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The Inhibitory Receptor IRp60 (CD300a) Is Expressed and Functional on Human Mast Cells

Ido Bachelet,2* Ariel Munitz,2* Alessandro Moretta,† Lorenzo Moretta,‡ and Francesca Levi-Schaffer3*

Mast cell-mediated responses are likely to be regulated by the cross talk between activatory and inhibitory signals. We have screened human cord blood mast cells for recently characterized inhibitory receptors expressed on NK cells. We found that IRp60, an Ig superfamily member, is expressed on human mast cells. On NK cells, IRp60 cross-linking leads to the inhibition of cytotoxic activity vs target cells in vitro. IRp60 is constitutively expressed on mast cells but is down-regulated in vitro by the eosinophil proteins major basic protein and eosinophil-derived neurotoxin. An immune complex-mediated cross-linking of IRp60 led to inhibition of IgE-induced degranulation and stem cell factor-mediated survival via a mechanism involving tyrosine phosphorylation, phosphatase recruitment, and termination of cellular calcium influx. To evaluate the role of IRp60 in regulation of allergic responses in vivo, a murine model of allergic peritonitis was used in which the murine homolog of IRp60, LMIR1, was neutralized in BALB/c mice by mAbs. This neutralization led to a significantly augmented release of inflammatory mediators and eosinophilic responses in vivo, a murine model of allergic peritonitis was used in which the murine homolog of IRp60, LMIR1, was neutralized in BALB/c mice by mAbs. This neutralization led to a significantly augmented release of inflammatory mediators and eosinophilic infiltration. These data demonstrate a novel pathway for the regulation of human mast cell function and allergic responses, indicating IRp60 as a candidate target for future treatment of allergic and mast cell-associated diseases. The Journal of Immunology, 2005, 175: 7989–7995.

The tissue-dwelling mast cells have key roles in allergic reactions, innate immunity, inflammatory diseases, fibrosis, and autoimmunity. They arise from circulating precursors that enter the tissues, where they undergo final maturation and begin expressing the high-affinity receptor for IgE, FcγRI. The central trigger for mast cell activation in allergy. Following allergen-induced aggregation of FcγRI, the mast cells degranulate and secrete an array of preformed and newly synthesized mediators and, later on, produce and secrete additional cytokines. Mast cells can also be activated by IgE-independent stimuli, such as anaphylatoxins, neuropeptides, and eosinophil basic proteins. A main factor regulating mast cell homeostasis in humans is stem cell factor (SCF). Through its tyrosine kinase receptor c-kit (CD117), SCF plays central roles in mast cell differentiation (1), survival (2, 3), activation (4, 5), and chemotaxis (6).

The responses coordinated by mast cells are tuned through a balance between activating and inhibitory signals. Over the last few years, it has become clear that mast cell activation can be regulated by various inhibitory receptors that are expressed and functional on the surface of murine and human mast cells (7). The functional cores of immune inhibitory receptors are specialized modules in their intracellular domain, termed ITIMs (8). Upon ligand-binding or immune complex-mediated cross-linking of the receptor, these modules undergo tyrosine phosphorylation and recruit Src homology 2-bearing phosphatases, such as Src homology 2 domain-containing phosphatase (SHIP)-1/2 and the inositol phosphatase SHIP (9). These phosphatases act by dephosphorylating the docking sites for activating kinases such as Syk, or alternatively degrading phosphatidylinositides produced by phosphoinositide 3-kinase (10), actively shutting these signals off and halting the activating cascade.

