Suppression of Japanese encephalitis virus infection by non-steroidal anti-inflammatory drugs

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Japanese encephalitis virus (JEV) infection generates a rapid inflammatory response including peripheral neutrophil leucocytosis and infiltration of neutrophils into extraneural tissue. The level of inflammation correlates well with the clinical outcome in Japanese encephalitis patients. Non-steroidal anti-inflammatory drugs (NSAIDs), used medicinally for their analgesic and anti-inflammatory properties, are being considered for prevention of cardiovascular disease and cancer, as well as for treatment of human immunodeficiency virus infection. Apart from their ability to inhibit prostaglandin synthesis, the mechanisms underlying the beneficial therapeutic effects are largely unknown. We used aspirin, indomethacin and sodium salicylate to study the role of NSAIDs in JEV propagation in vitro. We found that NSAIDs suppressed JEV propagation in neuronal and non-neuronal cells. Blockade of cyclooxygenase activity by NSAIDs caused decreased production of free radicals and prostaglandins. However, these pharmacological alterations did not seem to correlate well with the antiviral effects. When cells were treated with the mitogen-activated protein kinase (MAPK) inhibitors PD 98059 and SB 203580, salicylate lost its antiviral effect. The activation of MAPK by anisomycin mimicked the action of salicylate in suppressing JEV-induced cytotoxicity. The decreased phosphorylation of extracellular signal-regulated kinase (ERK) was induced by JEV infection and the decrease in ERK was reversed by salicylate. Our data suggest that the signalling pathways of MAPK play a role in the antiviral action of salicylate.

Introduction

Flaviviruses are important human pathogens causing a variety of diseases ranging from mild febrile illnesses to severe encephalitis and haemorrhagic fever. Among them, Japanese encephalitis virus (JEV) is an acute zoonotic infection that commonly affects children and is a major cause of acute encephalopathy (Chambers et al., 1990). JEV targets the central nervous system (CNS), clinically manifesting with fever, headache, vomiting, signs of meningeal irritation and altered consciousness leading to high mortality and neurological sequelae in some of those who survive (Kumar et al., 1990). After entry into the host, JEV generates a rapid inflammatory response, including peripheral neutrophil leucocytosis and infiltration of neutrophils into extraneural tissue (Chaturvedi et al., 1979; Mathur et al., 1988). The inflammation results in an increased level of cytokines such as macrophage-derived chemotactic factor (MDF), tumour necrosis factor alpha (TNF-α) and interleukin 8 (IL-8) in the serum and cerebrospinal fluid (CSF) (Khanna et al., 1991; Ravi et al., 1997; Singh et al., 2000). The increased levels of inflammatory mediators appear to play a protective role or to initiate an irreversible immune response leading to cell death. Accumulating evidence shows that the mortality rate increases with increasing concentrations of cytokines in the serum and CSF in Japanese encephalitis patients (Ravi et al., 1997).

Non-steroidal anti-inflammatory drugs (NSAIDs) have long been used to treat fever and inflammatory diseases. Traditional NSAIDs like aspirin, ibuprofen and indomethacin can inhibit the activity of both cyclooxygenase (COX) isoforms, COX-1 and COX-2, thereby blocking the production of prostaglandins (Vane, 1971). Aspirin is a pro-drug form of salicylate, which is rapidly hydrolysed to salicylate in vivo (Gilman et al., 1990). Salicylate, however, inhibits the synthesis of prostaglandins in vivo, but has little effect on COX1 and
COX2 activities in vitro (Gilman et al., 1990). Salicylate must therefore modulate the synthesis of prostaglandins through an alternate mechanism not involving direct effects on COXs. In addition to the anti-inflammatory action of salicylate, increasing evidence indicates its ability to protect against cancer, cardiovascular disease and viral infection (Huang & Dietsch, 1988; Primache et al., 1998; Speir et al., 1998; Chen et al., 2000; Patrignani, 2000). This suggests that some of the biochemical effects of salicylate are independent of effects on COX activity.

