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Publication Date

1994

DOI

10.1007/978-3-7091-9326-6_48

Peer reviewed

Comparative studies of $T = 3$ and $T = 4$ icosahedral RNA insect viruses

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Summary. Crystallographic and molecular biological studies of $T = 3$ nodaviruses (180 identical subunits in the particle) and $T = 4$ tetraviruses (240 identical subunits in the particle) have revealed similarity in both the architecture of the particles and the strategy for maturation. The comparative studies provide a novel opportunity to examine an apparent evolution of particle size, from smaller ($T = 3$) to larger ($T = 4$), with both particles based on similar subunits. The BBV and FHV nodavirus structures are refined at 2.8 Å and 3 Å respectively, while the NøV structure is at 6 Å resolution. Nevertheless, the detailed comparisons of the noda and tetravirus X-ray electron density maps show that the same type of switching in subunit twofold contacts is used in the $T = 3$ and $T = 4$ capsids, although differences must exist between quasi and icosahedral threefold contacts in the $T = 4$ particle that have not yet been detected. The analyses of primary and tertiary structures of noda and tetraviruses show that NøV subunits undergo a post assembly cleavage like that observed in nodaviruses and that the cleaved 76 C-terminal residues remain associated with the particle.

Introduction

There are a variety of unifying themes in the structure and function of positive strand RNA viruses and these have been used to construct

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detailed evolutionary relationships among these viruses [1, 2]. Most positive strand RNA viruses have icosahedral capsids with $T = 3$ quasi symmetry (primarily plant viruses) or a picornavirus type capsid (primarily animal viruses) [2]. These capsid types are themselves related, with an apparent triplication of the capsid protein gene observed in the $T = 3$ viruses forming the picornavirus capsids [3]. The identification of a particular capsid type with viruses infecting members of a particular kingdom is not universal, however, since there are plant viruses with capsids that are clearly related to the picornaviruses [4] and there are animal viruses with $T = 3$ symmetry [5, 6]. Because there are such limited examples of capsid types the only comparisons to date have been between $T = 3$ and picornavirus capsids [2, 3, 4]. We have been investigating two groups of insect viruses, nodaviruses [7] (displaying $T = 3$ quasisymmetry) and tetraviruses [8] (displaying $T = 4$ quasisymmetry). In this paper we report similarities in structure and function that are apparent from our biochemical and biophysical studies.

The $T = 3$ nodaviruses are among the simplest animal viruses known. Their genomes consist of roughly 4500 bases that are split between two single-stranded, messenger-sense RNA molecules encapsidated in one virion [9]. The genome encodes only three proteins [10]; a replicase (protein A), the coat protein precursor (protein α) and a protein of unknown function (protein B). Nodaviruses are small non-enveloped viruses that infect insects [7], mice [11], and fish [12]. They can be produced in large quantity and readily crystallized. They undergo a well characterized series of assembly and maturation steps [13]. An infectious clone is available for Flock House nodavirus (FHV) [14], and particles spontaneously assemble and package their own messenger RNA when the FHV capsid protein gene is expressed in a baculovirus system [15]. The structure of the black beetle nodavirus (BBV) has been determined [5] and was found to be similar to all $T = 3$ RNA plant virus structures analyzed, although the β -barrel subunits contained elaborate surface loops and an interior helical domain not observed in the plant viruses. Biochemical studies of FHV showed that 80% of the coat protein subunits α (407 amino acids) underwent a post assembly, autocatalytic cleavage to form protein β (363 amino acids) and protein γ (44 amino acids) in the mature virion and that this cleavage was required for infectivity [16]. This maturation is similar to that observed in picornaviruses [17] and suggests that the nodaviruses, although displaying a different capsid architecture, may share a common biological strategy for particle maturation and possibly uncoating.