Among the known mast cell inhibitory receptors are FcγRIIB (11), gp49B1 (12), myeloid-associated Ig-like receptors 1/2 (13), the mast cell function-associated Ag (14), paired Ig-like receptor A/B (15), and CD200R (16). Of these, FcγRIIB has been extensively studied on human mast cells (17), and attempts to target it have already been made for therapeutic mast cell inhibition (18, 19). Thus, characterizing additional inhibitory receptors on human mast cells is required for a better understanding of the signals involved in mast cell regulation, as well as for defining new immunopharmacological targets for treatment of allergic diseases. Therefore, we aimed to investigate the presence and function of a series of inhibitory receptors belonging to several receptor families (Ig superfamily, lectin type). In the present study, we focus on IRp60 (CD300a), an Ig superfamily receptor that is expressed on various cells like T cells, NK cells, and neutrophils (20). Ab-mediated cross-linking of IRp60 on NK cells results in down-regulation of NK cytolytic activity in vitro.

In this study, we report that IRp60 is expressed on human mast cells and that its cross-linking inhibits IgE-induced degranulation and SCF-mediated survival through a mechanism involving tyrosine phosphorylation and phosphatase recruitment. Neutralization of the murine homolog of IRp60, LMIR1, leads to an augmented response.

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4 Abbreviations used in this paper: SCF, stem cell factor; CBMC, human cord blood-derived mast cell; HLMC, human lung-derived mast cell; MBP, human eosinophil-derived major basic protein; ECP, human eosinophil cationic protein; EDN, human eosinophil-derived neurotoxin; EPO, human eosinophil peroxidase; SHP, Src homology 2 domain-containing phosphatase; PI, propidium iodide.

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Materials and Methods

Abs and reagents

All of the cell culture media, reagents, and buffers were purchased from Biological Industries. SCF is a kind gift from Agen (Thousand Oaks, CA). The following mAbs recognizing various inhibitory receptors were produced as described (20): P192 and E59 (mouse monoclonal anti-IRp60; isotypes are mouse IgG2b and IgG1, respectively), Z770 (mouse anti-NNK2A), XA185 (mouse anti-CD94), G8 (mouse anti-p58.2), GL183 (mouse anti-p58.2), Z77 (mouse anti-p70), Q66 (mouse anti-p140), AZ158 (mouse anti-p70/p140), F278 (mouse anti-LIR1/ITL2). The Ab recognizing LIR3(ILT5) (15F3) was kindly provided by Dr. M. Collmann (Washington University, St. Louis, MO). The following Abs and reagents were purchased as indicated: rat anti-mouse LMR1 (clone 224) and FITC-conjugated rat anti-mouse CCR3 from R&D Systems; anti-human CD117 Ab for human lung mast cell purification from BD Pharmingen; PE-conjugated anti-human FcRI (clone AER-37) from E Bioscience; anti-human tryptase (clone AA1) and isotype control (IgG1 and IgG2A) Abs from DakoCyto; sheep anti-mouse F(ab′)2 from ICN Biomedicals. Chimeric murine/human IgE anti-NP Ab from Serotec; goat anti-mouse λ-chain-specific Ab from Southern Biotech; polyclonal anti-human phosphotyrosine (pY99), SHP-1/2, and SHIP Abs from Santa Cruz; anti-human phospho-p58.2, Z27 (mouse anti-p70), Q66 (mouse anti-p140), AZ158 (mouse anti-p70/p140), F278 (mouse anti-LIR1/ITL2). The reaction was stopped by addition of 120 μl of ice-cold glycine (0.2 M) (pH 10.7), and the OD was immediately read in a standard spectrophotometer at 410 nm absorbance. For tryptase, 48 μl of sample was mixed with 2 μl of substrate solution (25 mM N-p-nitrophenyl-N-acetyl-β-D-glucosaminide in 48 mM citric acid and 56 mM NaHPO4 (pH 4.5)) and incubated for 2 h at 37°C. The reaction was read at 405 nm. The samples in which OD exceeded the reliable detection OD range were diluted and read. Percent release was calculated as follows: %R = 100 × supernatant/(lysate + supernatant). IL-4 release was measured by a commercial ELISA kit (Diaclone). Eotaxin-2 content was measured by a commercial ELISA kit (DuoSet; R&D Systems).