The antiviral effects of NSAIDs have been shown to exert an influence on the influenza virus, cytomegalovirus and varicella-zoster virus (Huang & Dietsch, 1988; Primache et al., 1998; Speir et al., 1998). Inhibition of COX activity, scavenging of free radicals and down-regulation of transcription factors may be attributed to the antiviral action of NSAIDs. Despite extensive studies of NSAIDs, little is known about their effects on viral infection in the CNS. The propagation of vesicular stomatitis virus (VSV) in mouse CNS is suppressed by NSAIDs leading to a decrease in encephalitis (Chen et al., 2000). Moreover, arachidonic acid and its metabolites are involved in the death of neuroblastoma cells induced by Dengue virus, one of the flaviviruses (Jan et al., 2000). In the present study, we explored the effects of NSAIDs on JEV infection. We found that salicylate suppressed JEV replication and its cytotoxicity in neuroblastoma cells. The mechanism of its antiviral action was shown to be by modulation of the mitogen-activated protein kinase (MAPK) signalling pathway, not by inhibition of COX activity.

Methods

■ Virus and cells. A local Taiwanese strain of JEV NT113, isolated from mosquito, was generously provided by the National Institute of Preventive Medicine, Taiwan (Chen et al., 1997). Virus propagation was carried out in C6/36 cells in Dulbecco’s modified Eagle’s medium (DMEM) containing 5% foetal bovine serum (FBS). N18 cells, a mouse neuroblastoma cell line, and baby hamster kidney (BHK21) cells were grown in DMEM containing 10% FBS.

■ Virus infection and titre determination. For infection of cells with JEV, monolayers of each cell type were first adsorbed with JEV at an m.o.i. of 5 for 1 h at 37 °C. After adsorption, unbound virus was removed by gentle washing with PBS, pH 7.4. Fresh medium was added to each plate for further incubation at 37 °C. To determine virus titres, culture media were harvested and used in plaque-forming assays. Briefly, various dilutions of the culture media were added to 80% confluent BHK21 cells and incubated at 37 °C for 1 h. After adsorption, the cells were washed and overlaid with 1% agarose (SeaPlaque; FMC BioProducts) in RPMI 1640 plus 2% FBS. After incubation for 4 days, the cells were fixed with 4% paraformaldehyde (Sigma) and overlaid with 1% agarose (SeaPlaque; FMC BioProducts) in RPMI and incubated at 37 °C for 4 h. After incubation, the MTT solution was removed and 500 µl isopropanol containing 0.04 M HCl was added to dissolve the dark-blue crystals precipitated in the wells. A 100 µl sample of the resulting solution was removed from each well and the absorbance at 540 nm was determined using a spectrophotometer (PowerWaveX 340, Bio-TEK Instruments).

■ MTT assay. An MTT [3-(4,5-dimethylthiazol-2-yl)-2,5-diphenyl-2H-tetrazolium bromide] assay was used to measure mitochondrial function as an index of living cells. In brief, MTT (Sigma) was dissolved in 0.1 M TBS to make a 5 mg/ml solution. Fifty µl of MTT solution was added to each well containing tested cells in a 12-well plate and incubated at 37 °C for 4 h. After incubation, the MTT solution was removed and 500 µl isopropanol containing 0.04 M HCl was added to dissolve the dark-blue crystals precipitated in the wells. A 100 µl sample of the resulting solution was removed from each well and the absorbance at 540 nm was determined using a microplate reader (PowerWaveX 340, Bio-TEK Instruments).

■ Assessment of intracellular redox potential. Levels of intracellular free radicals were analysed by the fluorescent signal produced after the oxidation of non-fluorescent 2′,7′-dichlorofluorescein (Molecular Probe) by reactive oxygen species (ROS), as described previously (Zhu et al., 1994). 2′,7′-Dichlorofluorescein was added to cultures to a concentration of 5 µM in a defined salt buffer (116 mM NaCl, 1.8 mM CaCl2, 0.8 mM MgSO4, 5.4 mM KCl, 1 mM NaH2PO4, 14.7 mM NaHCO3, 10 mM HEPES and 5.5 mM glucose) at 37 °C for 5 min, washed and then incubated with buffer for 60 min. The fluorescent signal resulting from oxidation of 2′,7′-dichlorofluorescein was observed using a fluorescent microscope (Leica; excitation 488 nm and emission 510 nm) or measured using a fluorometer (Fluoroskan Ascent, Labsystems).

