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Structural reorganization of the bacterial cell-division protein FtsZ from Staphylococcus aureus

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FtsZ is a key molecule in bacterial cell division. In the presence of GTP, it polymerizes into tubulin-like protofilaments by head-to-tail association. Protofilaments of FtsZ seem to adopt a straight or a curved conformation in relation to the bound nucleotide. However, although several bacterial and archaeal FtsZ structures have been determined, all of the structures reported previously are considered to have a curved conformation. In this study, structures of FtsZ from Staphylococcus aureus (SaFtsZ) were determined in apo, GDP-bound and inhibitor-complex forms and it was found that SaFtsZ undergoes marked conformational changes. The accumulated evidence suggests that the GDP-bound structure has the features of the straight form. The structural change between the curved and straight forms shows intriguing similarity to the eukaryotic cytoskeletal protein tubulin. Furthermore, the structure of the apo form showed an unexpectedly large conformational change in the core region. FtsZ has also been recognized as a novel target for antibacterial drugs. The structure of the complex with the inhibitor PC190723, which has potent and selective antistaphylococcal activity, indicated that the inhibitor binds at the cleft between the two subdomains.

1. Introduction

FtsZ is a prokaryotic homologue of eukaryotic cytoskeletal tubulin and is a key molecule in bacterial cell division (Adams & Errington, 2009; Margolin, 2005). During bacterial cell division, FtsZ polymerizes into tubulin-like protofilaments by head-to-tail association (Oliva et al., 2004). Subsequently, it recruits many accessory proteins that are also essential for cell division (Adams & Errington, 2009). In Escherichia coli (E. coli), these accessory proteins bundle the filaments and anchor them to the cytoplasmic membrane (Pichoff & Lutkenhaus, 2002); consequently, a contractile ring-like structure known as the Z-ring is formed at the midpoint of the cell (Margolin, 2005).

Structurally, FtsZ consists of an N-terminal enzymatic domain and a long C-terminal extension of about 80 residues. The enzymatic domain is composed of two globular subdomains (N- and C-terminal subdomains) separated by a central core helix (H7 helix). There is a nucleotide-binding pocket in the N-terminal subdomain (residues 12–171). The C-terminal subdomain is likely to be a GTPase-activating subdomain (residues 223–310). At the tip of the long C-terminal extension is the functional site that recognizes the accessory proteins (Mosyak et al., 2000; Yan et al., 2000).

FtsZ is a self-activating GTPase (de Boer et al., 1992; RayChaudhuri & Park, 1992). For polymerization, the I7 loop in the ‘upper’ subunit is inserted into the nucleotide-binding pocket of the ‘lower’ subunit (Löwe & Amos, 1999). Mutation
of Asn207, Asp209 and Asp212 in the T7 loop of E. coli FtsZ (EcFtsZ) severely affects GTP hydrolysis (Scheffers et al., 2002). These results suggested that the catalytic residues in the T7 loop are located near the γ-phosphate of GTP and thus GTP hydrolysis proceeds. GTPase activity therefore depends on FtsZ polymerization (Oliva et al., 2004; Scheffers et al., 2002).

Protofilaments of FtsZ seem to adopt a straight or a curved conformation in relation to the bound nucleotide (Lu et al., 1998; Leung et al., 2011). However, although several conformation in relation to the bound nucleotide (Lu et al., 2011), suggested that FtsZ acts as a nucleotide-regulated molecular switch in the assembly/disassembly cycle of cell division (Martín-Galiano et al., 2010; Chen & Erickson, 2011). EcFtsZ with GTP may switch from the curved to the straight conformation (Chen & Erickson, 2011). However, although several structures of bacterial and archaeal FtsZs have been determined (Löwe & Amos, 1998; Leung et al., 2004), they are all very similar irrespective of the bound nucleotide (Oliva et al., 2007). The slight differences observed to date seem to be related to interspecies differences. The crystal structure of Methanococcus jannaschii FtsZ (MJFtsZ) formed a tilted dimer (Oliva et al., 2004) and the relative disposition of the two monomers seemed to be related to the curved structures of tubulin (Buey et al., 2006). Thus, all FtsZ structures analyzed previously were considered to be in the curved conformation (Oliva et al., 2007) and the straight conformation has only been visualized at low resolution (Löwe & Amos, 1999). The latter conformation is necessary to understand the molecular mechanism of FtsZ, i.e. how it polymerizes and hydrolyzes GTP at the molecular level.

FtsZ is essential for bacterial cell division in almost all prokaryotes and is absent in eukaryotes, except in the chloroplasts of plants and in the mitochondria of some primitive organisms. Therefore, FtsZ has been recognized as a novel target for antibacterial drugs (Lock & Harry, 2008). Several compounds have been shown to block bacterial cell division and/or to inhibit the function of FtsZ, in vitro (Ohashi et al., 1999; Domadia et al., 2007; Stokes et al., 2005; Läppchen et al., 2008). In particular, the inhibitor 2,6-difluoro-3-[(6-chlorothiazolo[5,4-b]pyridine)-2-ylmethoxy]benzamide (PC190723) has been reported to have a potent and selective anti-staphylococcal activity (Andreu et al., 2010; Haydon et al., 2008). PC190723 binds to FtsZ with GTP (Andreu et al., 2010) and is therefore suggested to interact with straight FtsZ.

In the present study, we investigated the structures of FtsZ from Staphylococcus aureus (SaFtsZ) in apo, GDP-bound and PC190723-complex forms, and showed that FtsZ undergoes distinct conformational changes. Here, we discuss these structural features and relate them to the crucial functions of FtsZ.