Survival assay

CBMC (10^5) were washed with MEM-Alpha without growth factors and incubated in 200 μl MEM-Alpha with or without SCF (100 ng/ml) in a culture plate coated as described above. At 24 and 48 h, all samples were stained by addition of 5 μl of propidium iodide solution in PBS (10% v/v) and immediately analyzed by FACS.

Modulation of receptor expression

CBMC (2 × 10^5 per 200 μl) were cultured in the presence of 10–100 ng/ml (ranging between 1–15 and 1 μM) of either of the following proteins: cosinophil major basic protein (MBP), eosinophil cationic protein (ECP), eosinophil-derived neurotoxin (EDN), eosinophil peroxidase (EPO), or eosinophil cationic protein (ECP), for 45 minutes (Sigma-Aldrich; 11 g/ml, equal to 14–66 mM) for 12, 24, and 48 h at 37°C. At these time points, IRp60 expression and viability were assayed by FACS using anti-IRp60/propidium iodide double staining.

Intracellular Ca^{2+} mobilization

Before loading with calcium sensor, 3 × 10^9 EG-E-sensitized CBMC were blocked with 10% v/v human serum in MEM-Alpha (10 min on ice). Later, IRp60 was cross-linked by incubation of the CBMC with anti-IRp60 or isotype control Ab (5 μg/ml, 30 min on ice). Subsequently, cells were washed and incubated with sheep anti-mouse F(ab′)_2 (25 μg/ml, 30 min on ice) in MEM-Alpha. The cells were loaded with Calcium Green-1 AM (10 μM: 45 min, 37°C) in MEM-Alpha (FCS, 2% v/v), washed, and resuspended in 300 μl of Tyrode’s gelatin-calcium buffer (prewarmed to 37°C). The cells were allowed to flow freely in the cytometer for 40 s, at which time anti-EG-E (5 μg/ml) was added. Changes in FL-1 geo mean were recorded for a total of 5 min.

Immunoprecipitation and Western blot

CBMC (5 × 10^5) were lysed using a commercial lysis buffer (Pierce), run on 10% SDS-PAGE, transferred to polyvinylidene difluoride membranes (Pierce) and probed for IRp60 (anti-IRp60; 1 μg/ml). For IRp60 precipitation, CBMC (8 × 10^6) were treated with sodium orthovanadate (4 mM; 10 min, 37°C) or incubated with an immune complex (25 μg/ml sheep anti-mouse, 5 μg/ml anti-human IRp60, or isotype control Ab) for various time periods (0, 15, 30, 60, and 120 s). IRp60 was precipitated from CBMC using a commercial kit (Scientific Classic Mammalian kit; Pierce) according to the manufacturer’s instructions. The samples were run as described and blotted vs phosphotyrosine (pY99), SHP-1/2, and SHIP. For detection, HRP-conjugated anti-mouse or anti-rabbit Abs were used as recommended by the manufacturer.
Murine allergic peritonitis model

Allergic peritonitis was induced in 8- to 10-wk-old female BALB/c mice by OVA essentially as described (24). On days 0 and 7, mice were sensitized intradermally with 100 μg of OVA adsorbed on 1.6 mg of alum hydroxide in 300 μl of saline. On day 11, 30 min before allergen challenge (30 μg of OVA in 300 μl of saline i.p.), a group of mice were injected i.p. with anti-LMIR1 neutralizing Ab (5 μg/mouse). Mice were sacrificed either 45 min (for tryptase) or 24 h (for tryptase and IL-4; data not shown) later. At these time points, the peritoneal cavity was washed with 5 ml of Tyrode’s gelatin buffer. The recovered peritoneal lavage fluid was centrifuged (150 X g, 5 min), and cell pellets were resuspended in 2 ml of Tyrode’s gelatin buffer for mediator analysis and total cell counts. Peritoneal lavage cells were counted under a light microscope in a hemocytometer following trypan blue staining. Eosinophils were analyzed by FACS gating SSChigh.