The *Tetraviridae* family of viruses, formerly referred to as the *Nud-aurelia* β virus family, consists of seven members that form icosahedral particles with $T = 4$ symmetry [8]. All members of this virus group

identified to date propagate exclusively in insect hosts. The prototype, *Nudaurelia capensis* β virus (N β V), was originally isolated from the pine emperor moth, *Nudaurelia cytharea capensis* Stoll [18] and it has been the subject of recent studies [19]. This group of viruses form shells that are 350–400 Å in diameter, encapsidating a single-stranded RNA having a molecular mass of $1.8\text{--}1.9 \times 10^6$ daltons. The particles have sedimentation coefficients between 200S and 210S. Examination of the capsids by SDS-PAGE revealed in all cases a single capsid polypeptide estimated to be 65–68 kD. Compilations of these characteristics for individual members have recently been published [20, 21].

The striking differences between noda and tetraviruses are the size of the capsid subunit and the size of the particle (Table 1). Earlier work on these viruses did not suggest a relationship between them, however, structural studies at the primary and tertiary level of *Nudaurelia capensis* ω virus (N ω V), another tetravirus, now suggest that noda and tetraviruses are related [22]. The geometric concepts for generating quasi equivalent shells have been developed on the basis of theoretical and experimental data [23, 24]. The nodaviruses display $T = 3$ symmetry (180 subunits in the capsid) and the tetraviruses $T = 4$ symmetry (240 subunits in the capsid). The first two high resolution virus structures determined were for the $T = 3$ plant viruses, tomato bushy stunt virus [25] and southern bean mosaic virus [26]. Remarkably, they were found to have subunit tertiary and particle quaternary structures that were virtually superimposable in the contiguous shell, although the subunits displayed only limited sequence homology. The $T = 3$ plant and animal viruses have a shape that is strikingly similar to the rhombic triacontahedron [27] and this geometric solid is shown and discussed in Figs. 1a and b. Although structurally similar to the plant viruses in many respects, recent studies have shown that nodaviruses incorporated regions of duplex RNA in the capsid and that the RNA functioned as part of the molecular switch that regulates the formation of the $T = 3$ shell [28].

Comparison of subunit primary structures of noda and tetravirus

The segmented genome of N ω V consists of RNA1 (5 kb) and RNA2 (2.5 kb). The sequence of RNA2 was recently reported and the encoded amino acid sequence was compared with nodavirus capsid proteins [22]. Two similarities were observed. First, the N ω V coat protein (646 residues) probably undergoes a post translational cleavage. This was apparent when the virus particle was subjected to direct chemical protein sequencing. The 21 “Nterminal” amino acids obtained in this experiment aligned with residues 571 to 591 encoded by the RNA2 gene. The likely explanation for this result is that a posttranslational cleavage occurs

Table 1. A comparison of features between *Nodaviridae*, N ω V, and N β V

| Virus | Icosahedral symmetry | Number of subunits | Particle size (Å) | Buoyant density (g/cc) | Polypeptide composition | Genomic composition | Encoded products |
|--------------------|----------------------|--------------------|---------------------------------|------------------------|------------------------------------|--------------------------------|--|
| <i>Nodaviridae</i> | $T = 3$ | 180 | 312 (9.4×10^6 mD) | 1.33 | β (38 kD) γ (5 kD) | RNA1 (3.1 kb) RNA2 (1.4 kb) | protein A, B α (β, γ) |
| N ω V | $T = 4$ | 240 | 410 | 1.285 | β (62 kD) γ (8 kD) | RNA1 (5 kb) RNA2 (2.5 kb) | n.d. α (β, γ) |
| N β V | $T = 4$ | 240 | 397 (16.3×10^6 mD) | 1.295 | β (61 kD) γ (8 kD) | RNA1 (5.4 kb) | n.d. |

