Electron-tomographic analysis of intraflagellar transport particle trains in situ

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Intraflagellar transport (IFT) is the bidirectional movement of multipolypeptide particles between the ciliary membrane and the axonemal microtubules, and is required for the assembly, maintenance, and sensory function of cilia and flagella. In this paper, we present the first high-resolution ultrastructural analysis of trains of flagellar IFT particles, using transmission electron microscopy and electron-tomographic analysis of sections from flat-embedded Chlamydomonas reinhardtii cells. Using wild-type and mutant cells with defects in IFT, we identified two different types of IFT trains: long, narrow trains responsible for anterograde transport; and short, compact trains underlying retrograde IFT. Both types of trains have characteristic repeats and patterns that vary as one sections longitudinally through the trains of particles. The individual IFT particles are highly complex, bridged to each other and to the outer doublet microtubules, and are closely apposed to the inner surface of the flagellar membrane.

Introduction

Intraflagellar transport (IFT) is a motility process that occurs between the flagellar membrane and the axoneme in eukaryotes. It was first observed in the flagella of the biflagellate alga Chlamydomonas reinhardtii by differential interference contrast (DIC) microscopy as large, variably sized varicosities moving continuously to the flagellar tip (anterograde) at \( \sim 2.0 \mu \text{m/s} \), and smaller varicosities moving from tip to base (retrograde) at \( 3.5 \mu \text{m/s} \) (Kozminski et al., 1993). Transmission electron microscopy (TEM) of thin sections of flagella (Kozminski et al., 1995; Pedersen et al., 2006) showed that these varicosities were underlain by particle trains of varying length and appeared to be associated with the outer doublet microtubules (MTs) by thin connections, and even more closely associated with the inside of the flagellar membrane. The latter association was indicated by the fact that the otherwise loose-appearing flagellar membrane was always tightly applied to the surface of the trains of IFT particles facing the membrane (Kozminski et al., 1993; 1995). These trains of particles between the membrane and the axoneme were positively identified as IFT particles by immuno-EM using anti-IFT antibodies (Pedersen et al., 2006).

Since the initial observation and identification of IFT in C. reinhardtii flagella by DIC and TEM, IFT particle polypeptides have been found in many eukaryotic cilia and flagella (Beech et al., 1996; Cole et al., 1998; Rosenbaum et al., 1999; Pazour et al., 2002; Rosenbaum and Witman, 2002; Scholey, 2003; Sloboda and Howard, 2007; Pedersen and Rosenbaum, 2008), although ultrastructural observations of them have been confined principally to C. reinhardtii flagella (Kozminski et al., 1993, 1995; Dentler, 2005; Pedersen et al., 2006). There have been no studies that have focused specifically on the detailed 3D analysis of the trains of IFT particles.

This paper is the first to describe the ultrastructure of the trains of IFT particles using fixed and embedded material that has then been thin- and thick-sectioned for tomographic analysis in the transmission electron microscope. These studies were initiated with the knowledge that the rows of IFT particles were probably highly complex structures, as it had been described that they are required for transporting prefabricated axonemal components.
parts such as the radial spokes and dynein arms from the cytoplasm to the flagellar tip for assembly (Rosenbaum and Witman, 2002; Qin et al., 2004; Hou et al., 2007), as well as for movement of axonemal turnover products from the flagellar tip back to the cytoplasm (Marshall and Rosenbaum, 2001; Qin et al., 2004). In addition, kinesin-2–powered anterograde IFT was shown to carry the presumably inactive cytoplasmic dynein 1b to the tip, where it becomes engaged for the retrograde IFT trip back to the cytoplasm, now carrying the inactive kinesin-2 (Pazour et al., 1998, 1999, 2000; Orozco et al., 1999; Signor et al., 1999; Iomini et al., 2001). Finally, the IFT system, in addition to carrying axonemal proteins, is also responsible for the lateral movement of integral membrane polypeptides back and forth along the length of the flagella in the plane of the flagellar membrane bilayer (Qin et al., 2005; Huang et al., 2007). In spite of the presumed complexity of the IFT trains, repeating structures have already been observed in the few electron micrographs of IFT particles in situ that have been published (Kozminski et al., 1993, 1995; Dentler, 2005; Pedersen et al., 2006). Moreover, because the polypeptides composing isolated IFT particles sediment in discrete peaks at 16–17S in sucrose gradients (Cole et al., 1998), and because these particles in turn compose the IFT trains (Kozminski et al., 1995), one therefore might expect to find structures of a regular size and periodicity in the IFT trains located between the doublet MTs and the flagellar membrane.