Results

Human mast cells express IRp60

To investigate the expression pattern of inhibitory receptors on human mast cells, CBMC were incubated with a large panel of mAbs recognizing various inhibitory receptors characterized on NK cells. As shown in Fig. 1a, FACS analysis revealed that CBMC express high levels of IRp60, but not LIR1(ILT2), LIR3(ILT5), p58.1, p58.2, p70, p140, or NKG2A/CD94. To evaluate whether tissue mast cells express IRp60, HLMC and NPMC were stained for IRp60. As shown in Fig. 1b, HLMC and NPMC displayed significant levels of IRp60.

Eosinophil MBP and EDN down-regulate IRp60 expression on CBMC

We next investigated the capability of eosinophil-derived cytotoxic proteins, found in the allergic inflammatory milieu, to modulate IRp60 expression on CBMC. For this, CBMC were cultured with subactivating concentrations (1–10 ng/ml) of eosinophil MBP, ECP, EDN, EPO, and of poly-t-arginine at an equimolar concentration. As shown in Fig. 2, MBP and EDN selectively induced a decrease in the expression level of IRp60 in a dose-response manner (MFI of 9.12 ± 2.27 vs 2.69 ± 0.24 and 2.22 ± 0.25 for MBP at 10 and 100 ng/ml, respectively; or vs 3.03 ± 0.68 and 2.79 ± 0.71 for EDN at 10 and 100 ng/ml, respectively; p < 0.05 for all of the cases).

IRp60 cross-linking inhibits IgE-dependent mediator release from CBMC

Based on the observed inhibitory effect of IRp60 on NK-mediated cytotoxicity, we hypothesized that IRp60 inhibits CBMC activity as well. To induce coaggregation of IRp60 with FcεRI (as described for other inhibitory receptors) (11), we used chimeric IgE for sensitization and an anti-mouse cross-linking Ab. CBMC were sensitized with IgE and then triggered to degranulate by an anti-IgE Ab or by compound 48/80 in an anti-IRp60-coated plate. As shown in Fig. 3, a and b, cross-linked IRp60 strongly and significantly inhibited IgE-mediated release of β-hexosaminidase and tryptase (degranulation inhibited by 86.04% with anti-IRp60; p < 0.005) and IL-4 (release inhibited by 99.78% with anti-IRp60; p < 0.005). Interestingly, IRp60 did not inhibit compound 48/80-mediated release of either β-hexosaminidase (as shown in Fig. 3c), tryptase, or IL-4 (data not shown).

IRp60 cross-linking inhibits SCF-mediated CBMC survival

SCF is the most important survival factor for human mast cells. SCF signals upon binding to c-kit and initiating a signaling cascade that involves phosphatidylinositols-3’ kinase, protein kinase B, and syk. To examine the ability of IRp60 to interfere with c-kit signaling, CBMC were cultured in the presence or absence of SCF (100 ng/ml) in an anti-IRp60-coated plate, followed by FACS analysis of propidium iodide (PI)-positive cells. As shown in Fig. 4, IRp60 cross-linking significantly inhibited mast cell survival at 24 h (5.5-fold increase in number of PI+ cells with anti-IRp60; p < 0.005) and at 48 h (10.3-fold increase in PI+ cells with anti-IRp60; p < 0.005).

IRp60 cross-linking inhibits IgE-induced [Ca2+]i influx

One of the initial steps in FcεRI-dependent activation of CBMC is intracellular calcium influx due to phosphatidylinositide formation.
and store-operated channel opening. Therefore, the effect of IRp60 cross-linking on calcium influx was examined using the fluorescent sensor Calcium Green-1AM. As shown in Fig. 5 within 10–20 s of anti-IgE addition, a marked \([\text{Ca}^{2+}]\) increase was observed. This increase was completely abolished in response to IRp60 cross-linking compared with the isotype control.

