Respiratory cilia beat in a coordinated manner with a specific frequency and pattern, clearing mucus and debris from the airways. Acquired or congenital ciliary ultrastructural defects result in cilia which are either stationary or beat in a slow or dyskinetic fashion. Ineffective movement impairs mucociliary clearance. In primary ciliary dyskinesia this causes sinusitis and recurrent chest infections which may lead to bronchiectasis.\(^1,\)\(^2\)

An early diagnosis of primary ciliary dyskinesia is important as institution of appropriate respiratory care has been shown to halt the progressive decline in lung function.\(^3\)

A diagnosis is made on the basis of a supportive clinical history and an abnormal ciliary beat frequency accompanied, in most cases, by specific abnormalities of the ciliary axoneme on electron microscopy.\(^4\) Studies by Rossman and colleagues suggest that evaluation of beat pattern, in addition to beat frequency, may be helpful in the diagnosis of patients with primary ciliary dyskinesia.\(^5\)

Making a confident diagnosis of primary ciliary dyskinesia can at times be very difficult as abnormalities of the epithelium and cilia may also be found purely as a result of acquired ciliary defects.\(^6,\)\(^7\) It is therefore important to differentiate between primary and secondary ciliary structural and functional abnormalities.

Secondary ciliary ultrastructural defects are common.\(^8\) Defects may persist for up to 12 weeks following resolution of an upper respiratory tract infection.\(^9,\)\(^10\) and ultrastructural interpretation may be difficult.\(^1\) Quantitative ultrastructural analysis in healthy adult subjects is limited.\(^11,\)\(^12\) Paediatric studies of the ciliary ultrastructure have been small and have consisted of patients rather than healthy controls. Data suggest that 5% of cilia have abnormalities,\(^13,\)\(^14\) with reports only analysing microtubular defects.\(^15\) The analysis of the dynein arms has been limited to patients with respiratory infections; up to 30% of cilia have been found to be affected.\(^16,\)\(^17\) Reference ranges for healthy children are not available for either ciliary microtubules or the presence of dynein arms, and there are no data on the damage of nasal ciliated epithelium in a healthy control population.

While normal ranges of ciliary beat frequency in adults have been published,\(^18,\)\(^19,\)\(^20,\) there are few data for children. Cilia from neonatal patients\(^21\) and adolescents\(^22\) were found to beat at a higher frequency than cilia from adults. Other studies have suggested that ciliary beat frequency may either fall with age\(^23\) or remain constant.\(^24,\)\(^25\) Evaluation of cilia in children involves the sampling of nasal epithelium and analysis of ciliary beat frequency, beat pattern, and ultrastructure.\(^26,\)\(^27\) Few data from normal children are available to allow comparison with findings in patients suspected of having primary ciliary dyskinesia.

We have adopted a digital high speed imaging method that allows the exact movement of a cilium to be rapidly evaluated throughout the beat cycle and measurement of the ciliary beat frequency. The direct observation of ciliary movement in slow motion and the ability to archive such material for audit and research is a major advantage over existing methods. It is likely that high speed video analysis will become the preferred method for evaluation of ciliary beat pattern and beat frequency for the diagnosis of primary ciliary dyskinesia. Using digital high speed imaging we have been able to describe precisely the normal ciliary beat cycle and found it to differ from previously published data.\(^1\)

The high speed video method has also been evaluated against other existing indirect techniques such as the photodiode and photomultiplier methods for the measurement of ciliary beat frequency and significant differences were found.\(^1\) This again emphasises the need for a normal range to be established for each method. Reference ranges exist for both the photomultiplier\(^1\) and photodiode\(^8\) methods, but no normal reference range exists for digital high speed imaging.

The aim of this study was to measure ciliary beat frequency and to determine the ciliary beat pattern and ultrastructure in healthy children and adults. The second aim of the study was to determine the ultrastructure of the respiratory epithelium from healthy children and adults.
METHODS
Fifty three healthy children (31 male, age range 6 months to 17 years) were recruited from subjects undergoing elective surgery and 23 adult volunteers (16 male, age range 18–43 years) were also recruited. Subjects were excluded if they had a history of chronic respiratory or nasal disease or a symptomatic upper respiratory tract infection during the previous 6 weeks, were taking regular medication, or were known smokers.