■ TdT-mediated dUTP nick end-labelling (TUNEL). Apoptosis-induced DNA strand breaks were end-labelled with dUTP by use of terminal deoxynucleotidyltransferase (TdT) with a commercial kit (In Situ Cell Death Detection Kit, Roche Diagnostic). According to the manufacturer’s instructions, briefly, the cells were fixed with 4% paraformaldehyde in PBS for 30 min at room temperature and permeabilized in 0.1% Triton X-100–0.1% sodium citrate for 2 min on ice. The reaction was performed by labelling with fluorescein isothiocyanate–dUTP at 37 °C for 60 min, then incubated with an alkaline phosphatase-conjugated secondary antibody. The colour was developed by incubation with NBT/BCIP substrate and observed under a light microscope.

■ Western blot. Protein extracts (100 µg) were resolved by SDS–polyacrylamide gel electrophoresis and transferred on to a blotting membrane. The membrane was first incubated with 5% (w/v) skimmed milk in PBS for 30 min to reduce non-specific binding, then incubated with primary antibody overnight at 4 °C, followed by washing with 0.05% Tween 20 in PBS. After washing, the membrane was incubated with horseradish peroxidase-conjugated secondary antibody. The signals were developed by chemiluminescent detection. The intensity of signals was determined by a computer image system (Alpha Innotech Corporation, IS1000).

■ Determination of prostaglandin E2 (PGE2) concentration. PGE2 levels were detected by ELISA, following the instructions provided by the manufacturer (Cayman Chemical).
**Statistical analysis.** Data are expressed as mean ± SEM. For comparisons, the statistical significance between means was determined using one-way analysis of variance (ANOVA) followed by Dunnett's t-test. A level of P < 0.05 was considered statistically significant.

**Results**

**Cells treated with NSAIDs had lower viral production and cytotoxicity**

The cytopathic effect of JEV infection in N18 cells became apparent 32–48 h post-infection (p.i.), concurrent with the period in which the infected cells actively produced large quantities of virus. The cytopathic effect resulting in cell death was demonstrated by the efflux of LDH and the presence of chromosomal DNA fragmentation. To investigate whether NSAIDs had an effect on JEV propagation, we treated cells with either a non-selective cyclooxygenase (COX) inhibitor (aspirin), a selective COX-2 antagonist (indomethacin) or an aspirin derivative (sodium salicylate), after 1 h of virus adsorption. Cytotoxicity was assessed 40 h p.i. All three pharmacological agents attenuated JEV-induced LDH efflux, in a concentration-dependent manner (Fig. 1A). To determine whether chromosomal DNA breaks generated by JEV infection could be affected by NSAIDs, cells were labelled and analysed by TUNEL assay and microscopy for the presence of DNA fragmentation in the nuclei. After 32 h, JEV induced apoptotic cell death in 37–45% of N18 cells as indicated by TUNEL assay (Fig. 1B). JEV-induced apoptosis was decreased in the cells treated with sodium salicylate (21–28%, P < 0.01) and the other NSAIDs (data not shown). Furthermore, analysis of cellular viral protein expression (Fig. 1C) and viral titres (Fig. 1D) revealed that NSAID-treated cells produced less viral protein and virus compared with the control JEV-infected cells.

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**Fig. 1.** NSAIDs suppress JEV propagation. (A) After 1 h of virus adsorption (m.o.i. = 5), N18 cells were cultivated for a further 40 h in the presence of aspirin (1 and 5 mM), indomethacin (2, 10, 100 and 500 µM), or sodium salicylate (1 and 5 mM). Cell damage was assessed by measurement of LDH efflux (n = 3). *P < 0.05; **P < 0.01. (B) After 1 h of mock (control) or virus adsorption (m.o.i. = 5), N18 cells were cultivated for a further 32 h in medium alone (JEV), or in the presence of sodium salicylate (5 mM). Apoptotic cell death was examined by TUNEL assay and observed under a light microscope. Scale bar, 50 µm. (C) After 1 h of virus adsorption (m.o.i. = 5), N18 cells were cultivated for a further 24 h in the presence of aspirin (1 and 5 mM), indomethacin (0.1 and 0.5 mM) or sodium salicylate (1 and 5 mM), or with medium only (control). Western blot analysis of the JEV NS1 protein was performed using cell lysates. The intensity of the NS1 signal in control cells was defined as 100% (n = 3). **P < 0.01. (D) After 1 h of virus adsorption (m.o.i. = 5), N18 cells were cultivated for a further 24 h in the presence of aspirin (1 and 5 mM), indomethacin (2, 10, 100 and 500 µM) or sodium salicylate (1 and 5 mM), or with medium only (control). The JEV titres in the culture supernatants were measured by plaque assay (n = 4). *P < 0.05; **P < 0.01.
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Fig. 2. Kinetics of the antiviral effects of NSAIDs. After 1 h of virus adsorption (m.o.i. = 5), N18 cells were cultivated for up to 48 h in the absence (control) or presence of either aspirin (5 mM), indomethacin (500 µM) or sodium salicylate (5 mM). Cell damage was assessed by (A) measurement of LDH efflux (n = 3) and (B) MTT assay (n = 3).