n.d. Not determined

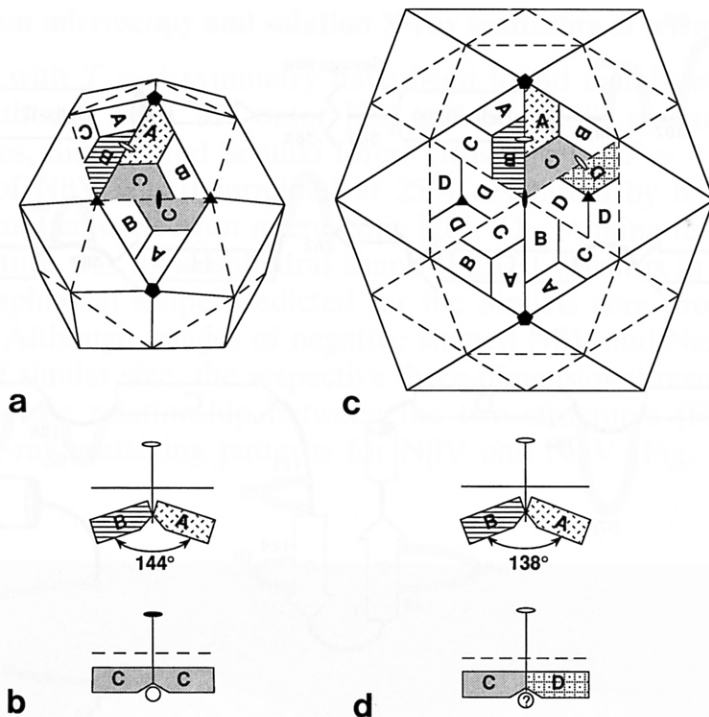


Fig. 1. Diagrammatic representations of the subunit associations accounting for contiguous shells in $T = 3$ (a, b) and $T = 4$ icosahedrons (c, d). Labeled trapezoids represent the individual capsid subunits. The packing relations, as viewed along an equatorial line within the structure, between C subunits related by the icosahedral twofold (solid ellipse) and between A and B subunits related by the quasi twofold (open ellipse) are shown for the $T = 3$ structure in b. Likewise, the C and D , and the A and B subunits of the $T = 4$ structure, related by different quasi twofold axes, are shown in d. A peptide and RNA duplex (open circle, b) maintains the planar C - C contact as observed in the BBV structure [4]. A similar peptide (d) may keep the C - D contact in the $T = 4$ structure planar. Open and closed ellipses, closed triangles, and closed pentagons represent quasi and icosahedral twofold, and icosahedral threefold and fivefold axes, respectively

between residues 570 and 571, making residue 571 an unblocked N-terminus of a polypeptide consisting of residues 571–646 (This would correspond to the γ peptide described for nodaviruses). The true N-terminus of the N ω V coat protein translation product is probably blocked like many other viral capsid proteins. Exactly this situation was found with the Flock House nodavirus [13]. When N ω V was analyzed on a SDS gel, there was clear evidence for a small polypeptide of molecular weight ~ 8 kD as well as the larger polypeptide at ~ 61 kD. Earlier studies had not reported the small protein probably because it ran off the end of the gel under typical electrophoresis conditions. The gene for the N ω V capsid protein has been cloned and expressed in *E. coli* and the resultant

Electron microscopy and solution X-ray scattering of tetraviruses

Structures with $T = 4$ symmetry have been found mainly within insect viruses, although both the outer [29] and core [30] structures of the alphaviruses, Sindbis and Semliki forest virus, display $T = 4$ shells. The structure of N β V was determined at 25 Å resolution by both negative stain [31] and cryo-electron microscopy [20]. The striking feature of the N β V structure was its icosahedral shape (Fig. 3) which is in contrast to the more spherical shape predicted for the Sindbis core protein $T = 4$ shell [30]. Although images of negative stained N β V and N ω V revealed particles of similar size, the respective three-dimensional reconstructions showed a close relationship between the two structures (Fig. 3). The solution X-ray scattering patterns for N β V and N ω V (Fig. 4) are also

