm pinhole collimator. The study commenced with the simultaneous instillation of 2 MBq ⁹⁹m-Tc tin colloid in 15 µl isotonic saline in each conjunctival sac with micropipettes. Data were collected for the next 10 minutes in the form of a series of 100 dynamic frames each of 6 s duration and stored in the computer. A summed view of these frames was produced at the end of the study to enable regions of interest to be defined. These consisted of the conjunctival sac, lacrimal sac, nasolacrimal duct, and nasal cavity. Curves representing the time course of radioactivity in these compartments, corrected for radioactive decay, were generated by the computer.

Before compartmental analysis was performed the original data from each compartment were corrected for the increase in counting sensitivity that occurs as the radioactive tracer moves towards the centre of the object plane. This is a feature of a pinhole type of collimator, and in the present system the counting sensitivity for a source at the lateral canthus of the eye was typically 30% less than at the inner edge of the lacrimal sac. Thus correction was made to the acquired count at each point in the image matrix by normalising the counting sensitivity to that at the centre of the object plane. Analysis was performed on the corrected time/radioactivity curves for each compartment.

The model used in the analysis consists of 4 compartments representing the conjunctival sac, the lacrimal sac, the nasolacrimal duct, and the nasal cavity respectively (Fig. 1). As indicated in the diagram, allowance is made for possible reflux between the first and second compartments and between the second and third compartments. Loss of tracer from the conjunctival sac by routes other than the canaliculi was neglected on the basis of findings which are presented later. If λij is the fractional transfer coefficient between each compartment—i.e., the fraction of the contents of compartment i transferred to compartment j per unit time—then the rate of change qj (the amount of tracer in compartment i at any time) is given by

\[
\frac{dq_i}{dt} = -q_i \sum_{j \neq i} \lambda_{ij} + \sum_{i \neq j} \lambda_{ji} q_j
\]

The method of determining the λij followed a standard approach readily performed on a digital computer and makes use of the fact that qj is known for each compartment. It consists of estimating the changes in qj for a given compartment over a series of 50 consecutive time intervals of 12 s and noting the values of qj at these times in neighbouring compartments. This produces for each compartment a set of 50 overdetermined linear equations with unknowns λij. Least sum of squares estimates of the λij, along with standard errors, were obtained from these equations by linear regression analysis. Only those estimates with a magnitude greater than 2 standard errors were considered significant.
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Results

In only 2 out of 11 systems studied with canalicular obstruction was there any significant loss of tracer (to tissues outside the lacrimal drainage system) in the 10-minute study period. The mean estimated fractional loss rate in these 2 systems was 0·018 min⁻¹ (Table 1), which is negligible. This gave justification to ignoring any transconjunctival loss of tracer in the compartmental analysis. The results of the analysis in all the 25 systems studied are given in Table 1, which shows the fractional transfer coefficients for the various compartments in the different types of obstruction. Fig. 2 shows an example of a system with an obstruction at the lower end of the lacrimal sac. It can be seen that the computed curves based on the estimated transfer coefficients seem to be good fits to the observed data. Figs. 3 and 4 are examples of a

Fig. 2 Results from a system with obstruction at the lower end of the lacrimal sac. The smooth curves represent the best fits to the observed data for the conjunctival and lacrimal sacs.

Fig. 3 Results from a system with obstruction at the distal end of the nasolacrimal duct. The quantity of radioactive tracer in each compartment has reached an equilibrium value by the end of the study period.
Table 1  Results of compartmental analysis showing mean (±SD) fractional transfer coefficients (min⁻¹)

<table>
<thead>
<tr>
<th>Level of obstruction</th>
<th>Common canalicular obstruction (1 compartment)</th>
<th>Obstruction at upper end of NLD (2 compartments)</th>
<th>Obstruction at lower end of NLD (3 compartments)</th>
<th>No obstruction (4 compartments)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of systems studied</td>
<td>11</td>
<td>10</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Mean transfer coefficient from conjunctival sac</td>
<td>0-018±0-017*</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Mean transfer coefficient from conjunct. sac to lac. sac</td>
<td>—</td>
<td>1-68±1-92</td>
<td>1-14±1-14</td>
<td>3-24±1-98</td>
</tr>
<tr>
<td>Mean reflux coefficient from lac. sac to conjunct. sac</td>
<td>—</td>
<td>0-78±0-54</td>
<td>0-66±0-36</td>
<td>0-72±0-60</td>
</tr>
<tr>
<td>Mean transfer coefficient from lac. sac to nasolac. duct</td>
<td>—</td>
<td>—</td>
<td>0-30±0-06</td>
<td>0-90±0-66</td>
</tr>
<tr>
<td>Mean reflux coefficient from nasolac. duct to lac. sac</td>
<td>—</td>
<td>—</td>
<td>0-54±0-24</td>
<td>0-36±0-12</td>
</tr>
<tr>
<td>Mean transfer coefficient from nasolac. duct to nose</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>0-18±0-12</td>
</tr>
</tbody>
</table>