2. Materials and methods

2.1. Protein expression and purification of SaFtsZ

Full-length FtsZ from S. aureus Mu50 (SaFtsZ) and its enzymatic domain (residues 12–316; SaFtsZt) were amplified by PCR and cloned into the NdeI/XhoI sites of the pET-28b(+) vector (Merrick KGaA). The primers were designed based on the DNA sequence in GenBank (accession No. 15924176). SaFtsZt and SaFtsZt were expressed and purified using the same procedure. The proteins were overexpressed in E. coli strain BL21 (DE3) as recombinant fusion proteins with an N-terminal hexahistidine tag and TEV protease recognition sequence. Cells were grown at 310 K in Luria broth with 25 mg l⁻¹ kanamycin until the optical density reached 0.6. After the addition of 0.25 mM isopropyl β-d-1-thiogalactopyranoside, growth was continued for 3 h at 310 K. The cells were harvested and resuspended in lysis buffer (50 mM Tris–HCl pH 8.0, 300 mM NaCl, 10% (v/v) glycerol, 0.5 mg ml⁻¹ lysozyme, 0.1 mg ml⁻¹ DNase I). The cell lysate was sonicated and then centrifuged at 40 000g for 30 min at 283 K. The supernatant was loaded onto a 5 ml HisTrap HP column (GE Healthcare). After washing the column with buffer A (50 mM Tris–HCl pH 8.0, 300 mM NaCl, 10% (v/v) glycerol), the fusion protein was eluted using a stepwise increasing imidazole concentration: 50, 250 and 500 mM. Fractions containing the desired protein were incubated with TEV protease (Merrick KGaA) and dia lyzed against buffer A at 277 K; the mixtures were then loaded onto a 5 ml HisTrap HP column. The flow-through fraction was collected and further purified by gel filtration on HiLoad 16/60 Superdex 200 (GE Healthcare) pre-equilibrated with buffer B (50 mM Tris–HCl pH 8.0, 300 mM NaCl). After gel filtration, SaFtsZ was diluted fivefold with buffer C (50 mM Tris–HCl pH 8.0) and purified on a 1 ml Resource Q column (GE Healthcare) using a linear gradient of buffer C to buffer D (50 mM Tris–HCl pH 8.0, 1 M NaCl). The purified protein was exchanged into buffer B using a Vivaspin 20 10k ultrafiltration device (GE Healthcare). SaFtsZt were over-expressed in E. coli strain BL21 (DE3). Cells were grown at 310 K in M9 medium containing 1 mM MgSO₄, 0.1 mM CaCl₂, 1× BME vitamins solution (Sigma–Aldrich), 0.4% glucose, 25 mg l⁻¹ selenomethionine, 14 mg l⁻¹ each of 19 amino acids and 50 mg l⁻¹ kanamycin until the optical density reached 0.3. After the addition of 0.25 mM isopropyl β-d-1-thiogalactopyranoside, growth was continued for 11 h at 310 K. Purification of SaFtsZt (SeMet) was performed as described above.

SeMet-labelled SaFtsZ [SaFtsZt (SeMet)] was over-expressed in E. coli strain B834 (DE3). Cells were grown at 310 K in M9 medium containing 1 mM MgSO₄, 0.1 mM CaCl₂, 1× BME vitamins solution (Sigma–Aldrich), 0.4% glucose, 25 mg l⁻¹ selenomethionine, 14 mg l⁻¹ each of 19 amino acids and 50 mg l⁻¹ kanamycin until the optical density reached 0.3. After the addition of 0.25 mM isopropyl β-d-1-thiogalactopyranoside, growth was continued for 11 h at 310 K. Purification of SaFtsZt (SeMet) was performed as described above.

2.2. SaFtsZ mutagenesis

Mutant SaFtsZ was prepared using a Stratagene QuikChange mutagenesis kit (Agilent Technologies) with SaFtsZt expression vector as a template. Asn208 was substituted by Ala (to give SaFtsZt N208A). The DNA sequence was confirmed using an ABI 310 Genetic Analyzer (Applied Biosystems). The mutant protein was prepared as described above.

2.3. Crystallization and structure determination

All crystals were obtained using the conditions shown in Table 1 and appeared after a few weeks at 293 K. (Although
we did not add GDP to the crystallization buffer, the SaFtsZ and SaFtsZt crystals contained GDP. Therefore, they are hereafter referred to as SaFtsZt-GDP and SaFtsZt-GDP† respectively. To obtain SaFtsZ-GDP crystals complexed with PC190723 (PC190723 complex), co-crystallization experiments were carried out using the microseeding technique. X-ray diffraction data for SaFtsZt-GDP were collected on beamline BL41XU at SPring-8, Hyogo, Japan under cryogenic conditions at 100 K. The diffraction data were processed and scaled with the HKL-2000 program package (Otwinowski & Minor, 1997). Molecular replacement was performed for SaFtsZt-GDP with MOLREP in the CCP4 suite (Vagin & Teplyakov, 2010; Winn et al., 2011) using PDB entry 2vxy (Bacillus subtilis FtsZ; BsFtsZ; Haydon et al., 2008) as the search model. The structure was rebuilt using the automatic refinement program LAFFIRE (Yao et al., 2006; Zhou et al., 2006) running with CNS (Brünger et al., 1998), modified manually with Coot (Emsley & Cowtan, 2004) and refined with PHENIX (Adams et al., 2010). Single-wavelength anomalous diffraction data were collected from a crystal of apo SaFtsZt (SeMet) on beamline BL5A at Photon Factory, Tsukuba, Japan under cryogenic conditions at 100 K. A wavelength of 0.9791 Å was used for data collection based on the fluorescence spectrum of the Se K absorption edge (Rice et al., 2000). The diffraction data for apo SaFtsZt (SeMet) were processed and scaled using the HKL-2000 program package. Se sites were determined with

### Table 1

Summary of crystallization conditions, data-collection and refinement statistics.

<table>
<thead>
<tr>
<th>PDB code</th>
<th>SaFtsZt-GDP</th>
<th>SaFtsZt-GDP†</th>
<th>Apo SaFtsZt (SeMet)†</th>
<th>Apo SaFtsZt†</th>
<th>PC190723 complex</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample condition</td>
<td>Native SaFtsZt</td>
<td>Native SaFtsZt</td>
<td>Native SaFtsZt</td>
<td>Native SaFtsZt</td>
<td>Native SaFtsZt</td>
</tr>
<tr>
<td>Crystallization conditions</td>
<td>0.2 M lithium sulfate, 0.1 M Tris–HCl pH 8.5, 30% (w/v) PEG 4000</td>
<td>0.2 M lithium sulfate, 0.1 M Tris–HCl pH 8.5, 30% (w/v) PEG 5000 MME, 10% (v/v) ethylene glycol</td>
<td>1.0 M lithium chloride, 0.1 M sodium acetate, 30% (w/v) PEG 6000, pH 7.0</td>
<td>1.0 M lithium chloride, 0.1 M sodium acetate, 30% (w/v) PEG 6000, pH 7.0</td>
<td>0.2 M lithium sulfate, 0.1 M Tris–HCl pH 8.5, 25% (w/v) PEG 5000 MME, 10% (v/v) ethylene glycol</td>
</tr>
<tr>
<td>Inhibitor</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>0.5 mM PC190723, 10% (v/v) 1-methyl-2-pyrrolidone</td>
</tr>
</tbody>
</table>