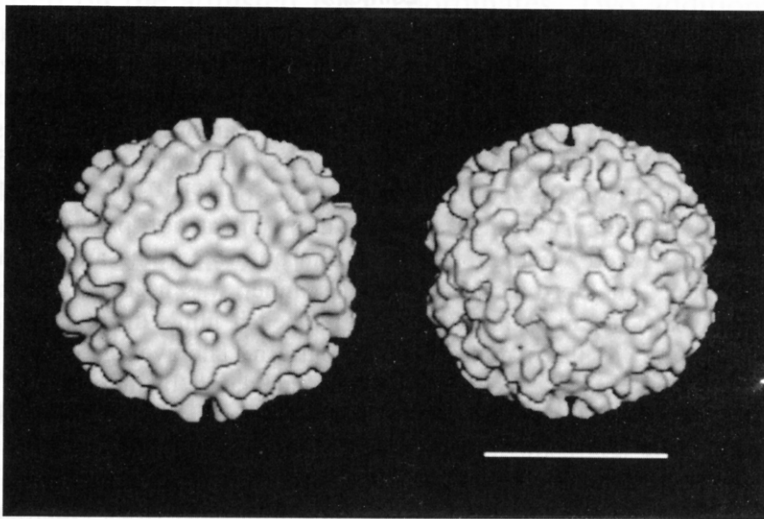


Fig. 3. Shaded-surface representations of three-dimensional reconstructions of N β V (left) and N ω V (right) computed from images of frozen-hydrated virions. The bar on the right is 250 Å. Specimens were prepared for cryo-electron microscopy by applying small drops of each sample to perforated carbon films on 400 mesh copper grids. The grids were briefly blotted with filter paper and then rapidly plunged into liquified ethane. They were then transferred to liquid nitrogen before being inserted into a cold, Gatan cryotransfer holder and then into a Philips EM420 transmission electron microscope. The images were recorded at $\sim 1.5 \mu\text{m}$ underfocus, at 49 000X magnification, and with an electron dose of $\sim 20 \text{e}^-/\text{Å}^2$. Selected micrographs were digitized, individual particle images from each were boxed, and the background density of each image was subtracted. The initial centers of density of each image were determined by cross correlation methods [36] and the orientation of each particle, with respect to the view axis, was determined with established icosahedral processing procedures [37–39]. Refined data sets of twenty-five images of N β V and 57 of N ω V were used to calculate three-dimensional reconstructions of each virus with an effective resolution of 31 Å and 28 Å, respectively