In this paper, we describe our observations on the 3D structure of trains of anterograde and retrograde IFT particles in situ by use of electron tomography of sectioned flat-embedded _C. reinhardtii_ flagella. In addition, we provide the first evidence for ultrastructural differences between the anterograde and retrograde IFT trains.

**Results**

Trains of IFT particles can be observed in flagella of sedimented, randomly sectioned, whole _C. reinhardtii_ cells, but it is more efficient to use flat-embedded _C. reinhardtii_ cells. _C. reinhardtii_ can attach to a coverslip by their flagella and undergo gliding motility (Bloodgood, 1981); when fixed and embedded in this position, one can obtain serial longitudinal sections through many flagella in a single area (Fig. 1 a). If, instead, the flat-embedded material is repositioned at 90° to the knife, serial cross sections of the flagella and IFT trains can be obtained (Fig. 1 b).

**2D analysis**

**IFT trains in longitudinal sections of wild-type (WT) flagella.** Thin (~60 nm) longitudinal sections of flat-embedded flagella, from WT cells, show trains of IFT particles located in the space between the flagellar membrane and the outer axonemal doublets (Figs. 1 c and 2). The trains appear as electron-opaque structures with an intrinsin repeat of particles. These repeats were previously observed in EM studies of longitudinal sections of _C. reinhardtii_ flagella (Kozminski et al., 1993, 1995; Dentler, 2005; Pedersen et al., 2006), although the periodicities have not been measured. Depending on the level at which the IFT trains are sectioned, it is possible to observe connections linking IFT trains to both the outer doublet MTs and the flagellar membrane (Fig. 2). The links between the IFT train and the outer doublet MTs may represent the molecular motors (kinesin-2 and cytoplasmic dynein 1b) responsible for the movement of the trains. In the absence of IFT complexes, the flagellar membrane appears loosely associated with the underlying axoneme (Fig. 2 g); when an IFT train is present, the membrane always appears to be tightly associated with the IFT train all along its length (Figs. 1 c and 2), with a mean of 37.5 nm between the membrane and the axonemal MTs.

A careful analysis of many thin longitudinal sections of flagella from WT cells clearly revealed the occurrence of two distinct categories of IFT trains (Figs. 1 c and 2): short, thick, electron-opaque trains; and long, thin, less opaque trains. When the lengths of trains that were clearly contained in a single section were measured, they formed two peaks with mean lengths of 250 nm and 700 nm (Fig. 3, a and b). In reviewing the micrographs from which the trains were measured, those trains that clustered around 250 nm were all of the electron-opaque type, with a unit periodicity of ~16 nm, as shown in Fig. 2 (a–e). The periodicities were determined by measuring the total length of each IFT train and dividing by the number of units in the train minus one. These “short” trains were the ones first identified by Ringo (1967) and later noted by others after the discovery of IFT (Kozminski et al., 1993, 1995). The trains whose lengths were 500 nm or more were all of the less electron-opaque type, with a periodicity of ~40 nm, as seen in Fig. 2 (f–l). Based on this morphology, there are two categories of IFT trains that presumably have a different composition or function in the flagellum.

**Determination of the number of IFT trains per flagellum.** Using standard TEM on serial sections (section thickness of ~40 nm) of flat-embedded WT _C. reinhardtii_ cells, the IFT trains were counted in seven flagella that were sectioned longitudinally along almost their entire length, (see Fig. S1 and Table S1). The mean number of IFT trains in a flagellum was 18.1 (SD 5.6), with numbers ranging from 12 to 27 IFT trains. The determined numbers of IFT trains per flagellum are almost certainly underestimated, as the long trains, in particular, tend to go in and out of the plane of sectioning and therefore are difficult to quantify.