*Only 2 systems showed loss of tracer from the conjunctival sac. Lac. = lacrimal. Conjunct. = conjunctival.

system with an obstruction at the distal end of the nasolacrimal duct and a system with no obstruction respectively.

In 7 out of 9 systems with no evidence of obstruction there were 2 exponential components in the tracer disappearance curve for the conjunctival sac, as determined by an exponential curve stripping routine. The rate constant of the first component, the fast component, had a mean value of 4-61 min⁻¹ and the second, slower component had a mean value of 0-063 min⁻¹ (Table 2). These 2 phases of tracer disappearance are clearly seen in the curve for conjunctival sac in Fig. 4, where 50% of the initial radioactivity has left the conjunctival sac well within the first minute. The 2 remaining cases with no evidence of obstruction demonstrated only one component of tracer disappearance from the first compartment; in one case loss of tracer took place rapidly, while in the other the clearance was much slower (Table 2).

An example of an unobstructed system where the flow pattern was variable is given in Fig. 5. The curves are consistent with a sudden increased clearance of tracer from the lacrimal sac towards the end of the study period.

Discussion

At first sight it might be concluded that the experimental data from a dynamic radionuclide investiga-

![Fig. 4](image_url) Results from a system showing continuous drainage of tracer from each compartment. Tracer can be seen in the nasal cavity within 1 minute.
tion of the lacrimal drainage system are ideally suited for linear compartmental analysis with reflux between compartments. However, problems were encountered at the outset of the present work when asymptomatic systems with no clinical evidence of obstruction were studied to establish normal values for the various parameters of a 4-compartment linear model.

First, approximately 25% of the asymptomatic systems selected for study manifested apparent obstruction by the end of the 10-minute study period at either the upper or, more often, the lower end of the nasolacrimal duct. These are similar to the findings of Chavis et al., where no tracer was detected in the nasal cavity in 32% of normal asymptomatic systems by the end of a 12-minute study period. In all present cases the apparent obstruction was cleared by the repeated instillation of 15 μl drops of saline at 1-minute intervals. However, in such cases lacrimal drainage in the normal course of events was likely to be nonlinear, and thus these cases had to be excluded from the compartmental analysis. Secondly, within the remaining asymptomatic cases there were some where the clearance of tracer manifested definite nonlinearity within the 10-minute study period (Fig. 5). The findings in these cases suggest that, while there was probably a small but steady flow of tear fluid through the system, this could be augmented periodically by sudden increases in flow due to pressure build-up within the lacrimal sac and nasolacrimal duct. Systems manifesting such features could not be included in the compartment analysis. Finally, even within those cases where the flow of tracer between compartments appeared to be linear, and where the tracer had reached the nasal cavity before the end of the study, difficulties were found in obtaining consistent results in the analysis procedure. This was in spite of the fact that correction had been made to the observed data for counting sensitivity variations which if left uncorrected would have affected the analysis.

One possible source of difficulty might be the transconjunctival loss of tracer, which was ignored in the analysis. Sørensen and Jensen13 reported a significant loss of tracer through the conjunctiva in their study using 99mTc pertechnetate, but 99mTc tin colloid was employed in the present study. The studies in subject with canaliculular obstruction would suggest that with the tin colloid there is little transconjunctival loss (Table 1), and there would appear to be a justification for neglecting it. It is also unlikely that adherence of the tracer to the surfaces in the lacrimal drainage system is a problem, since Murai10 has shown that 99mTc pertechnetate does not adhere to the mucous membrane lining the lacrimal passage. Indeed, other studies14 have shown that colloidal tracer is less likely to adhere to a surface than ionic pertechnetate. Perhaps a more probable source of error is the difficulty encountered in practice in separating the compartments, particularly the nasolacrimal duct from the lacrimal sac, when the regions of interests are defined on the computer display (Fig. 6). This could lead to overlap of the regions of interest, resulting in distortion of the dynamic curves for each compartment. The magnitude of this problem, however, is dependent on the resolution of the

Table 2 Analysis of time activity curves for conjunctival sac in 9 systems with 4 compartments present

<table>
<thead>
<tr>
<th>Number of systems</th>
<th>Fast component (min^-1) (mean ± SD)</th>
<th>Slow component (min^-1) (mean ± SD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>4.61 ± 1.58</td>
<td>0.063 ± 0.036</td>
</tr>
<tr>
<td>1</td>
<td>3.316</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td></td>
<td>0.065</td>
</tr>
</tbody>
</table>
imaging system used in the study. Any improvements in resolution would reduce the difficulty in separating the compartments.