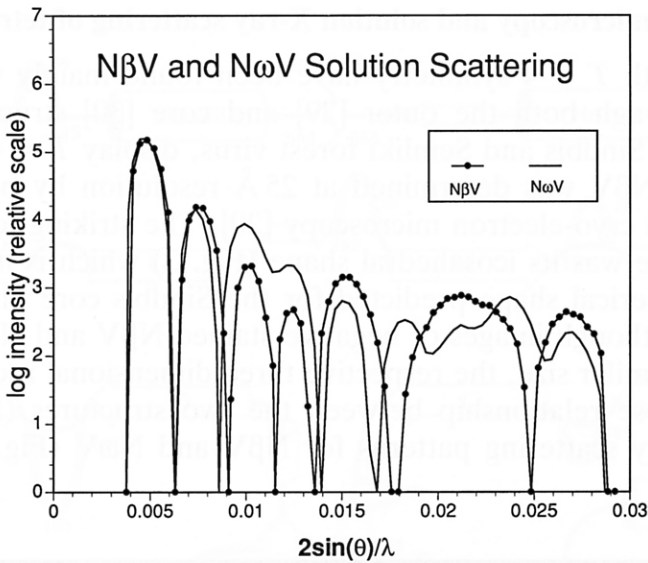


Fig. 4. $N\beta V$ and $N\omega V$ solution scattering patterns. Each virus was pelleted, resuspended in buffer at approximately 150 mg/ml, and placed in a 1 mm quartz capillary. Diffraction data were then collected, at 267.5 mm sample-to-film distance, using $CuK\alpha$ radiation, a double-mirror focusing camera [40, 41] with an order-to-order resolution of $\sim 1500 \text{ \AA}$, and an Elliott GX-20 rotating anode generator with a $0.15 \times 2.5 \text{ mm}$ focal spot. Exposure time was about 85 h at an X-ray power of 35 kV and 30 mA. In order to fully record the wide intensity range of each virus's diffraction pattern, three Kodak DEF-5 films were stacked together, with each film both recording and attenuating the scattered radiation. An Optronics C4100 film scanner was used to digitize the film optical densities on a $50 \mu\text{m}$ raster. The center of each film's diffraction pattern was determined using the circular symmetry of the pattern. The average optical density at each radial distance from the center was then calculated by integrating all optical densities within $50 \mu\text{m}$ thick circular shells. Each film's final radial intensity distribution was then obtained by subtracting a smooth background curve fitted through the nodes. The three radial intensity distributions (from the three stacked films) were then scaled together to produce the final intensity profile shown for each virus. Additional experimental details can be found in [42]

different, but display an underlying similarity consistent with the electron microscopy reconstructions.

Figures 1c and d represent the tetravirus $T = 4$ structure diagrammatically and show the similarity with the rhombic triacontahedron of the $T = 3$ structure. On the basis of this comparison a detailed model of the $N\omega V$ $T = 4$ shell was constructed with the subunit tertiary structure observed in the $T = 3$ shell of BBV [5]. The icosahedral asymmetric unit of the $T = 4$ shell (A, B, C, D) (Fig. 1c) was defined as the A, B, C and C2 subunits in the $T = 3$ shell (Fig. 1a). The coordinates of atoms in these four subunits in BBV were adjusted radially until a non-overlapping contiguous shell was formed with atoms in neighboring asymmetric units

generated by the icosahedral symmetry operations. Table 2 lists the coordinates and radial distances of well-defined features observed in the subunits of BBV as they were positioned in the $T = 4$ N ω V modeled structure. These are compared with features in the electron density map of N ω V below.

Electron density of N ω V at 8 Å resolution

Crystals of N β V and N ω V have been produced and they diffract X-rays to 2.7 Å resolution [32, 33]. Both viruses crystallize in an unusual but similar unit cell. Cell dimensions and crystallization conditions are given in Table 3. The proposed similarity of the noda and tetraviruses is supported by the 8 Å resolution N ω V electron density map recently computed. There is clear evidence for a β -barrel core in the electron density for the contiguous shell of N ω V and it agrees well with the $T = 4$ model based on the adjusted BBV coordinates. Two additional characteristics found in nodavirus structures that were obvious in the 8 Å electron density map were the helical interior domain that probably contains the C terminal portion of the cleaved capsid protein γ (residues 571 to 646) and a peculiar “doughnut” shaped density feature surrounding the fivefold symmetry axes. Both of these features were clear in the N ω V map (Figs. 5a and b) and they served as markers to compare the model of N ω V generated with the BBV subunits with the actual N ω V structure. The γ peptides of the BBV subunits are placed in helical density in the N ω V map (Fig. 5a). In addition the leucine residues on the β D- β E loop of BBV are directly in contact with the “doughnut” shaped density appearing in that structure about the fivefold axes, and the BBV subunits modeled in the N ω V map occupy exactly the same position relative to the “doughnut” shaped density in N ω V (Fig. 5b). Thus, at 8 Å resolution the electron density supports the similarities between nodaviruses and tetraviruses based on geometric arguments and the sequence alignments.

Discussion

The noda and tetravirus systems offer a unique opportunity to study the factors affecting capsid architecture. Evidence presented here suggests that the subunit building blocks of noda and tetraviruses are similar, particularly with regard to the β -barrel that forms the contiguous protein shell. Other features of the $T = 3$ and $T = 4$ shells, in addition to the β -barrel, are also comparable. These include the helical domain that lies inside the barrel, which is the location of the autocatalytic maturation cleavage in FHV and BBV, and the “doughnut” shaped density that exists on the fivefold symmetry axes in nodavirus structures and N ω V.