**fla14 mutant analysis permits selective observation of anterograde IFT trains.** The _fla14_ _C. reinhardtii_ mutant is characterized by the deletion of the LC8 gene, a component of both flagellae (Piperno and Luck, 1979) and cytoplasmic dyneins (King et al., 1996). Although deletion of the LC8 gene does not affect cell growth or cell morphology, and the LC8 gene product is not required for essential cellular process in _C. reinhardtii_ (Pazour et al., 1998), the flagella of _fla14_ are immotile, approximately half length, with missing or defective radial spokes, and the outer and inner dynein arms are reduced in number (Pazour et al., 1998). Because the deletion of LC8 disrupts the molecular motor for retrograde IFT (dynein 1b), retrograde IFT movement is missing in _fla14_ cells, whereas the kinesin-powered anterograde IFT is normal (Pazour et al., 1998). Most importantly,
flagella of fla14 contain 10–20-fold the amount of IFT particle polypeptides found in WT (Pazour et al., 1998), and, unlike flagella of WT cells, only anterograde IFT occurs. Flagella from fla14 cells therefore constitute excellent material for studying the structure of anterograde IFT trains by electron tomography. Many nearly identical particles can be sampled from a single tomogram, so this material is also suitable for the study of anterograde IFT particle/train structure by particle-averaging strategies.

The analysis of many longitudinal sections of fla14 flagella showed that IFT trains very similar to the ones identified as long trains in WT cells were abundant in this mutant. In >150 longitudinal sections of fla14 flagella analyzed, we observed 700 sections of IFT trains (Fig. 3 a). All of these were of low electron density and/or had the 40-nm periodicity characteristic of long trains in WT flagella (compare Fig. 2, f–l, with Fig. 2, m–o; and see Fig. S2). Only 71 of these trains appeared to be contained completely in a single section, and so were...
In WT flagella, outer dynein arms and IFT particles are often seen contacting each other, sometimes making the identification of IFT particles difficult (Fig. 1b). To overcome this problem, we analyzed cross sections from flagella of the pf28 mutant, which is missing outer dynein arms (Fig. 4a–g). The cross-section images of both WT and pf28 flagella show IFT particles connected to the B subfiber of the doublet by one or two links, and also connected to the flagellar membrane (Figs. 1b and 4a–g). The analysis of serial cross sections from pf28 flagella also revealed that neighboring trains, visible as separate entities (Fig. 4f), sometimes contact each other, appearing as a single structure with a wider cross section extending over two sets of MT doublets (Fig. 4g). Because it is known that IFT trains carry cargo, one might expect to see evidence of cargo in cross sections; however, no consistent placement of electron-opaque measured. The mean length of these trains was 755 nm with a standard deviation of 139 nm (Fig. 3b and c). None of the short, electron-dense trains were observed in these sections. In contrast, 110 longitudinal sections of flagella from WT cells contained 102 short trains (Fig. 3a). The overall results of the comparative analysis of WT and fla14 trains support the conclusion that the short, compact, electron opaque trains, absent in the retrograde mutant, are responsible for retrograde IFT, whereas the longer and less compact trains found in both fla14 and WT flagella underlie anterograde IFT.

**IFT trains in cross sections of WT and pf28 flagella.** TEM analyses of thin (~60 nm) cross sections from WT flagella confirmed the presence of IFT particles located between the MT doublets and the flagellar membrane (Fig. 1b), as previously shown (Kozminski et al., 1993; Pazour et al., 1998). In WT flagella, outer dynein arms and IFT particles are often seen contacting each other, sometimes making the identification of IFT particles difficult (Fig. 1b). To overcome this problem, we analyzed cross sections from flagella of the pf28 mutant, which is missing outer dynein arms (Fig. 4a–g). The cross-section images of both WT and pf28 flagella show IFT particles connected to the B subfiber of the doublet by one or two links, and also connected to the flagellar membrane (Figs. 1b and 4a–g). The analysis of serial cross sections from pf28 flagella also revealed that neighboring trains, visible as separate entities (Fig. 4f), sometimes contact each other, appearing as a single structure with a wider cross section extending over two sets of MT doublets (Fig. 4g). Because it is known that IFT trains carry cargo, one might expect to see evidence of cargo in cross sections; however, no consistent placement of electron-opaque
material that might be cargo was observed near the IFT particles, and, without specific labeling, we would be unable to identify such cargo.

3D analysis
Electron tomographic analysis of IFT trains from thick sections. We reconstructed several 3D maps from thick sections (~100 nm) of flagella of fla14 cells. The flagella of this retrograde IFT mutant are filled with long IFT trains, many in the proper location bounded by outer doublets and the flagellar membrane. Other trains overlap, forming bulges filled with multiple IFT trains between the flagellar membrane and axoneme (Fig. 5, a and b; Pazour et al., 1998). On the basis of ultrastructure and periodicity, these long trains, whether in the bulges or not, appear to be identical.