Paediatric samples were obtained immediately after induction of anaesthesia with propofol. This agent has been shown to have no effect on ciliary beat frequency. No premedication had been given to any subject before surgery. In all subjects ciliated samples were obtained by brushing the inferior nasal turbinate with a 2 mm cytology brush. Nasal brushings were placed in medium 199 (pH 7.3) which contained antibiotic solution (streptomycin 50 µg/ml, penicillin 50 µg/ml; Gibco, UK).

The study was approved by the Leicestershire ethical review committee and written consent was obtained before sampling.

Figure 1  Transmission electron micrographs illustrating the parameters assessed to examine epithelial damage in comparison with normal epithelium shown in fig 2A. (A) Severe loss of cilia, grade 3 (bar 10 µm). (B) Projection of a cell from the epithelial edge, grade 3 (bar 10 µm). (C) Cytoplasmic blebbing, grade 2 (bar 10 µm). (D), (E) Mitochondrial damage: a cell with a normal healthy mitochondrion (arrowhead, E) is shown against a cell with a damaged mitochondrion (arrow, D), grade 1 (bar 2 µm).
The ciliated epithelium was assessed blindly for both epithelial and ciliary ultrastructural changes. Epithelial integrity was assessed by firstly examining cell type. The number of ciliated cells, mucous cells, and dead cells were totalled and expressed as a percentage of all cells examined. Disruption and damage to the tissue was quantified using the scoring system previously described. Briefly, the tissue was scored for the following parameters: loss of cilia from ciliated cells: 0 (fully ciliated), 1, 2, 3 (a few cilia visible); projection of cells from the epithelial edge: 0 (normal alignment), 1, 2, 3 (cell projected from edge but some contact with other epithelial cells); cytoplasmic blebbing: 0 (absent), 1 (minor), 2 (major); mitochondrial damage: 0 (absent), 1 (present) (fig 1).

To give an overall evaluation of epithelial damage an epithelial integrity score was given to the epithelium which incorporated ciliary loss, cellular projection, cytoplasmic blebbing and mitochondrial damage. A healthy intact epithelial edge was scored 0 and a severely disrupted edge was scored 5 (0=no damage, 1=minor, 2=mild, 3=moderate, 4=major, 5=severe damage; fig 2). The scoring system was evaluated by comparing it against all measurements used to measure epithelial damage.

Damage to individual cilia was evaluated by examining the ciliary ultrastructure for microtubular and dynein arm defects. Alignment of individual cilia within a cell was assessed by measuring ciliary orientation as previously described.

The percentage of cells with loss of cilia, cellular projections, cytoplasmic blebbing, mitochondrial damage and with microtubular or dynein arm defects was calculated.

Ciliary beat frequency and beat pattern
Ciliary beat frequency and beat pattern were evaluated as previously described. Briefly, ciliated strips of epithelium were suspended in a chamber created by the separation of a cover slip and glass slide by two adjacent cover slips. The slide was placed on a heated stage (37°C) of a Leitz Diaplan microscope and examined by transmission electron microscopy. The ciliated epithelium was assessed blindly for both epithelial and ciliary ultrastructural changes. Epithelial integrity was assessed by firstly examining cell type. The number of ciliated cells, mucous cells, and dead cells were totalled and expressed as a percentage of all cells examined. Disruption and damage to the tissue was quantified using the scoring system previously described. Briefly, the tissue was scored for the following parameters: loss of cilia from ciliated cells: 0 (fully ciliated), 1, 2, 3 (a few cilia visible); projection of cells from the epithelial edge: 0 (normal alignment), 1, 2, 3 (cell projected from edge but some contact with other epithelial cells); cytoplasmic blebbing: 0 (absent), 1 (minor), 2 (major); mitochondrial damage: 0 (absent), 1 (present) (fig 1).