Fig. 3. NSAIDs reduce JEV-induced intracellular redox potential change. After 1 h of mock or virus adsorption (m.o.i. = 5), N18 cells were cultivated for a further 24 h in the presence of aspirin (1 and 5 mM), indomethacin (2 and 10 µM) or sodium salicylate (1 and 5 mM). Intracellular redox change was indicated by the fluorescent signal produced by 2',7'-dichlorofluorescein (5 µM) oxidation. The fluorescent intensity of uninfected control cells was defined as 100%. **P < 0.01; n = 3.

In addition, the protective effects of NSAIDs against JEV-mediated cytotoxicity were assessed kinetically. NSAIDs suppressed JEV-induced LDH efflux (P < 0.01, Fig. 2A) and JEV-induced reduction of MTT reaction (P < 0.01, Fig. 2B), in a time-dependent manner. Taken together, NSAID treatment suppresses JEV replication and propagation in neuroblastoma cells and leads to the attenuation of virus-induced cytotoxicity.

Fig. 4. NSAIDs reduce JEV-induced PGE₂ release. After 1 h of mock or virus adsorption (m.o.i. = 5), N18 cells were cultivated for a further 24 h in the presence of aspirin (1 and 5 mM), indomethacin (2 and 10 µM) or sodium salicylate (1 and 5 mM). The release of PGE₂ in the culture supernatants was measured by ELISA. *P < 0.05; **P < 0.01; n = 3.

Fig. 5. Effects of arachidonic acid and PLA₂ inhibitor on JEV-induced LDH efflux. After 1 h of mock or virus adsorption (m.o.i. = 5), N18 cells were cultivated for a further 40 h in the presence of arachidonic acid (10, 50 and 100 µM) or CDP-choline (0.1 and 0.2 mM), a PLA₂ inhibitor. Cell damage was assessed by measurement of LDH efflux. *P < 0.05; **P < 0.01; n = 3.

Effects of NSAID treatment on virus-induced redox potential change and prostaglandin release

We have previously shown that JEV infection of neuroblastoma cells generates intracellular reactive oxygen species (ROS), which can be assessed by quantification of the fluorescent signals produced by the oxidation of 2',7'-dichlorofluorescein (Raung et al., 2001). Both aspirin and indomethacin diminished JEV-induced ROS generation in a concentration-dependent manner (Fig. 3). This effect was not entirely due to the inhibition of COX enzymes since sodium
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salicylate also diminished ROS generation (Fig. 3). This compound has only minimal COX inhibitory activity (Weissmann, 1991) but, like aspirin and indomethacin, is a potent ROS scavenger (Sagone & Husney, 1987). To further characterize the involvement of COX enzymes in NSAID-mediated antiviral action, we assessed the COX activity as measured by PGE_{2} production. At 24 h after infection of N18 cells with JEV, there was a considerably higher level of PGE_{2} in the medium compared with the control medium containing uninfected cells (Fig. 4). We found that aspirin, indomethacin and even sodium salicylate decreased PGE_{2} release in a concentration-dependent manner (Fig. 4). These results indicate that aspirin, indomethacin and sodium salicylate do attenuate JEV-induced ROS generation and PGE_{2} production. However, these actions did not correlate well with their antiviral effect because the antioxidant treatments failed to suppress JEV-induced cytotoxicity (Raung et al., 2001) and the concentrations that exerted an antiviral effect were higher than those needed to diminish ROS generation and PGE_{2} release.