| Cryoprotectant | 20% (v/v) glycerol | — | — | — | — |
| Data collection | | | | | |
| | Beamline | SPring-8 BL41XU | In-house | PF BL5A | Spring-8 BL41XU |
| | Wavelength (Å) | 1.0000 | 1.54 | 0.9791 | 1.0000 |
| | Space group | P21 | P21 | P21 | P21 |
| | Unit-cell parameters (Å, °) | a = 44.0, b = 44.1, c = 86.0, α = 96.9, β = 103.6, γ = 108.0 | a = 72.8, b = 49.6, c = 88.4, β = 111.6 | a = 72.9, b = 80.7, c = 225.3 | a = 72.1, b = 50.5, c = 88.3, β = 111.0 |
| | Resolution range (Å) | 50.0–2.25 (2.31–2.25) | 50.0–1.73 (1.78–1.73) | 50.0–2.70 (2.80–2.70) | 50.0–2.70 (2.80–2.70) |
| | Completeness (%) | 97.7 (91.3) | 95.4 (90.3) | 99.6 (100) | 99.8 (99.8) |
| | (I/σ(I)) (%) | 20.8 (4.1) | 14.2 (4.5) | 7.2 (3.9) | 7.2 (3.9) |
| | Multiplicity | 8.3 (28.5) | 5.0 (14.9) | 12.3 (48.5) | 11.5 (35.2) |
| | No. of unique reflections | 77083 | 80661 | 523986 | 435385 |
| | | | | | 27346 |
| | No. of solvent atoms | 100 | 326 | 36669 | 47728 |
| | | | | | 8238 |
| | | | | | |
| | Refinement | | | | |
| | Resolution (Å) | 35.54–2.25 | 19.99–1.73 | 35.49–2.50 | 32.35–2.70 |
| | Overall Rwork (%) | 18.8 | 22.7 | 21.0 | 19.5 |
| | Overall Rfree (%) | 23.7 | 27.2 | 25.8 | 24.7 |
| | Total atoms | 4553 | 2510 | 8529 | 8492 |
| | No. of protein atoms | 4395 | 2215 | 8452 | 8353 |
| | No. of ligand atoms | 56 | 28 | — | — |
| | No. of solvent atoms | 2 | 1 | — | — |
| | Average B factors (Å²) | 32.0 | 22.8 | 48.1 | 57.6 |
| | Protein atoms | 25.3 | 16.6 | — | — |
| | Lipid atoms | 34.3 | 20.6 | — | — |
| | Solvent atoms | 30.7 | 39.5 | — | — |
| | R.m.s.d. from ideal bond lengths (Å) | 0.009 | 0.007 | 0.012 | 0.009 |
| | Bond angles (°) | 1.155 | 1.246 | 1.256 | 1.256 |
| | Ramachandran plot | 596 [98.5%] | 301 [98.7%] | 1063 [96.0%] | 1126 [99.0%] |
| | | | | | 292 [96.7%] |
| | | | | | |

† Met–1 and His–2 derived from NdeI and Gly–3, the C-terminal residue of the TEV recognition site, are also included in the structure. ∗ Rwork = ∑hkl ∑j |Fobsj| − |Fcalcj|/∑hkl ∑j |Fobsj|, where Fobs and Fcalc are observed and calculated structure-factor amplitudes, respectively. ‡ The Rmerge value was calculated as Rmerge but using only an unfixed subset of reflection data.
SHLEXD (Sheldrick, 2008, 2010). The sites were refined and initial phases were calculated with Phaser in PHENIX. Phase improvement and automatic model building were performed using RESOLVE (Terwilliger, 2000) in PHENIX. The structure of apo SaFtsZt (SeMet) was refined with PHENIX and manually modified with Coot. X-ray diffraction data for apo SaFtsZt were collected on beamline BL41XU at SPring-8, Hyogo, Japan under cryogenic conditions at 100 K. The diffraction data for apo SaFtsZt were processed and scaled with the HKL-2000 program package. Molecular replacement was performed for apo SaFtsZt with MOLREP in the CCP4 suite using apo SaFtsZt (SeMet) as the search model. The structure was modified manually with Coot and refined with PHENIX.

The diffraction data for SaFtsZt-GDP and the complex of SaFtsZt-GDP with PC190723 were collected under cryogenic conditions (100 K) using in-house X-ray diffraction equipment consisting of a Rigaku FR-E SuperBright microfocus rotating-anode X-ray generator with VariMax optics, an X-stream 2000 low-temperature system and an R-AXIS VII detector. These diffraction data were processed and scaled with the HKL-2000 program package. Molecular replacement was performed for SaFtsZt-GDP with MOLREP in the CCP4 suite using apo SaFtsZt-GDP as the search model. After phase determination, automatic restrained positional and isotropic B-factor refinement was performed using ARP/wARP (Langer et al., 2008) with REFMAC5 (Murshudov et al., 2011). The final step of refinement was carried out using LAIFIRE (Yao et al., 2006; Zhou et al., 2006), REFMAC5 and Coot. Molecular replacement was performed for the PC190723 complex with MOLREP in the CCP4 suite using SaFtsZt-GDP as the search model. The structure was modified manually with Coot and refined with PHENIX.

Data-collection and refinement statistics are summarized in Table 1. Structures were displayed using PyMOL (Delano, 2002). The coordinates and structure factors of SaFtsZt-GDP, apo SaFtsZt, apo SaFtsZt, SaFtsZt-GDP and the complex of SaFtsZt-GDP with PC190723 have been deposited in the RCSB Protein Data Bank under accession codes 3vo8,
2.4. Hypothetical model building of the GTP-bound form

The conformation of the N-terminal subdomain of SaFtsZ-GDP was very similar to that of GTP-bound MjFtsZ. Based on the superimposed structures of SaFtsZ-GDP and GTP-bound MjFtsZ, a hypothetical model of GTP-bound SaFtsZ was built by adding a γ-phosphate to SaFtsZ-GDP at the end of the β-phosphate of GDP using Coot (Emsley & Cowtan, 2004). The model was refined using REFMACS (Murshudov et al., 2011) to ensure that there was no steric hindrance between the hypothetical γ-phosphate and the other parts of the molecule apart from two water molecules. These water molecules were removed.