Table 2. N ω V ($T = 4$) model based on BBV

| | Residue # (C α) | X | Y | Z | D (Å) |
|--|-------------------------|------|------|-------|-------|
| Farthest distance along Q3 | B207 | 59. | -1. | 183. | 192. |
| Farthest distance along I5 | A306 | 103. | -3. | 163. | 193. |
| Farthest distance along I3 | C207 | -2. | 1. | 183. | 183. |
| Farthest distance along I2 | A305 | 18. | -42. | 159. | 165. |
| γ Peptide of A subunit | A379 | 76. | -3. | 119. | 142. |
| | A364 | 92. | 2. | 133. | 161. |
| Doughnut along I5 | A182 | 108. | -0. | 154. | 188. |
| | A181 | 106. | 1. | 150. | 184. |
| Ca ²⁺ on Q3 axis | A249 | 62. | 1. | 141. | 154. |
| | A251 | 61. | 5. | 145. | 157. |
| Residue (measured at) | strand | X | Y | Z | D (Å) |
| CHEF-sheet of β -barrel of a subunit | | | | | |
| 190 | E | 85. | -6. | 150. | 173. |
| 299 | H | 85. | -3. | 154. | 176. |
| 113 | C | 84. | 1. | 157. | 178. |
| 277 | F | 48. | 19. | 165. | 173. |
| BIDG-sheet of β -barrel of a subunit | | | | | |
| 241 | G | 84. | 0. | 145. | 167. |
| 174 | D | 87. | 6. | 147. | 172. |
| 314 | I | 86. | 9. | 150. | 173. |
| 100 | B | 87. | 13. | 152. | 176. |
| Loops facing fivefold axis measured at | loop | X | Y | Z | D (Å) |
| 108 | β B- β C | 96. | -5. | 165. | 191. |
| 306 | β H- β I | 103. | -3. | 163. | 193. |
| 183 | β D- β E | 105. | 1. | 156. | 188. |
| 236 | β F- β G | 98. | -0. | 149. | 178. |
| 135 | β C- β C' | 80. | -9. | 168. | 186. |
| Heavy atom positions (site) | X | Y | Z | D (Å) | |
| A | 99. | 2. | 164. | 192. | |
| B | 38. | -38. | 166. | 174. | |
| C | 34. | 36. | 164. | 171. | |
| D | 24. | -36. | 166. | 172. | |

Sites A, B and C are related by quasi threefold symmetry and sites C and D by quasi twofold symmetry

Table 3. Tetravirus crystals

| Crystal form (virus) | Space group | Lattice constants | Z |
|-----------------------------------|-------------|---|---|
| Form III N β V ^a | P1 | 408.7 Å, 403.14 Å, 409.67 Å, 59.35°, 58.97°, 63.21° | 1 |
| N ω V ^b | P1 | 413.55 Å, 410.22 Å, 419.67 Å, 59.13°, 58.9°, 64.04° | 1 |