Fig. 5 is a montage of tomographic sections from the most informative areas we identified. Fig. 5 (a and b) was obtained by combining 20 contiguous individual (0.66 nm thick) planes from the middle of a tomogram to form virtual, 13.2-nm thick, sections. In the upper part of Fig. 5 a, two long trains of IFT particles are visible between the flagellar membrane and the MT doublets. One IFT train from this tomogram measured ~750 nm × 80 nm × 25 nm. Links between the IFT particles and the membrane (Fig. 5, a and b, black arrowheads) are shown as well as connections to the MT doublet (Fig. 5, a and b, white arrowheads). The shape and the position of the particles confers a wavelike pattern to the train that is present in almost all the longitudinal planes of the tomogram containing the long IFT trains. Video 1 shows the tomographic reconstruction in Fig. 5 a. We further studied the ultrastructure of IFT trains by analyzing individual planes of several tomograms from fla14 flagella oriented as in Fig. 5 (a and b). These views confirmed the wavelike pattern seen in IFT trains and afforded a better image of the associations of IFT particles with the flagellar membrane and MT doublets (Fig. 5, c–f). The mean spacing of these links to the MT, measured in 71 areas from three tomograms, was 41.4 nm (SD 2.5).

In the bulges of fla14 flagella, where IFT trains accumulate between the membrane and the axoneme, some trains maintain their association with MT doublets (Fig. 5, a and b, white arrowheads), and others with the flagellar membrane (Fig. 5, a and b, black arrowheads); these associations appear to be mediated by typical IFT train–MT or train–membrane links, respectively. In the core of a bulge, lines of particles constituting IFT trains are less discernible but are still visible (Fig. 5 b, circled areas), despite having lost their connections with both the flagellar membrane and MTs (Fig. 5, a, b, and f). This indicates that there are connections that link individual IFT particles together, stabilizing the IFT train even in the absence of interactions with the flagellar membrane or axoneme.

The encircled area in the inset between Fig. 5, panels a and b, indicates how volumes have been selected for particle averaging from the tomogram so that each volume contains three contiguous IFT particles with a portion of the flagellar membrane on one side and a tract of the MT doublet on the opposite side. We picked these individual volumes within a single train based on the clarity and ease of detection of the individual IFT units.

<table>
<thead>
<tr>
<th>Strain</th>
<th>Flagella Assayed</th>
<th>Distinct Long Trains Total Observed</th>
<th>Distinct Short Trains Total Observed</th>
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<tbody>
<tr>
<td>WT</td>
<td>110</td>
<td>29/82</td>
<td>102/157</td>
</tr>
<tr>
<td>fla14</td>
<td>150</td>
<td>71/700</td>
<td>0/0</td>
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Figure 3. Length distribution of IFT trains in WT and fla14 flagella. (a) Table of the number of clearly identifiable and measurable long and short IFT trains in WT and fla14 flagella. (b and c) Histograms of the length distributions of IFT trains in flagella of WT (b) and fla14 (c) cells. The arrows mark the mean length (±SD) of the long (grey) and short (black) IFT trains.

Fig. 6 shows the images that result from serial sectioning along the z axis of a volume reconstructed by averaging 15 individual volumes from within the same train, with each single volume containing one set of three contiguous IFT particles like those shown in Fig. 5 a (inset). This kind of rendering revealed that the IFT structure presents patterning variations depending on the sectioning level of the 3D density map. Panels 1 and 6 (Fig. 6), corresponding to the top and the bottom sections of the IFT train, respectively, show the connections between adjacent IFT particles and the links to the flagellar membrane. In panels 2 and 5 (Fig. 6), each particle appears to be formed of two separate oblong and spherical profiles that alternate to form the IFT train. In panels 3 and 4 (Fig. 6), the three IFT particles show
links to both the membrane and to the B subtubule of the MT doublet. The symmetry seen in each pair of sections suggests that each IFT particle is composed of two similar parts, one on top of the other.

A surface-rendering representation of part of a long IFT train is shown in Fig. 7. The model in Fig. 7 a is oriented like the tomogram section shown in Fig. 5; i.e., a longitudinal view from the top. From this vantage point, it is possible to identify the same wave pattern (highlighted by the white waving frame in Fig. 7 a) shown in Fig. 2 (f–o) and in Fig. 5. In addition, the longitudinal top view shows the links between IFT particles and the flagellar membrane on one side as well as links between IFT trains and the surface of MT doublets. These links are also visible in the cross view shown in Fig. 7 b and in most of the cross sections in Fig. 1 b and Fig. 4 (arrowheads).