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Figure 2 Transmission electron micrographs showing assessment of epithelial integrity. (A) Normal tissue with an intact well ciliated surface and minimal disruption; epithelial integrity score=0 (bar 10 µm). (B) Abnormal tissue with severely disrupted cell surface and marked loss of cilia; epithelial integrity score=5 (bar 10 µm).

Analysis of data
As ciliary beat frequency may change with age, we wanted to see if other parameters showed such variation. As suggested by Roth et al, a cut off was made at 18 years of age. To allow sufficient subjects in each age group, three age ranges were used: 0–6, 7–12, and 13–18 years of age. Adults were classified as ≥19 years.

To form reference ranges the mean ciliary beat frequency, standard deviation, 5th and 95th percentiles were calculated for individual age groups. A one way analysis of variance was performed between groups. Individual groups were compared using a Student’s t-test. Similarly, the mean percentage, 5th and 95th percentiles of edges exhibiting areas of dyskinetically beating cilia were calculated. For all ultrastructural

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parameters the mean and the 5th and 95th percentiles were calculated. A one way analysis of variance was performed between groups.

RESULTS

Ciliary beat frequency and beat pattern were measured in all subjects; 56 had sufficient tissue for epithelial integrity measurements and 60 for ciliary ultrastructure. Ciliary beat frequency and beat pattern were the initial measurements to be made after which samples were then processed for electron microscopy. During this procedure tissue may be lost. Consequently, some subjects had an inadequate sample for full ultrastructural analysis.

Table 1 shows the percentage of different cell types seen in the epithelial strips obtained. Analysis showed no difference between the percentage of different cells identified and the age of the subject. Ciliated cells formed 65% of the cell population.

Analysis of the factors involved in epithelial integrity are summarised in table 2. Even within the healthy population there is evidence of loss of cilia, cellular extrusion, cytoplasmic blebbing, and mitochondrial damage. Analysis of variation found no difference between groups for all measurements analysed. The epithelial integrity score, which reflects a combination of all the measurements used to assess epithelial damage, also showed no significant difference between the age groups.

Table 3 shows the analysis of ciliary ultrastructure by transmission electron microscopy. No significant difference in mean ciliary beat frequency between individual age groups was found (ANOVA, p=0.10). However, there was a significant difference in ciliary beat frequency between patients under the age of 18 (12.8 Hz [95% CI 12.3 to 13.3]) and those over the age of 18 (11.4 Hz [95% CI 10.2 to 12.6 Hz], p<0.01, $t$ test). Approximately 10% of all edges analysed exhibited areas of ciliary dyskinesia.

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Analysis of cell type by transmission electron microscopy</th>
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<tr>
<td>Age (years)</td>
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<td>0–6</td>
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<td>≥19</td>
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Results are expressed as the mean percentage (5th and 95th percentiles) for individual age groups.

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<th>Table 2</th>
<th>Transmission electron microscopy assessment of epithelial integrity</th>
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<tr>
<td>Age (years)</td>
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<td>0–6</td>
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Results are for individual age groups and expressed as the mean (5th and 95th percentiles).

<table>
<thead>
<tr>
<th>Table 3</th>
<th>Analysis of ciliary ultrastructure by transmission electron microscopy</th>
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<tr>
<td>Age (years)</td>
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Results for individual age groups are expressed as the mean (5th and 95th percentiles).

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<th>Table 4</th>
<th>Summary of analysis of ciliary beat frequency measurements</th>
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<td>Age (years)</td>
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<td>≥19</td>
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*Mean ciliary beat frequency, standard deviation (SD), and 5th and 95th percentiles. †Mean (5th, 95th percentiles) percentage of edges exhibiting areas of ciliary dyskinesia.
dyskinetically beating cilia. This was found to be higher in the 13–18 year group.

To establish a reference range the mean ciliary beat frequency was plotted against age (fig 3A). A weak negative correlation was found between mean ciliary beat frequency and increasing age ($r=-0.30$, $p=0.008$). This was modelled and a linear relationship was found. Quadratic and other relationships were modelled and found not to be significant.

Within each sample cilia were found to beat at different frequencies. To evaluate sample variation in ciliary beat frequency the edges with the highest and lowest ciliary beat frequencies from several edges and from different sites along an edge.