2.5. GTPase assay

The FtsZ GTPase assay was performed as described previously, with slight modifications (Haydon et al., 2008). Exchange from GTP to GDP was monitored by determining the concentration of released phosphate using BIOMOL GREEN (BIOMOL Research Laboratories). GTP was added with denaturing buffer [50 mM Tris–HCl pH 8.0, 300 mM NaCl, 10% (v/v) glycerol, 6 M urea] and incubated at 303 K for 1 h. To estimate the effect of calcium ions, the same experiments were performed in the presence of varying concentrations of CaCl₂ (0–10 mM).

2.6. Refolding of SaFtsZ

As SaFtsZf captures a calcium ion during culture of E. coli cells and the captured calcium ion is hardly removed, a calcium-ion-free form of SaFtsZf was prepared by refolding chemically denatured SaFtsZf. SaFtsZf was purified by ion-exchange chromatography and denatured by 20-fold dilution with denaturing buffer [50 mM Tris–HCl pH 8.0, 300 mM NaCl, 10% (v/v) glycerol, 6 M urea]. After incubation at 277 K for 2 h, SaFtsZf was refolded by dialysis against buffer C. Refolded SaFtsZf was further purified by passage through a 1 ml Resource Q column with a linear gradient of buffer C to buffer D. The refolded sample was used for circular-dichroism measurements and sedimentation assay of SaFtsZf.

2.7. Sedimentation assay

The sedimentation assay was performed using the procedure described previously, with slight modifications (Jaiswal & Panda, 2009). Samples containing 15 μM protein were incubated for 30 min at 298 K in polymerization buffer (20 mM HEPES–KOH pH 7.5, 50 mM KCl, 1 mM MgCl₂) containing 1 mM GTP and various concentrations of CaCl₂ (0–7.5 mM). The polymers were collected by ultracentrifugation at 223 000g for 10 min at 298 K. The precipitates were resuspended in SDS–PAGE running buffer and subjected to SDS–PAGE.

2.8. Circular-dichroism measurements

Native and refolded SaFtsZf were dialyzed against polymerization buffer. Samples of 0.2 mg ml⁻¹ with or without 1 mM CaCl₂ were incubated at 298 K for 30 min in polymerization buffer with 1 mM GTP. The CD spectra of the samples were measured using a J-805 circular-dichroism spectrometer (JASCO Co.) in a quartz cell with an optical path length of 0.2 cm. The spectra were collected by taking the average of eight scans from 300 to 190 nm and were normalized to molar ellipticities. The helical content of the protein was estimated from the molar ellipticity at a wavelength of 222 nm (Price & Nairn, 2009).

3. Results

3.1. Structures of SaFtsZ with GDP (SaFtsZ-GDP)

We prepared crystals of full-length SaFtsZ (residues 1–390; SaFtsZf) and of the enzymatic domain (residues 12–316; SaFtsZt). The structures of SaFtsZf and SaFtsZt were solved by the molecular-replacement method and were refined at resolutions of 2.25 and 1.73 Å, respectively (Table 1). The SaFtsZf crystal had two molecules in the asymmetric unit; only residues 12–316 and 12–315 in molecules A and B, respectively, were visible. The two molecules superposed well, with a root-mean-square deviation (r.m.s.d.) of 0.19 Å for backbone Cα atoms. The SaFtsZf crystal had one molecule in the asymmetric unit and residues 12–315 were observed in the electron-density map. Molecule A of SaFtsZf superposed well with SaFtsZt, with an r.m.s.d. of 0.39 Å for backbone Cα atoms (Supplementary Fig. S1). Although GDP was not added to the crystallization conditions, the electron-density maps of the two crystals indicated the presence of GDP in the nucleotide-binding pocket of all molecules. Fig. 1(a) shows the structure of SaFtsZf-GDP (molecule A); SaFtsZf-GDP is composed of two globular subdomains separated by a long central H7 helix (residues 179–202) with two adjacent loops (the H6–H7 loop, residues 172–178, and the T7 loop, residues 203–209).

Although the two crystals belonged to different space groups (Table 1), they showed similar prototifament-like molecular associations (Fig. 2); two independent molecules of SaFtsZf-GDP were aligned on the a and b axes in the unit cell of space group P1 and the SaFtsZt-GDP molecules were aligned in the (a + b)/2 direction in the unit cell of space group C2. The repeating distances of the aligned molecules were approximately 44.0 Å (Table 1). As SaFtsZf-GDP and SaFtsZt-GDP have the same structural features, they are hereafter referred to as SaFtsZ-GDP or the GDP form, unless otherwise indicated.

3.2. Structural comparison between SaFtsZ and other FtsZs

A previous investigation suggested that the conformational differences observed in FtsZ crystals were related to inter-
species differences rather than interconversion between straight and curved conformations (Oliva et al., 2007). That is, there were few conformational differences in the previous structures. In contrast to these previous results, the structures of SaFtsZ showed clear differences from the structures reported to date. Figs. 3(a) and 3(b) show a structural comparison between the GDP-forms of SaFtsZ and BsFtsZ (PDB entry 2rhl, molecule A; Raymond et al., 2009). Although the conformations of the N- and C-terminal subdomains in the SaFtsZ were similar to those in BsFtsZ (Table 2, Figs. 3(a) and 3(b)), a large difference was observed at the interface region around the H7 helix (Fig. 3a): the H7 helix was downshifted by about one helical pitch (Figs. 3a, 4a, 4b and 4c) and the following T7 loop with a coordinated calcium ion (as shown in §3.3) was inserted into the wider pocket of the ‘lower’ subunit (Fig. 4a). In addition, the H6–H7 loop moved away from the nucleotide-binding pocket (Fig. 4b).