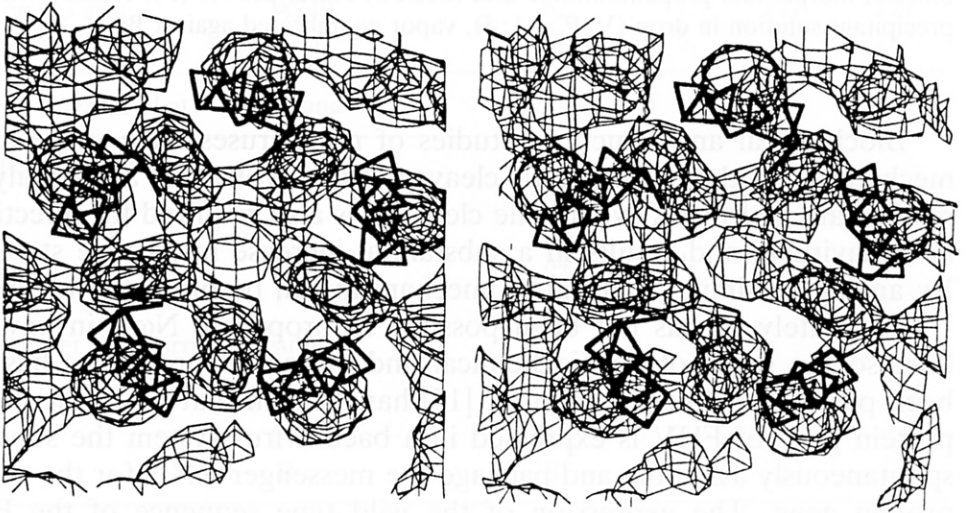
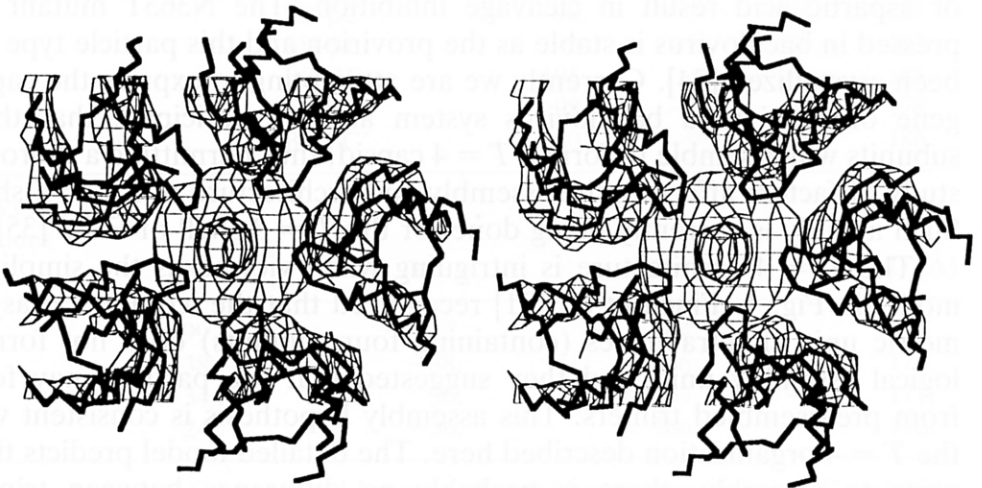
^a Growth conditions: Virus (8–14 mg/ml) in 0.07 M acetate buffer pH 5.0 (V) precipitated by vapor diffusion with 0.1 M Ca(NO₃)₂, 2.25% PEG 8000 and 0.5% β -octyl glucoside in acetate buffer pH 5.0 (P). Ratio of virus to precipitant solution in drop (V:P = 1:1), vapor equilibrated against P

^b Growth conditions: Virus (8–10 mg/ml) in 0.07 M acetate buffer pH 5.0 (V) precipitated by vapor diffusion with 2% PEG 8000, 0.25 M CaCl₂ and 0.001 M NaN₃ in 0.075 M morpholino propanesulfonic acid (MOPS) buffer pH 7.0 (P). Ratio of virus to precipitant solution in drop (V:P = 1:4), vapor equilibrated against P

Biochemical and structural studies of nodaviruses have suggested a mechanism for the autocatalytic cleavage that involves an acid-catalyzed main-chain hydrolysis event. The cleavage is also required for infectivity in nodaviruses and results in a substantial increase in particle stability. By analogy a similar maturation mechanism can be predicted for N ω V. Unfortunately, it has not been possible to propagate N ω V in any cell line, so the study of its biochemical and biological properties has not been possible. Schneemann et al. [15] have shown that when the capsid protein gene of FHV is expressed in a baculovirus system the subunits spontaneously assemble and package the messenger RNA for the capsid protein gene. The expression of the wild type sequence of the FHV capsid protein gene results in normal subunit processing and maturation. Mutation of the asparagine(N) at residue 363 to threonine(T), alanine, or aspartic acid result in cleavage inhibition. The N363T mutant expressed in baculovirus is stable as the provirion and this particle type has been crystallized [34]. Currently we are attempting to express the capsid gene of N ω V in a baculovirus system and we anticipate that these subunits will assemble to form a $T = 4$ capsid, thus permitting a thorough study of factors affecting the assembly and architecture of a $T = 4$ shell. Such a study is currently being done for the $T = 3$ shell of FHV [35].