**IRp60 undergoes tyrosine phosphorylation, recruits SHP-1 and SHP-2, and induces syk dephosphorylation**

In NK cells, IRp60 has been shown to mediate its inhibitory effect via recruitment of SHP-1 and SHP-2 (20). To establish the mechanism of the inhibitory activity of IRp60 on human mast cells, CBMC were treated with sodium orthovanadate or alternatively cross-linked, precipitated, and blotted for phosphotyrosine, SHP-1 and -2, and SHIP. Upon orthovanadate pretreatment, IRp60 underwent tyrosine phosphorylation (Fig. 6a). In addition, IRp60 co-precipitated with SHP-1 and SHIP, but not with SHP-2. Upon Ab-driven cross-linking (Fig. 6b), IRp60 underwent tyrosine phosphorylation and precipitated with SHIP, but not SHP-1. Moreover, by intracellular FACS analysis of phosphorylated syk, it was detected that IRp60 cross-linking with immune complex, but not the isotype control, caused a rapid dephosphorylation of syk (Fig. 6c).

The murine homolog of IRp60 regulates mast cells activation and consequent inflammatory response in an allergic-peritonitis mouse model

Bioinformatic analysis that included sequence homology comparison revealed a murine homolog for IRp60. This receptor has been cloned, characterized, and termed LMIR1 (25). We reconfirmed that murine mast cells from both bone marrow and peritoneum express LMIR1. Furthermore, LMIR1 cross-linking specifically inhibited β-hexosaminidase release from IgE-activated BMMC in 10–20 s of anti-IgE addition, a marked \([\text{Ca}^{2+}]\) increase was observed. This increase was completely abolished in response to IRp60 cross-linking compared with the isotype control.

**FIGURE 4.** The cross-linking of IRp60 inhibits SCF-induced CBMC survival. CBMC were incubated with or without SCF (100 ng/ml) in the presence of anti-IRp60 or isotype control Abs for 24 and 48 h, stained for PI, and analyzed by FACS (n = 3; **, p < 0.005).
To assess whether IRp60 has a role in regulating mast cell activation in vivo, a murine model of experimental allergic peritonitis was used (24). Mice injected with neutralizing anti-LMIR1 mAb before allergen challenge, displayed enhanced mast cell activation in response to allergen challenge as demonstrated by the early (45-min) increase in tryptase activity in the peritoneal lavage (Fig. 7a). Eotaxin-2 levels 24 h after allergen challenge were significantly increased (Fig. 7b). Also, the peritoneal eosinophilic infiltration was doubled (eosinophil counts $4.199 \times 10^6$ with anti-LMIR1 vs $2.056 \times 10^6$ without; $p < 0.05$) (Fig. 7c).

### Discussion

A major issue in modulating mast cell responses is the identification of new inhibitory pathways that counteract their activity. In the present study, we have found that the inhibitory receptor IRp60 is expressed and functional on human mast cells. We found that CBMC selectively express IRp60. To date, the functionally characterized inhibitory receptors on human mast cells are the tetraspanins CD63 (26) and CD81 (27), CD200R (16), immune receptor expressed on myeloid cells 1 (28), FcγRIIB (11), and signal regulatory protein-α (29).

CBMC are in vitro-derived, mostly tryptase-containing mast cells, with a phenotype similar to HLMC (30). We therefore aimed to verify whether tissue in vivo-derived mast cells express IRp60 as well. Indeed, IRp60 was found to be expressed both on lung (tryptase-positive) and nasal polyp (tryptase- and chymase-positive) (31) mast cells, indicating that IRp60 may have a functional significance in mast cell regulation in vivo, of the two mast cell subtypes. Still, because HLMC in this study were obtained from lung specimens taken from cancer patients, it is possible that these mast cells display an abnormal pattern of IRp60 expression and function.