A more fundamental problem, however, is the underlying assumption that the flow of tears is indeed constant when the transfer of tracer between compartments appears to be occurring at a steady rate (Fig. 4). If there is a short period of increased tear flow due to irritation of the conjunctiva at the moment of instillation of the tracer, this would also produce time radioactivity curves similar to those shown in Fig. 4. In fact the present analysis of curves from the conjunctival sac into exponential components has confirmed the apparent existence of 2 phases of clearance, a finding that has been interpreted as indicating early increased flow.7 There is good agreement between the mean rate constant of the slow component in the present series, 0.063±0.036 min⁻¹ and a previously published value of 0.088±0.018 min⁻¹.7 Both sets of values compare reasonably with a recent estimation of 0.12±0.03 min⁻¹ for the mean fluorescein turnover rate.15 It is inappropriate, however, to compare the estimated rate constants for the first component because an exponential curve stripping routine was used in the present work, whereas Sørensen and Jensen' simply determined slopes from a log/linear plot of the data, and because the sensitivity correction in the present procedure enhances the early part of the curve from the conjunctival sac.

Thus the present observations in asymptomatic lacrimal systems would suggest that variable tear flow is a normal feature of lacrimal drainage. Such systems cannot be described adequately by a linear compartmental model. In some cases, however, it may be possible to analyse the observed data on the basis of this type of model. The results in 2 cases in which analysis was carried out satisfactorily are consistent with the occurrence of reflux between the conjunctival and lacrimal sacs and between the lacrimal sac and nasolacrimal duct (Table 1).

Further information on the dynamics of lacrimal drainage, in particular on the question of reflux,16 can be gleaned from the present studies of obstructed systems. The analysis of 2-compartment systems—i.e., where there was obstruction at the upper end of the nasolacrimal duct—clearly points to the existence of reflux between the conjunctival and lacrimal sacs. This would appear to be the most likely explanation for the rapidity with which equilibrium can be reached between the 2 compartments (Fig. 2), considering there is no net fluid flow through such systems. The administered radioactive tracer is simply mixed uniformly throughout the system by the lacrimal pump, which presumably is still functional. Furthermore, the compartmental analysis of 3 compartment systems—i.e., where there was obstruction at the lower end of the nasolacrimal duct—revealed, albeit in only 2 systems, that there can be reflux between the nasolacrimal duct and the lacrimal sac (Table 1). Thus the present work has demonstrated that lacrimal drainage is a complex process with variable tear flow and reflux between compartments being possible. It does not lend itself easily to simple analysis.

In spite of these problems it is interesting to consider whether lacrimal scintigraphy can provide some indication of the magnitude of tear flow. On the assumption that the slow component of clearance from the conjunctival sac represents the net fractional turnover of that compartment, and taking a compartmental volume of 7 μl,16,17 a mean tear flow of 0.45 μl per min can be estimated from the present data (Table 2). This compares well with a value of 0.6 μl per min.
published by Sørensen and Jensen,17 who used the same method of calculation. An alternative method of calculating tear flow is based on the compartmental model of Fig. 1. Net flow through the system is given by \( V_1 \lambda_{12} - V_2 \lambda_{21} \) where \( V_1 \) and \( V_2 \) are the volumes of the conjunctival and lacrimal sacs respectively. Taking \( V_1 \) as 7 \( \mu l \) and estimating \( V_2 \) to be 20–30 \( \mu l \) from published anatomical data,18 and taking \( \lambda_{12} \) and \( \lambda_{21} \) to be 3-24 and 0-72 min\(^{-1} \) respectively (Table 1), a tear flow of 1–8 \( \mu l \) per min can be estimated. These estimates of tear flow of course depend very much on the estimated volumes of each compartment, but they give order of magnitude results which compare favourably with the published range of 0-2–20 \( \mu l \) per min as reviewed by Sørensen and Jensen.17

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