To evaluate these conformational changes, we used the DynDom program, which determines protein domains, hinge axes and hinge-bending residues by comparing two conformations (Hayward & Berendsen, 1998). This program indicated that the C-terminal subdomain is rotated by about 25.2° (Hayward & Berendsen, 1998). This program determines protein domains, hinge axes and hinge-bending residues by comparing two conformations (Hayward & Berendsen, 1998). This program indicated that the C-terminal subdomain is rotated by about 25.2°.

3.3. Coordination of divalent cation

The $F_o - F_c$ map showed a clear peak at coordination distances to Leu200, Val203, Asn208 and Leu209 in the T7 loop and to two water molecules (Fig. 5a). The distances between this residual peak and the carbonyl O atom of Leu200, the carbonyl O atom of Val203, Asn208 O$, the carbonyl O atom of Leu209 and two water molecules in SaFtsZf-GDP were 2.31, 2.29, 2.40, 2.43, 2.45 and 2.46 Å, respectively (Supplementary Table S1). Although calcium ions were not added to the crystallization conditions, the observed distances and the coordination number were those of calcium coordination (Harding, 1999, 2001).

Calcium ions are known to promote the assembly and bundling of protofilaments in E. coli (Yu & Margolin, 1997; Mukherjee & Lutkenhaus, 1999; Jaiswal & Panda, 2009; Marrington et al., 2004). The calcium concentration in E. coli cells can reach millimolar levels under some conditions (Yu & Margolin, 1997; Holland et al., 1999). Moreover, the calcium concentration during cell division in E. coli is almost 20-fold higher than that in non-dividing cells (Chang et al., 1986). A previous study suggested that millimolar concentrations of calcium ions promote the assembly and bundling of protofilaments in E. coli FtsZ, but do not polymerize Mycobacterium tuberculosis FtsZ (MfFtsZ; Jaiswal & Panda, 2009). However, it was not clear whether calcium ions also contribute to the assembly of SaFtsZ. To examine the effect of calcium ions on assembly, we performed a sedimentation assay with CaCl$_2$ (Fig. 5b). A small amount of SaFtsZf was precipitated on incubation with neither calcium ions nor GTP. Although SaFtsZf was precipitated with GTP, polymerization of SaFtsZf with 1 mM GTP was promoted by calcium ions in a concentration-dependent manner.

Circular-dichroism (CD) measurements of SaFtsZf with and without CaCl$_2$ showed that calcium ions induced small alterations in the secondary structure of FtsZ (Fig. 5c). These results showed that calcium ions contribute to the assembly of SaFtsZ, as previously observed for EcFtsZ (Yu & Margolin, 1997; Mukherjee & Lutkenhaus, 1999; Jaiswal & Panda, 2009; Marrington et al., 2004).

To confirm that calcium ions also affect GTPase activity, we measured the GTPase activities of SaFtsZf in the presence of varying concentrations of CaCl$_2$ (Fig. 5d). The results indicated that the GTPase activity of SaFtsZf was suppressed by calcium ions in a concentration-dependent manner. SaFtsZf

Table 2

R.D.S.E. conformational differences (Å) between SaFtsZf-GDP and BsFtsZ and between SaFtsZf-GDP and the apo form.

<table>
<thead>
<tr>
<th>Calculation region</th>
<th>Alignment region</th>
<th>N-terminal subdomain</th>
<th>C-terminal subdomain</th>
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<tr>
<td>SaFtsZf-GDP and BsFtsZ</td>
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<td></td>
<td>C-terminal subdomain</td>
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<td>1.93</td>
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<tr>
<td></td>
<td>C-terminal subdomain</td>
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<td>2.15</td>
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</tbody>
</table>

Figure 2

Crystal packing of SaFtsZf-GDP (molecule A). An asymmetric molecule and symmetry-related molecules are coloured red and grey, respectively. GDP and calcium ions are represented as blue sticks and green spheres, respectively.
showed a complete loss of GTPase activity in the presence of 10 mM CaCl₂.

3.4. Structure of apo SaFtsZ (apo form)

As calcium ions were shown to promote the polymerization of SaFtsZ by inhibiting hydrolysis (Fig. 5), we attempted to determine the crystal structure of SaFtsZ in the absence of calcium ions. SaFtsZ crystals without calcium ions were obtained by adding 340 mM sodium malonate pH 7.0 as a chelating reagent. The crystal structures of apo SaFtsZ (SeMet) and native apo SaFtsZ were solved at resolutions of 2.71 and 2.50 Å by the single-wavelength anomalous diffraction method and the molecular-replacement method, respectively (Table 1, Fig. 1b, Supplementary Fig. S2). There were four molecules in the asymmetric unit of space group \(P2_12_12_1\) and the electron-density map allowed us to build residues 12–315, with the exception of some disordered residues. The r.m.s.d. values of these molecules were less than 0.77 Å, except for in high-flexibility regions (Supplementary Fig. S3a and Table S2). The T3 loop (residues 66–75) and the S7–H9 loop (residues 231–236) have different conformations in the four asymmetric molecules and the H1–S2 loop (residues 31–37) and T5 loop (residues 136–146) were disordered, except for in molecule \(C\). The conformations of the native and the SeMet protein were the same (r.m.s.d. of 0.42 Å; Supplementary Fig. S2). As neither GDP nor malonate ions were found in the crystals, we refer to these crystals as the apo form.

The overall structure of the apo form was very different from any of the previously determined FtsZ structures (Fig. 1, Table 2). The conformational changes were mainly in the interface region from the H6 helix to the H8 helix (in the GDP form). The residues from the H6 helix to Gln192 in the H7 helix of the GDP form formed a new kinked helix in the apo form (Fig. 4d). A new strand was also formed in the region from Asp199 of the H7 helix to Ser204 of the T7 loop in the GDP form. This new strand participates in both N- and C-terminal \(\beta\)-sheets. Thus, the secondary structure of the apo form was markedly changed from that of the GDP form (Figs. 4e and 4f). The conformational changes were accompanied by a change in the relative orientation between the two subdomains. The subdomain rotation from \(BsFtsZ\) (36.0°) was larger than that of the GDP form from \(BsFtsZ\) (25.2°). The DynDom program (Hayward & Berendsen, 1998) estimated that the hinge regions were residues 164–165 in the S6 strand, 192–199 in the H7 helix, and 197–224 from the H7 helix to the H8 helix in the GDP form.