In the 3D model, as well as in most of these EM cross sections, the IFT train seems to be built of two rows of similar particles, each connected by at least two links to the membrane, and by one link to the B subtubule of the MT doublet. The lateral view of the IFT trains, looking outward from the axoneme interior (Fig. 7 c), shows the two rows of particles (circles). The similarity between the particles of the two rows is striking and suggests a twofold rotational symmetry; i.e., the lower particle looks like the upper particle rotated 180°. Oblique links (Fig. 7 c, labeled with d) form lateral connections between neighboring particles. A second set of links (Fig. 7 c, labeled with l), oriented parallel to the longitudinal axis of IFT trains, connect adjacent particles. Fig. 7 c also shows a link (Fig. 7 c, labeled with k) of each individual particle to the surface of the MT doublet. Fig. 7 d shows a lateral view of the three pairs of IFT particles, as seen from the exterior of the flagellum. 1, 2, 3, and 4 indicate the contact points between the particles and the flagellar membrane. A video of the surface rendering in Fig. 7 is available online (Video 2). Because we see these connections between the IFT trains and membrane and MTs in raw EM sections, we are convinced that they represent real structures and not artifacts of the filtration procedure.

To support the reliability of our 3D alignment protocol, we have compared virtual sections from a raw unaveraged density map (Fig. 8 a) of an IFT train from fla14 flagella (Fig. 8, b and d) with virtual sections of an averaged 3D model cut at the same sectioning levels (Fig. 8, c and e).

We sectioned the tomogram along both the yellow and red sectioning planes shown in Fig. 8 a (i.e., parallel to the axoneme). The ~15-nm-thick digital sections obtained, cutting through the longitudinal axis of the IFT train, are shown in Fig. 8 (b and d). The white arrows indicate the 40-nm repeat of IFT particles along the train. At these section levels, the pairs of particles (Fig. 8, b–e, yellow and red masks) appear connected to each other by obliquely oriented bridging domains (Fig. 8, d and e, arrowheads). As expected, sections from both the tomogram and the averaged model display strikingly similar contours.

Short (retrograde) IFT trains in WT flagella.

To define the structure of the short, retrograde IFT trains, double tilt tomographic analysis was performed on flat-embedded flagella from both WT and p28 outer dynein armless mutant cells. The structure of the short trains is more heterogeneous and
compact than that of the long trains, which are less opaque and more spread out. Consequently, the short trains are less suitable for the averaging protocols used for modeling the long IFT trains. The short, compact, and more opaque retrograde trains, like the long trains, also vary in structure depending on the level of longitudinal sectioning.

By sectioning at three different levels along the z axis of the tomograms of IFT retrograde trains, we observed the patterns shown in Fig. 9. Fig. 9 (a and d) shows the association of IFT trains with the flagellar membrane. At this sectioning level, IFT trains also show projections linking them to the MT doublets. Fig. 9 (b and e), sectioned at the level of the axial core of the retrograde IFT trains, reveals the presence of a rodlike structure at the interface between the MT doublet and the rest of IFT train facing the flagellar membrane. This structure appears to be continuous, running along the length of the IFT train and parallel to the longitudinal axis of the MT doublet, with no obvious internal periodicity. Fig. 9 (c and f) shows sections of IFT trains cut through the “lollipop-shaped” particles previously described by others in short, dense IFT trains (Kozinski et al., 1993, 1995; Dentler, 2005; Pedersen et al., 2006) in C. reinhardtii flagella. These “lollipop-like” particles occur along the IFT trains with a 16-nm repeat, as previously observed in 2D EM pictures of short trains (Fig. 2 e). Colored diagrams superimposed onto the original pictures are shown in Fig. 9 (g, h, and i) to highlight these ultrastructural features.
between the two ends of the IFT train is confirmed when the surface model of this same IFT train is observed from the inside of the axoneme looking out toward the membrane (Fig. 10 b) and from the outside of the flagellum, looking inward the MT doublet, with the membrane removed (Fig. 10 c); this suggests the presence of a polarity in the retrograde train. The IFT train in Fig. 10 measures $\sim 250 \text{ nm} \times 50 \text{ nm} \times 20 \text{ nm}$. For a direct comparison between surface renderings of long and short trains, see Fig. S4.