Effect of arachidonic acid (AA) on viral cytotoxicity

COX inhibitors are reported to cause AA accumulation by blocking the catabolism of AA (Axelroid et al., 1988; Kalgutkar et al., 1998). AA, a lipid secondary messenger, is generated by hydrolysis of membrane phospholipids via phospholipase A_{2} (PLA_{2}). We found that cytidine-5’-diphosphocholine (CDP-choline), a phospholipase A_{2} inhibitor, did not affect JEV-induced cytotoxicity (Fig. 5). Moreover, the addition of AA was ineffective in preventing JEV-induced cytotoxicity. Instead, AA increased JEV-induced LDH efflux in a concentration-dependent manner (Fig. 5). Exogenous AA itself also caused cell damage at a concentration of 100 µM (Fig. 5). These results strongly suggest that AA does not play a role in the antiviral action of NSAIDs.
Discussion

NSAID-treated cells are more resistant to JEV-induced cytotoxicity. Both the non-selective and selective COX inhibitors, aspirin, indomethacin and sodium salicylate, reduced virus replication and yield in vitro. These antagonists suppressed JEV-induced intracellular redox potential change and PGE$_2$ production. The antiviral action of salicylate is independent of the inhibition of COX activity, since the doses used to suppress JEV amplification are higher than those required to inhibit prostaglandin synthesis. In addition, COX activity inhibition-induced AA accumulation failed to eliminate viral toxicity. Instead, MAPK inhibitors reversed the antiviral effect of salicylate. Taken together, these results show that salicylate suppresses JEV propagation in vitro through the modulation of the MAPK signalling pathway.

Phospholipids play roles in many biological processes, including the generation of proinflammatory lipid mediators, such as prostaglandins and leukotrienes, and the regulation of lipid metabolism (Glaser, 1995). The mobilization of AA from phospholipids requires the involvement of PLA$_2$. AA serves as a substrate for COX enzymes, resulting in the production of prostaglandins. Prostaglandins activate cellular receptors, resulting in the subsequent initiation of signal cascades involving G-protein and cyclic AMP (Cirino, 1998). These signalling cascades have an important role in cellular injury via their ability to mediate inflammatory responses. NSAIDs inhibit the activity of both COX isoforms, leading to decreased production of prostaglandins and the accumulation of AA. Therefore, the inflammatory action of prostaglandins and COX activity-associated free-radical generation are suppressed. In contrast, the biological action of AA is apparent.

NSAIDs such as aspirin, indomethacin and sodium salicylate suppressed JEV propagation in neuroblastoma cells, as indicated by the attenuation of cell death and the reduction of viral protein expression and virus yield (Figs 1 and 2). Numerous studies have used PGE$_2$ release as a marker for COX activity. JEV infection slightly increased the production of PGE$_2$ by neuroblastoma cells (Fig. 4). These NSAIDs sup-
pressed mock-infection (data not shown) and JEV-induced PGE₂ production, indicating the well-known pharmacological effects on COX enzymes. Previously, we reported that JEV infection caused generation of free radicals in neuroblastoma cells via the involvement of the flavon-containing enzymes (Raung et al., 2001). The increased production of free radicals induced by JEV could be eliminated by NSAIDs (Fig. 3). This result suggests that JEV-induced free-radical generation might be through the COX-associated pathway. However, it should be noted that the reduction of free radicals may be derived from the direct scavenging effect. Recently, Jan et al. (2000) reported that AA, superoxide anion and nuclear factor kappa B (NF-κB) were sequentially involved in Dengue virus-triggered apoptotic pathways. However, exogenous AA and an inhibitor of PLA₂ failed to mimic the action of NSAIDs in suppressing JEV-induced cell death (Fig. 5). Although reduction of superoxide anion generation by superoxide dismutase protected Dengue virus-induced apoptosis (Jan et al., 2000), antioxidants showed no protective actions against JEV-mediated cytoxicity (Raung et al., 2001). Moreover, the doses of NSAIDs used to eliminate free-radical generation (Fig. 3) and PGE₂ production (Fig. 4) were lower than those required to suppress JEV propagation (Figs 1–4). Therefore, these results suggest that the antiviral effect of NSAIDs was not through the conventional COX pathway.