The $T = 4$ architecture is intriguing when viewed as the simplified model in Fig. 1. Finch et al. [31] recognized that the icosahedral asymmetric unit of tetraviruses (containing four subunits) does not form a logical assembly unit, and they suggested that the particle may form from preassembled trimers. This assembly hypothesis is consistent with the $T = 4$ organization described here. The detailed model predicts that, prior to assembly, there is probably no difference between trimers

related by icosahedral symmetry (DDD) and trimers related by quasi threefold symmetry (ABC) (Fig. 1c) and it is only after the shell starts to assemble that the two classes of trimers begin to differ slightly. The nature of the two classes of quasi twofold axes (bent and flat) in the $T = 4$ particle are nearly identical to the quasi (bent) and icosahedral (flat) twofold axes in the $T = 3$ nodaviruses (Fig. 1). The nodaviruses architecture results from ordered RNA and a 10 amino acid polypeptide that are visible only at the “flat” contact between trimers at the icosahedral twofold axes. At the “bent” quasi twofold axes the RNA and protein polypeptide do not obey icosahedral symmetry and are invisible. Portions of the capsid protein that interact with the RNA and polypeptide at the

**a****b**

flat contact interact with each other at the bent contact. A similar mechanism can be invoked for formation of bent and flat contacts in $T = 4$ structures (Fig. 1b), but at present we have no suggestion for differentiating the two trimers. The difference between $T = 3$ and $T = 4$ structures is apparent at the quasi sixfold axes, which exist in both. In $T = 3$ shells the quasi sixfold axis is coincidental with an icosahedral threefold axis and the actual structure is best described as a trimer of BC dimers. The quasi sixfold axis in the $T = 4$ shell is coincident with an icosahedral twofold axis and thus is probably best described as a dimer of BCD trimers. The 2.8 Å structure of N ω V should clearly show what portions of the coat protein or RNA regulate this aspect of the $T = 4$ particle.

Acknowledgements

We thank D. Hendry for supplying samples of *Nudaurelia capensis* ω virus, and S. Fateley for help in preparing the manuscript. This work was supported by a NIH grant (GM34220) to JEJ.

Fig. 5. Features in the electron density map of N ω V. The electron density map was computed with structure factors between 20 and 8 Å resolution. Data were recorded on photographic films by oscillation photography at the Cornell High Energy Synchrotron Source. 574 films were indexed and intensities were estimated for 4411246 observations measured 3σ above the background to 2.7 Å resolution. 2626720 reflections were unique accounting for 81% of data to 8 Å resolution and 43% of the data to 2.8 Å. The overall scaling agreement factor was 12.3%. An initial set of phases for data between 20 and 15 Å were calculated from the Fourier transform of a spherical shell of inner and outer radii of 139 and 192 Å respectively placed in the N ω V unit cell. These phases were refined by real space molecular averaging procedures. The phases were extended to 8 Å resolution in steps of one reciprocal lattice point, followed by 5–6 cycles of density averaging. The handedness of the map was determined by calculating difference Fourier between native data and data collected on the crystals of N ω V soaked in 2–5 mM flourecene mercury acetate. The mercury atoms were identified (Table 2) in the negative electron density suggesting the Babinet opposite (phase = phase + 180) solution for the phases. The electron density map at 8 Å was computed with observed amplitudes and phases for the correct hand and compared with the BBV based $T = 4$ model structure identified in bold. **a** A stereoview of the electron density in the helical interior of N ω V with the adjusted BBV model superimposed. The γ peptide C α positions are shown. Note their proximity to the rod-shaped electron density characteristic of a helix. **b** A stereoview of electron density close to the fivefold symmetry axes displaying a characteristic feature observed in both BBV and N ω V electron density. The chemical nature of this “doughnut” feature has not been determined in BBV or N ω V. Note the proximity of the loops defined by C α positions from the adjusted BBV coordinates. The same relation between this density feature and the β D- β E loop (closest to ring shaped density) is seen in the BBV structure

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