Discussion

Although IFT was described over 15 yr ago (Kozminski et al., 1993), the ultrastructural basis for IFT has received little attention. In the initial description of IFT, linear arrays of electron-opaque particles were identified by TEM lying between the flagellar membrane and the outer doublet MTs, and were hypothesized to be the structures being moved by IFT (Kozminski et al., 1993). This relationship was confirmed soon thereafter using correlative DIC microscopy and EM of flat-embedded cells showing that the varicosities seen moving along the flagella by DIC microscopy (Kozminski et al., 1993) corresponded to the electron-dense rows or trains of IFT particles between the membrane and the outer doublet MTs (Kozminski et al., 1995). These early electron micrographs showed hints of periodicities of “lollipop-shaped” subunits that composed the IFT trains as well as links between the B tubules of the outer MT doublets and the trains (Kozminski et al., 1993).

Even these initial observations of IFT suggested that anterograde and retrograde IFT trains were different: anterograde IFT movement was easier to visualize by DIC imaging than retrograde movement (Kozminski et al., 1993) because the varicosities appeared larger than the retrograde varicosities. The size difference visualized by DIC microscopy was reflected in kymographs of IFT in which the traces of anterograde varicosities were wider than those of retrograde varicosities (Piperno et al., 1998; Iomini et al., 2001), but these images provided little information about the size or structure of the IFT train underlying the membrane. Despite the different size of anterograde and retrograde varicosities seen by DIC, the typical IFT train shown by EM in the literature was $\sim 250 \text{ nm}$ long, with distinct anterior and posterior ends. Certainly, this was what Ringo (1967) described in his early study of these structures. We now recognize that WT flagella also contain a second class of IFT trains that are more heterogeneous in length, less electron opaque, and that have anterior and posterior boundaries that are less well defined. In individual planes of tomographic reconstructions, the appearance of the two categories of trains is also different: the shorter and more compact IFT trains show a repeat of 16 nm, whereas the longer trains have a repeat of $\sim 40 \text{ nm}$. Furthermore, the long IFT trains are more amenable to tomographic analysis than short trains because of their relatively open structure. Such analysis suggests that each unit of the long anterograde train is made of two similar particles, so the train appears to be made up of a double string of particles.

The tomograms and the 3D models of long IFT trains presented in this paper were derived from flagella of the retrograde

Figure 6. Sectioning of the 3D density map obtained by aligning and averaging IFT particles from fla14 mutant cells. The density map was obtained by averaging 15 tomographic volumes from a single train, each one containing three contiguous IFT particles as shown in the inset of Fig. 5 a. The images 1–6 were produced by serial sectioning along the z axis of the cubic volume shown on the left. To illustrate the spatial orientation of sectioning planes in the model, a cross section of it is shown on the frontal face of the cube and a longitudinal section is shown on the top face. The cutting planes, represented by the white lines on the cube, are numbered from 1 to 6, proceeding along the z axis from the top to the bottom of the 3D map. Each section is 0.66 nm thick. The glycocalyx, the flagellar membrane [m], the IFT, and the MT doublet [md] have been manually segmented using the same color coding shown in Fig. 5 (green, glycocalyx; white, membrane; red, IFT particles; yellow, MT doublet). This kind of rendering revealed fine structural details of IFT particles with patterning variations depending on the sectioning level of the 3D density map. Panels are oriented so that the tip of flagellum is oriented downward.

One of the tomograms obtained by dual-axis tomography of a retrograde IFT train from WT flagella was processed by semiautomatic segmentation. The longitudinal view in Fig. 10 a shows the retrograde IFT train in the space between the plasma membrane and the MT doublet. Its left end (the one pointing toward the cell body) is slender and thinner than its opposite end, which displays a more rounded contour. This asymmetry
Another explanation for the existence of short and long trains, however, is that both categories of trains are traveling in both directions, and that the short trains represent long trains that have picked up cargo either at the flagellar base or tip. The long trains would, therefore, represent empty IFT trains. According to this hypothesis, \textit{fla14} has principally long, thin trains because it lacks much of the cargo present in WT flagella; e.g., dynein arms and radial spokes. The reduction of cargo would result in a predominance of long (unloaded) trains. We are currently testing this possibility by quantifying the number of long and short trains in flagella of mutant \textit{fla14} cells because of the abundance of IFT trains in these flagella. Unlike other retrograde mutants (Piperno et al., 1998), \textit{fla14} does not present any deficiency in IFT proteins of either complex A or complex B (Pazour et al., 1998). These \textit{fla14} IFT trains, therefore, appear to be assembled normally, with the same structure as the long trains in WT cells. This was confirmed by comparing longitudinal sections of long IFT trains from WT and \textit{fla14} (Figs. 2 and S2) and by comparing sections of the 3D model, which was based on data derived from \textit{fla14} (Figs. 6 and 7), to sections of WT trains shown in Fig. 2. Only the long category of IFT train was found in \textit{fla14}, and this retrograde IFT mutant displays anterograde but not retrograde IFT (Pazour et al., 1998), which strongly suggests that the longer, less opaque trains are anterograde trains and the shorter, compact trains are retrograde trains.