The CV for measurement of ciliary beat frequency along an edge was 0.7 (2.0)% (95% CI –1.0 to 2.4; range –3.5 to 8.5).

**DISCUSSION**

Examination of the nasal ciliated epithelium from a large group of healthy children and a smaller group of adults has enabled us to establish normal age related reference ranges for both ciliary structure and function.

There are few data quantifying the ciliary epithelial ultrastructure following brush biopsy. We found evidence of minimal epithelial damage in the tissue from healthy subjects. Our results show a greater degree of epithelial damage than previously described. However, these data were from organ culture models and it is possible that, in the process of brushing and tissue preparation, minor damage may have occurred. Although two previous studies have evaluated the use of nasal brushing to sample cilia for ultrastructural measurement, they did not assess epithelial damage.

A scoring system for evaluation of epithelial integrity has been developed. This has been validated against the measurements used to assess epithelial ultrastructural damage and found to be representative of the minimal epithelial damage observed in healthy subjects.

The percentage of dynein arm and microtubular abnormalities were both found to be less than 5%, which agrees with other published data. The mean orientation of cilia in the paediatric population has only been described in eight children under the age of 2 years and was reported to be 14.9°. This is higher than the values we obtained (10.7–10.9°) in 60 subjects of differing ages.

The quantification of inner and outer dynein arms is important in the diagnosis of primary ciliary dyskinesia as dynein arm defects are the most common abnormality found in these patients. The majority of inner and outer dynein arms were visualised in all subjects. Our results are consistent with other published data on the number of outer dynein arms visible, but we were able to identify a greater proportion of inner dynein arms than has previously been reported. This may be because of the healthy nature of the tissue.

As suggested by Veale and colleagues, we examined ciliary beat frequencies from several edges and from different sites along an edge. The ciliary beat frequency was found to vary between edges within a sample, with a mean beat frequency of <11 Hz in some subjects. This is in keeping with other reports which have found cilia in healthy adults to beat maximally at a frequency of >10 Hz (range 10.2–14.6) and minimally at a frequency of >7 Hz (range 7.5–11.2). This was limited to 20 volunteers and no children were included. Adults were found to have slower beating cilia with frequencies as low as 6–9 Hz. Two healthy children were also reported to have cilia beating as slowly as 6 Hz.

The CV for measurement of ciliary beat frequency along an epithelial edge has been shown to vary from 9% to 58% compared with 10% in our study. We found no significant difference in inter-observer or intra-observer CV using the digital high speed video technique.

The ciliary beat frequency of the children was found to be significantly greater than the adult population. This is supported by studies which have shown ciliary beat frequency

![Figure 3](http://thorax.bmj.com/)
of neonates\textsuperscript{3} and teenagers\textsuperscript{3} to be greater than adult subjects. Our data suggest a slight fall in ciliary beat frequency with increasing age, which is in agreement with other studies,\textsuperscript{7} although Jorissen et al.\textsuperscript{10} found ciliary beat frequency to be independent of age. However, their readings were conducted at 22°C rather than at body temperature which makes the comparison difficult. At this temperature cilia beat at a much slower frequency and the association may therefore have been lost.\textsuperscript{12}

Digital high speed video imaging allowed us to visualise precisely the normal ciliary beat pattern in healthy subjects; 10% of edges had evidence of dyskinetically beating cilia. The remainder of the cilia were found to beat forward and backwards within the same plane without a classical sideways recovery sweep. This is consistent with our earlier description.\textsuperscript{1} Analysis of ciliary beat pattern may improve our understanding of the actions of the various respiratory pathogens—for example, cilia following infection have been found to have a dyskinetic beat pattern despite beating at a normal ciliary beat frequency.\textsuperscript{14}

In summary, we have established an extensive age related normal reference range for both ciliary structure and function. We have also examined the epithelial integrity in a healthy population. Such data will help with our evaluation of patients suspected of having primary ciliary dyskinesia and in research studies looking at the effects of various pathogens on nasal ciliary ultrastructure, function, and epithelial integrity.

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