Signal transduction pathways convey signals generated at the cell surface into the cell nucleus in order to initiate a programme of gene expression that is characteristic for particular stimuli. Among them, MAPKs, including ERK, p38 protein kinase and c-Jun N-terminal kinase (JNK), play a critical role in the regulation of cell proliferation and differentiation in response to mitogens and other extracellular stimuli (Karin, 1998). The activation of MAPKs can be modulated by salicylate (Schwenger, 1998). We found that the antiviral effect of salicylate against JEV could be blocked by inhibitors of mitogen-activated protein kinase (MEK) (PD 98059) or p38 MAPK (SB 203580) (Fig. 6). In addition, direct activation of p38 MAPK by anisomycin also markedly suppressed JEV-induced LDH efflux (Fig. 6). The involvement of MAPK modulation on the antiviral effect of salicylate was observed not only in neuroblastoma cells but also in non-neuronal BHK21 cells (Fig. 7). Recently, Liao et al. (2001) have demonstrated that the antiflavivirus effect of salicylates was partially reversed by blocking p38 MAPK activation with SB 203580 in BHK21 cells. In this study, we have provided further evidence showing the involvement of p38 MAPK and ERK in JEV-mediated cytotoxicity as well as in the antiviral effect of salicylates. In general, the dynamic balance between branches of the MAPK family is believed to regulate neuronal decisions to live or die in response to stressors (Xia et al., 1995). In particular, ERK activation may play a pivotal role. For example, many neuroprotective/neurotrophic factors activate receptor tyrosine kinases transmitting signals through the activation of ERK (Segal & Greenberg, 1996). ERK activation appears to antagonize apoptotic pathways in some cell systems (Xia et al., 1995). In contrast, several recent studies indicate that ERK activation may also play a pathologic role in neurons exposed to increased oxidative stress (Oh-hashi et al., 1999; Stanciu et al., 2000). Although the detailed mechanisms underlying the antiviral effect remain unclear, JEV infection-induced decreased phosphorylation of ERK could be reversed by salicylate (Fig. 6). In addition, the activation of p38 MAPK also suppressed JEV-induced toxicity (Fig. 6). Thus, the activation of MAPK plays a role in host-cell protection against JEV infection.

Oxidative stress has been suggested to be a mediator of apoptosis/necrosis induced by a variety of triggers, including virus infections (Schwarz, 1996; Peterhans, 1997; Speir et al., 1998; Schweizer & Peterhans, 1999). Some antioxidants are known to inhibit cell death in virus systems (Cossarizza et al., 1995; Verhaegen et al., 1995; Lowy & Dimitrov, 1997), although antioxidants do not protect cells against JEV-induced toxicity (Raung et al., 2001). Free radicals are potent triggers for NF-κB activation. Accumulating evidence indicates the antiviral effects of NF-κB inhibition in cytomegalovirus, Dengue virus, respiratory syncytial virus and human immunodeficiency virus (Schwarz, 1996; Bitko et al., 1997; Peterhans, 1997; Speir et al., 1998; Jan et al., 2000). In these viruses, antioxidant therapy is effective against virus infection (Staal et al., 1990; Schwarz, 1996; Bitko et al., 1997; Peterhans, 1997; Speir et al., 1998; Jan et al., 2000). NF-κB inhibition has been shown to be a potential mechanism of the neuroprotection effect exerted by aspirin and salicylate (Grilli et al., 1996). However, both antioxidants (Raung et al., 2001) and the inactivation of NF-κB (Liao et al., 2001) failed to attenuate JEV propagation and JEV-mediated cytoxicity. Therefore, the inactivation of NF-κB is not involved in the antiviral effect of salicylate against JEV.

The generation of ROS has been demonstrated to be critical in the rapid degradation of phagocytosed JEV viral protein and nucleic acid (Srivastava et al., 1999). In addition, nitric oxide appears to be effective in restricting JE amplification (Lin et al., 2000). Usually, oxidative stress is well associated with the activation of MAPK. In this study, we have demonstrated that MAPK signalling pathways are also involved in suppression of JEV propagation.

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References


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