Another explanation for the existence of short and long trains, however, is that both categories of trains are traveling in both directions, and that the short trains represent long trains that have picked up cargo either at the flagellar base or tip. The long trains would, therefore, represent empty IFT trains. According to this hypothesis, \textit{fla14} has principally long, thin trains because it lacks much of the cargo present in WT flagella; e.g., dynein arms and radial spokes. The reduction of cargo would result in a predominance of long (unloaded) trains. We are currently testing this possibility by quantifying the number of long and short trains in flagella of
doublets (Fig. 7 b, arrows; and Fig. 7 c, “k”). These connections may represent the position of the anterograde motor, kinesin-2. If there is one kinesin in every 40 nm, our model predicts a ratio of one putative kinesin for every five tubulin dimers (8 nm/dimer) along an outer doublet protofilament. The presence of these links is also supported by the analysis of cross ultrathin sections of *C. reinhardtii* flagella, where pairs of IFT particles are often linked to the B subtubule by two electron-dense bridges (Figs. 1 b and 4). Although these bridges are located between the IFT particles and the MTs, where one would expect to find kinesin motors, as of yet we have no direct evidence of the molecular nature of the bridges.

At present, we know very little about the molecular composition of the various protrusions/extensions/connections from the IFT particles observed in the tomograms, or even about the placement of motors or complex A and B in the IFT trains. This could be determined by analysis of various IFT mutants lacking certain IFT polypeptides using electron tomographic techniques similar to those used in this paper, as well as cryo-EM of isolated IFT particles. Indeed, *C. reinhardtii* IFT mutant *fla15*...
We also do not know where the IFT cargo is located, and analysis of cross and longitudinal sections provides little information on its placement. Cargo could be associated with the IFT trains themselves, and/or it could be associated with the inner aspect of the flagellar membrane, being moved by the underlying IFT trains, which appear to be tightly associated with the inner surface of the flagellar membrane (Fig. S3). This latter possibility is appealing, not only because of the ultrastructural evidence for IFT–membrane associations, but because it has been proposed (Rosenbaum and Witman, 2002) that some IFT cargo, synthesized on free polysomes (e.g., tubulin) might become associated with the outer surface of cytoplasmic vesicles before their exocytosis near the basal body. Once these vesicles progressed through exocytosis, the cargo proteins would be associated with the inner aspect of the flagellar membrane, as well as with the IFT trains, which, like cargo, become associated
trains with the flagellar membrane. The flagellar membrane channel, is dependent on IFT (Huang et al., 2007). Thus, movement of PKD-2 (polycystin-2), another multipass membrane (Qin et al., 2005). Likewise, in the axoneme, movement of vesicles from the Golgi to the ciliary membrane is known to occur, as best illustrated by the movement of IFT trains with proteins in the flagellar membrane near the base of the flagella and subsequently on the inner aspect of the axoneme. (c) The IFT train as seen from the exterior of the axoneme. Note in b and c the asymmetry between the head and the tail ends, and the presence of repeating structures along the train. Black arrows in each frame indicate the flagellar tip orientation.

Evidence for an interaction of IFT and cytoplasmic vesicles comes from work on IFT20, a peripheral subunit of the complex B (Lucker et al., 2005) that may play a role in trafficking of ciliary membrane proteins from the Golgi complex into the flagellar membrane and the MT doublet. The two ends of the IFT train have different appearances, which suggests the presence of a polarity in the retrograde train. (b) The retrograde IFT train as seen from the interior of the axoneme. (c) The IFT train as seen from the exterior of the axoneme. The data in this paper provide a 3D view of anterograde IFT trains and a dramatic representation of the extensive restructuring that must accompany the conversion of anterograde to retrograde IFT trains at the flagellar tip.