**Figure 3**
Structural comparisons (a, b) between GDP-form SaFtsZ and GDP-form \(BsFtsZ\) (PDB entry 2rhl) and (c) between straight (PDB entry 1jff; taxol complex; Löwe et al., 2001) and curved (PDB entry 1sa0; colchicine complex; Ravelli et al., 2004) \(\beta\)-tubulin. The structures in (a) and (b) are shown after superposition of the N-terminal subdomain (residues 13–171) and the C-terminal subdomain (residues 223–310), respectively. GDP-form SaFtsZ and GDP-form \(BsFtsZ\) are coloured red and cyan, respectively. GDPs bound to SaFtsZ and \(BsFtsZ\) are coloured blue and grey, respectively. In (c), straight and curved tubulin is shown in orange and yellow, respectively, after superposition of the N-terminal domain (residues 2–215). GDPs bound to the straight and the curved forms are represented as blue and cyan sticks, respectively. Subdomain-interface regions between the H6 helix and the T7 loop, including the H7 helix, in straight and curved tubulin are highlighted in red and black, respectively.
Conformational changes also occurred around the nucleotide-binding pocket in the N-terminal subdomain. The H7 helix moved away from the pocket and the T4 loop moved into and buried the pocket (Fig. 6). Although Phe183 in the H7 helix and Glu139 in the T5 loop showed significant interactions with nucleotides in the GDP form, these residues were no longer located near the pocket in the apo form. In particular, Phe183 in the H7 helix of the GDP form moved away by about 24 Å owing to the formation of the kinked helix in the apo form. All of these changes disrupted the nucleotide-binding pocket. In contrast, the conformation of the C-terminal subdomain was similar to that in the GDP form (Table 2, Supplementary Fig. S3c).

3.5. Structure of SaFtsZt-GDP complexed with PC190723 (PC190723 complex)

It has been shown that PC190723 binds to FtsZ with GTP, thereby promoting the polymerization of FtsZ (Andreu et al., 2010). This can be interpreted as indicating that FtsZ with GTP creates a new cleft between the subdomains owing to the orientational change between the GDP-bound and GTP-bound states (Chen & Erickson, 2011). These observations suggested that PC190723 only interacts with straight FtsZ. However, the docking model calculated previously was based on curved FtsZ (Haydon et al., 2008). As our SaFtsZt-GDP structure has the features of straight FtsZ, we attempted to determine the structure of the complex between SaFtsZt-GDP and PC190723 (the PC190723 complex).

The PC190723 complex crystal was obtained by cocrystallization and the structure was solved at a resolution of 2.70 Å by the molecular-replacement method (Table 1, Fig. 7). The unit-cell parameters of the PC190723 complex were very similar to those of SaFtsZt-GDP. Based on the well defined $F_o - F_c$ map, we
found the ligand in a novel hydrophobic cleft (Fig. 7c) near the T7 loop, referred to as the PC-site, the conformation of which was stabilized by an octahedrally coordinated calcium ion. PC190723 possesses two distinct chemical moieties, benzamide and thiazolopyridine, both of which seem to make key interactions with SaFtsZ (Fig. 7c). The ether linkage between the two moieties seems to function as an adjusting spacer that properly places the two moieties in the PC-site. The benzamide moiety of PC190723 has two important functional groups: the amide group and fluoro groups at the 2- and 6-positions. The amide group interacted with the PC-site in two ways: (i) the carbonyl group was bound to the calcium ion (3.2 Å) and (ii) the primary amino group was hydrogen bonded to the carbonyl of the Asn263 (3.4 Å) side chain as well as to the main-chain carbonyl of Val207 (2.9 Å). To simultaneously achieve proper coordination of the calcium ion and construction of the hydrogen-bond network, the amide group was twisted out of the plane of the benzene ring. The fluoro groups were located in the internal space surrounded by hydrophobic residues. While the 2-fluoro group was located in a hydrophobic core generated by residues Leu209 (3.1 Å) and Leu200 (3.5 Å), the 6-fluoro group was in a core generated by residues Val203 (3.5 Å) and Leu297 (3.5 Å). The thiazolopyridine moiety of PC190723 was located in a hydrophobic cleft between the H7 helix and the C-terminal subdomain formed by amino-acid residues Gly193 (3.8 Å), Gly196 (2.9 Å), Ile197 (4.4 Å), Met226 (4.1 Å), Ile228 (4.1 Å), Thr309 (3.3 Å) and Ile311 (3.3 Å). The 5-chloro group of the thiazolopyridine moiety was found in the hydrophobic space surrounded by Gly193 (3.8 Å), Met226 (4.1 Å) and Ile228 (4.1 Å). To examine whether a conformational change occurred upon PC190723 binding, we superposed the SaFtsZ structures with and without PC190723. The structural comparison revealed some changes in the side-chain conformations, especially for Leu200, Val203, Ile228 and Thr309. Moreover, the water-mediated hydrogen-bond network was reconstructed. In the structure without PC190723, the calcium ion was coordinated by Asn208 O, three main-chain carbons (Leu200, Val203 and Leu209) and two water molecules. In the structure with PC190723, the benzamide moiety replaced the inner of the two coordinating water molecules.

Very recently, the structure of the PC190723 complex was determined by another group independently of our work (Tan et al., 2012). Although their crystal was obtained by a soaking method and the unit-cell parameters were slightly different from ours, the binding site appeared to be very similar. They showed that this site corresponds to the predominant locations of mutations that confer resistance to PC190723.