Materials and methods

Sample preparation: flat-embedding
C. reinhardtii cells were pipetted onto clean glass coverslips (18 × 18 mm, # 1; Carl Roth GmbH) and allowed to settle and adhere for 5–15 min (Mitchell and Nakatsugawa, 2004; Pedersen et al., 2006). The coverslips were fixed by pipetting MI containing 2.5% glutaraldehyde (Serva Electrophoresis), pH 7.2, onto the coverslips. After 30 min at RT, the fixative was replaced with MI containing 2.5% glutaraldehyde and 0.2–0.4% tannic acid (Malinckrodt Baker), pH 7.2, and the fixation continued for another 30 min at RT. After a rinse with distilled water, the cells were postfixed with 1% OsO4 (in distilled water) at 4°C for 30 min. After washes with distilled water, the specimens were dehydrated using a graduated series of ethanol and infiltrated with epon 8123 (Serva Electrophoresis). Polymerization was performed for 48 h at 65°C and the coverslips were dissolved off the epon layer by immersion in hydrofluoric acid. Areas of interest were cut out of the flat embeddings under a dissecting microscope and mounted on dummy blocks using two-component epoxy adhesive (UHU plus endfest 300, UHU GmbH and Co. KG). When cutting longitudinal sections of the flagella, a very accurate alignment of the block face with the axoneme is essential, as flagella are ~250-nm thick and only the first few sections contain flagella. Serial sections (~60 nm for standard TEM and 100 nm for tomography) were cut with a diamond knife (type ultra 35°; Diatome) on an ultramicrotome (EM UC6; Leica) and collected on formvar-100 nm for tomography) were cut with a diamond knife (type ultra 35°; Diatome) on an ultramicrotome (EM UC6; Leica) and collected on formvar-coated 100 hexagonal mesh copper-rhodium grids. Specimens were stained with lead citrate and uranyl acetate (Reynolds, 1963).

TEM and electron tomography

Standard TEM was done using a transmission electron microscope (JEM-2100, JEOL Ltd.) equipped with a 4,000 × 4,000 charge-coupled device camera (UltraScan 4000; Gatan, Inc.) and Gatan Digital Micrograph software (version 1.70.16). Tomography was performed with a transmission electron microscope CM200 field emission gun (Philips) operating at 160 kV, equipped with a 2,000 × 2,000 charge-coupled device camera (TVIPS TemCam-F224HD) and the EMmenu4 software package (both from Tietz Video and Image Processing Systems GmbH). 100-nm-thick sections (~30-60 nm for standard TEM and 100 nm for tomography) were cut with a diamond knife (type ultra 35°; Diatome) on an ultramicrotome (EM UC6; Leica) and collected on formvar-coated 100 hexagonal mesh copper-rhodium grids. Specimens were stained with lead citrate and uranyl acetate (Reynolds, 1963).

Figure 10. Surface rendering of a short retrograde IFT train from a WT flagellum tomogram. The density map was semi-automatically segmented, and colors have been assigned as in previous models [white, flagellar membrane (m); red, IFT particles (IFT); yellow, MT doublets (md)]. (a) Longitudinal view of the model. The IFT train is located in the space between the flagellar membrane and the MT doublet. The two ends of the IFT train have different appearances, which suggests the presence of a polarity in the retrograde train. (b) The retrograde IFT train as seen from the interior of the axoneme. (c) The IFT train as seen from the exterior of the axoneme.
References


Online supplemental material

Fig. S1 shows the analysis of the number of IFT particles per flagellum using serial section TEM. Fig. S2 shows longitudinal, virtual sections through a tomogram of a WT and a fla14 flagellum. Fig. S3 shows a schematic cross section of a C. reinhardtii flagellum showing the organization of an anterograde IFT train. Fig. S4 shows a combination of Figs. 7 and 10 for direct comparison between 3D surface-rendering models of long and short IFT trains. Video 1 shows a virtual flight along the z axis of a tomographic reconstruction obtained from a flagellum of the fla14 C. reinhardtii mutant. Video 2 shows rotation of surface-rendering model of three anterograde IFT units from a fla14 mutant cell. Table S1 shows the number of IFT trains per flagellum as determined by serial section standard EM.

We wish to thank Elisa Vannuccini (University of Siena) and Dirk Scholz (University of Bayreuth) for technical assistance and Caterina Mencarelli (University of Siena) and Romano Dallai (University of Siena) for stimulating discussions during the course of this work. We thank Christopher R. Wood (Yale University) for the hypothesis that the short IFT trains carry cargo in both directions. These studies were supported by grants from TELTHER (OGP07269) and Monte dei Paschi di Siena (2008-2009) to P. Lepri and the National Institutes for Health (NIH-GMS-14642) to J.L. Rosenbaum.

Submitted: 19 May 2009
Accepted: 3 September 2009