Figure 5
Interactions between the T7 loop and the calcium ion. (a) The residues of the T7 loop are indicated as sticks. The calcium ion was coordinated to Leu200, Val203, the side chain of Asn208 and Leu209. The calcium-bound residues are coloured cyan. The calcium ion and water molecules are represented as green and orange spheres, respectively. Grey mesh represents Fo/C1 maps of the calcium ion displayed over 3.0σ. (b) Results of the sedimentation assay are shown. SaFtsZf was incubated with 1 mM GTP in the presence of varying concentrations of CaCl2. The samples in lanes 2–7 were precipitated by ultracentrifugation and the precipitates were then analyzed by SDS–PAGE. Lane 1, 15 mM SaFtsZf as a control; lane 2, precipitation without GTP and CaCl2; lane 3, without CaCl2; lane 4, 1 mM CaCl2; lane 5, 2 mM CaCl2; lane 6, 5 mM CaCl2; lane 7, 7.5 mM CaCl2; 1 mM GTP was added to the buffer in lanes 3–7. (c) CD spectra of SaFtsZf with and without CaCl2 are shown. 0.2 mg ml−1 SaFtsZf with or without 1 mM CaCl2 was incubated at 298 K for 30 min in polymerization buffer with 1 mM GTP. Refolded SaFtsZf with CaCl2, refolded SaFtsZf without CaCl2, native SaFtsZf with CaCl2 and native SaFtsZf without CaCl2 are indicated by black, green, grey and red lines, respectively. (d) The GTPase activity of SaFtsZf was inhibited by CaCl2 in a concentration-dependent manner. The error bars represent the relevant standard deviations from three independent experiments.
4. Discussion

4.1. The conformation of the GDP form has the structural features of straight FtsZ

Previous investigations have suggested that FtsZ has a highly dynamic structure (Martín-Galiano et al., 2010; Chen & Erickson, 2011; Mingorance et al., 2001; Buey et al., 2006). Based on the results of molecular-dynamics simulations, FtsZ has been suggested to have several distinct conformations with hinges around the H7 helix, and an assembly/disassembly cycle has been proposed which involves intermediate states including a GTP-bound curved polymer and a GDP-bound straight polymer (Martín-Galiano et al., 2010). A large rotational change occurred between the subdomains on adding GTP to EcFtsZ, probably resulting in the straight conformation (Chen & Erickson, 2011). However, all previously reported FtsZ structures were considered to have the curved conformation (Buey et al., 2006; Oliva et al., 2007), as exemplified by the tilted dimer of MjFtsZ (Oliva et al., 2004).

In this study, we found new conformations of FtsZ with and without bound nucleotide. The conformational changes from the previous structures occurred in the region from the H6 helix to the H8 helix and were accompanied by rearrangement of the inter-subdomain interactions. Although the bound nucleotide was GDP, the structure has the features of the straight conformation; the H6–H7 loop moved away from the

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Figure 6
Structural comparison of the nucleotide-binding pockets of GDP-form (red) and apo-form (green) SaFtsZ shown in cartoon (a, b) and surface (c, d) representations. GDP bound to the GDP form is represented as blue sticks. Note that the T4 loop overlaps the GDP site in the apo form.
nucleotide-binding pocket (Fig. 4b). The H7 helix was downshifted by one helical pitch (Fig. 4c) and the T7 loop was deeply inserted into the expanded pocket, placing the active residues close to the γ-phosphate and blocking solvent accessibility to the pocket (Fig. 4a and Supplementary Fig. S4). It should be noted that the eukaryotic homologue tubulin undergoes a similar structural change; the H7 helix in straight tubulin is downshifted in comparison with that in the curved conformation (Fig. 3c). All of these observations suggest that SaFtsZ-GDP has the conformation of straight FtsZ just after

Figure 7
Crystal structure of the PC190723 complex. (a) Structure of the PC190723 complex (blue) superposed on that of the GDP form (red). GDP, a calcium ion and PC190723 in the PC190723 complex are represented as blue sticks, a green sphere and cyan sticks, respectively. Orange mesh represents the Feo–Fc map of PC190723 displayed over 3.0σ. (b) Conformational detail of the PC-site. The residues interacting with PC190723 are indicated and their interactions are indicated by dotted lines. Cl, N, O, S and F atoms in PC190723 are coloured green, blue, red, yellow, sky-blue and cyan, respectively. (c) Structural comparison between the SaFtsZ–PC190723 complex and the tubulin–taxol complex (PDB entry 1jff) after superposing the whole structures. Tubulin and taxol are represented as a yellow cartoon and magenta sticks, respectively. (d) Structural comparison between the SaFtsZ–PC190723 complex and the tubulin–colchicine complex (PDB entry 1sa0) after superposing the whole structures. Tubulin and colchicine are represented as a yellow cartoon and red sticks, respectively.
GTP hydrolysis, as expected for the intermediate state of the GDP-bound straight polymer (Martín-Galiano et al., 2010). The conformational change in tubulin is transmitted from one monomer to the other; thus, the intramolecular change may affect the intermolecular conformation (Ravelli et al., 2004; Buey et al., 2006). Similarly, the reorganization of the FtsZ subdomains may be an important factor affecting filament formation.

4.2. Molecular basis of the polymerization of FtsZs and the GTPase activity

We showed that the presence of calcium ions promoted the polymerization of SaFtsZ and inhibited the GTPase activity (Fig. 5). However, it was unclear how calcium ions contributed to polymerization and inhibition at the molecular level. To determine the effect of calcium ions, we prepared a mutant in which Asn208 (an important residue for calcium coordination; Fig. 5a) was substituted by Ala. This mutant did not polymerize in the presence of calcium ions (Fig. 8a) and showed no GTPase activity (Fig. 8b).

GTPase activity is known to depend on FtsZ polymerization (Oliva et al., 2004; Scheffers et al., 2002). Asn208, Asp210 and Asp213 have been shown to be important for GTPase activity in EcFtsZ (Scheffers et al., 2002) and it was proposed that two aspartic acid residues in the upper subunit of MjFtsZ polarize the attacking water molecule (Oliva et al., 2004). However, the molecular details underlying this process are not known in the absence of the structure of GTP-bound straight FtsZ.

![Figure 8](image)

Figure 8
Sedimentation assay and GTPase activity of SaFtsZ N208A. (a) 15 μM SaFtsZ N208A was incubated with 1 mM GTP in the presence of varying concentrations of CaCl₂. The samples in lanes 2–7 were precipitated by ultracentrifugation and the precipitates were analyzed by SDS–PAGE. Lane 1, 15 μM SaFtsZ N208A as a control; lane 2, precipitation without GTP and CaCl₂; lane 3, without CaCl₂; lane 4, 1 mM CaCl₂; lane 5, 2 mM CaCl₂; lane 6, 5 mM CaCl₂; lane 7, 7.5 mM CaCl₂; 1 mM GTP was added to the buffer in lanes 3–7. (b) GTPase specific activities of SaFtsZ and SaFtsZ N208A.

Structural comparison between SaFtsZ-GDP and GTP-bound MjFtsZ (Fig. 4b) suggested that the nucleotide-binding sites superposed well. Thus, we attempted to build a hypothetical GTP-bound straight model by adding a γ-phosphate to the SaFtsZ structure (Fig. 9a). We built such a model without any steric hindrance and the model showed that Asp210 and Asp213 could bind to the γ-phosphate through water molecules (Figs. 9a and 9c). In contrast, Asn208 in the T7 loop could not interact with GTP. It is likely that Asn208 helps the calcium ion bind to the T7 loop, thereby forming the appropriate conformation for the T7 loop to be inserted into the nucleotide-binding pocket of the second molecule. Moreover, our structure suggested that the nucleotide is buried in the pocket by conformational change of the T7 loop. Thus, calcium ions promote the formation of a stable polymer owing to the slow hydrolysis to GDP. It is also possible that this conformational change makes it difficult to release the phosphate from the pocket.

4.3. Structure of the apo form

The apo-form structures determined previously were very similar to those of the previous GDP form (Oliva et al., 2007), possibly because citrate or sulfate ions were located in the nucleotide-binding pocket. Unlike these previous observations, the conformation of the apo form found in the present study was very different from those in other FtsZs (Fig. 1). The nucleotide-binding pocket of the apo form was severely disrupted owing to conformational changes in the T4 loop, T5 loop and H7 helix (Figs. 6b and 6d). A similar conformational change in the T4 loop was also found in M. tuberculosis FtsZ, which did not bind the nucleotide (PDB entries 2q1x and 1rq2; Leung et al., 2004). In the apo form, a new β-strand was formed at the H7 helix in the GDP form owing to calcium-ion chelation. This change could also occur in solution, as shown by CD measurements with and without calcium ions (Fig. 5c). The helical contents of SaFtsZ with and without calcium ions were 34.9 and 32.0%, respectively, as calculated from the CD spectra. These values were consistent with those calculated from the obtained structures, i.e. 36.7 and 33.8%, respectively, assuming that the region from residue 317 to 390 does not adopt a helical conformation.

It has not been clarified at the molecular level how GDP is replaced by GTP. SaFtsZ has several hinges around the H7 helix and has sufficient flexibility to act as a molecular switch in the assembly cycle. The present apo-form conformation may be one of the intermediate conformations in the physiological assembly cycle. It is possible that nucleotide turnover is caused not only by the difference in affinity between GTP and GDP but also by conformational change in the nucleotide-binding pocket.

4.4. Relative orientations between subdomains regulate the function of FtsZ

In the present study, we determined the structures of the apo form and GDP form of FtsZ by X-ray crystallography and found that FtsZ undergoes large conformational changes at
the subdomain interface. In particular, coordination of the calcium ion to the T7 loop contributed to this large change, regulating the polymerization and inhibition of GTPase activity (Fig. 5). However, we could not obtain crystals of the curved structure. It is possible that both structures are present under physiological conditions but that only the straight conformation of SaFtsZ could be crystallized. It is also possible that the stable conformations of SaFtsZ and other FtsZs differ and that a more stable straight conformation is obtained for SaFtsZ.

It has been shown that PC190723 binds exclusively to the GTP form of FtsZ, thereby accelerating its polymerization (Andreu et al., 2010). Therefore, it was speculated that FtsZ with GTP may form a new cleft between the subdomains owing to the reorientation between the GDP-bound and the GTP-bound states (Chen & Erickson, 2011). It has also been speculated that the binding site for PC190723 is similar to the taxol-binding or colchicine-binding site of tubulin (Haydon et al., 2008). Taxol and PC190723 both stabilize straight polymers and both ligands were expected to target structurally related assembly switches (Andreu et al., 2010; Elie-Caille et al., 2007). In this study, we determined the structure of the PC190723 complex and found that PC190723 binds to the cleft (Fig. 7) located between the H7 helix and the C-terminal subdomain in close proximity to the T7 loop. This site does not necessarily correspond to the taxol-binding or colchicine-binding site of tubulin (Figs. 7d and 7e). However, the general inhibitory mechanism would be shared between the taxol and PC190723 cases. Alteration of the inter-subdomain orientations has been confirmed to be important for GTPase activity in FtsZ (Chen & Erickson, 2011). Binding of the ligand to the cleft fixes the movement and may prevent the active residues in the T7 loop from being located at the appropriate site for GTPase activity.

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**References**


Figure 9
Hypothetical structural model of GTP-bound SaFtsZ and its putative interactions. (a) The hypothetical GTP-bound model of SaFtsZ is shown. This model was built based on superposition of SaFtsZ-GDP and GTP-bound MjFtsZ (see §2.4 and Fig. 4b). The upper and lower subunits of SaFtsZ are coloured pink and salmon pink, respectively. GTP is coloured blue. The side chains of Asn208, Asp210 and Asp213 in the upper subunit and the side chains of Asn44, Asp46, Gln48 and Phe183 in the lower subunit are represented as sticks. Amide and carbonyl atoms in the side chains are coloured blue and red, respectively. The calcium ion and water molecules are represented as green and orange spheres, respectively. Hydrogen bonds between subunits are indicated by green dotted lines. Hydrogen bonds related to GTP are indicated by red dotted lines. Calcium coordinations are indicated by black dotted lines. (b) The tilted dimer interaction of GTP-bound MjFtsZ (PDB entry 1w5a) is shown. MjFtsZ was superposed on the N-terminal region (residues 13–171 in SaFtsZ) of the lower subunit in (a). The illustrations are represented in the same manner as in (a). The upper and lower subunits of MjFtsZ, are coloured teal and cyan, respectively. GTP is coloured blue. The side chains of Phe208, Asp233, Asp235 and Asp238 are represented as sticks. Phe208, Asn233, Asp235 and Asp238 correspond to Phe183, Asn208, Asp210 and Asp213 in SaFtsZ, respectively. The magnesium ion is represented as a magenta sphere. (c) The hydrogen bond network around the phosphates of GTP in the hypothetical model is illustrated. Water molecules are represented as orange spheres. Hydrogen bonds are represented in the same manner as in (a). GTP is shown in blue. The distances (Å) of each hydrogen bond are indicated in the figure.