Because we believe that mast cell-eosinophil interactions form a crucial axis in allergic inflammatory and fibrotic diseases, we have examined the influence of eosinophil-derived granule proteins on...
the expression of IRp60 on mast cells. Although IRp60 is expressed constitutively, it was selectively down-regulated by eosinophil-derived MBP and EDN, but not by ECP or EPO. This effect is not likely due to the positive charge shared by the four molecules, because poly-L-arginine in an equivalent concentration did not induce a significant effect. This effect is also receptor specific, because CD117 was not affected by eosinophil granule proteins (data not shown). Furthermore, although MBP and ECP share a similar isoelectric point (πl \( \approx 10.9 \)) and a similar net charge at pH 7.0 (e \( \approx 15 \)), the traits of EDN differ significantly from those values (πl \( = 8.9 \); e \( = 7.5 \)) (32). In fact, selective activities of the four eosinophil basic proteins have been described. For example, MBP and EPO induce eosinophil degranulation, EDN release, and synthesis of IL-8 (33). MBP also activates neutrophils to release superoxides by a mechanism involving phosphoinositide 3'-kinase and protein kinase Cζ (34). We believe that the decrease in IRp60 expression induced by eosinophil granule proteins is extremely important in the context of chronic allergic-inflammation where mast cells and eosinophils interact (35).

Mast cells are principally activated in allergy through IgE, but they are also able to degranulate upon IgE-independent activation (21). Therefore, the effect of IRp60 was examined on both modalities. The cross-linking of IRp60 inhibited β-hexosaminidase, tryptase, and IL-4 release from IgE-activated CBMC. However, it did not influence the IgE-independent compound 48/80-mediated CBMC activation. This differential effect indicates that IRp60 interferes with pathways involving tyrosine phosphorylation, but not with GTP/GDP-dependent pathways.

An important question arising from the observed inhibitory effect of IRp60 is whether it should or should not be coaggregated with the activatory receptor, such as FcεRI and c-kit, to achieve an inhibitory effect. Although such coaggregation is considered as mandatory for inhibitory receptors, several observations have clearly demonstrated that this is not the case (36, 37). Our results demonstrate that, when IRp60 is coaggregated with FcεRI, it elicits a much stronger effect than that achieved when IRp60 is self-ligated (data not shown). Interestingly, the effect on mast cell survival did not vary significantly when IRp60 was coaggregated with c-kit.

Another important tyrosine kinase-dependent pathway in mast cell regulation is the SCF-CD117 axis, mediated primarily by phosphatidylinositol 3-0H kinase, Akt, and syk. Consistent with this, we have examined the effect of IRp60 on the SCF-mediated survival of CBMC, and found that IRp60 cross-linking led to increased cell death. These data are in accordance with reports that demonstrated the ability of FcγRIIB to block SCF-mediated survival of mast cells (11). Moreover, gp49B1 was reported to decrease the activation of mast cells in vivo via SCF (4). It is noteworthy that IRp60 did not actively induce apoptosis but rather blocked the survival-inducing signals generated by the SCF-CD117 axis.

By orthovanadate treatment, IRp60 undergoes tyrosine phosphorylation and recruits the protein phosphatases SHP-1 and the inositol phosphatases SHIP, two well-established negative regulators of cell activation and survival. In addition, by immune complex-derived cross-linking, IRp60 recruited SHIP but not SHP-1. This could be due to the lower level of phosphorylation induced by immune complex compared with orthovanadate. Yet, syk was dephosphorylated by immune complex-driven cross-linking, and therefore it is possible to assume that SHP-1 is recruited by this stimulus as well. The observation that IRp60 does not recruit SHP-2, unlike in NK cells, supports recently reported data in which IgSF13, a close family member of IRp60 expressed on dendritic cells, follows exactly the same phosphatases deployment pattern (38). By phosphatase recruitment and activation, IRp60 prevents IgE-mediated syk phosphorylation, thus blocking mast cell activation in an early stage. Interestingly, Ab-cross-linked IRp60 did not precipitate with SHP-1. Although this may be related to the robust phosphorylation induced by orthovanadate rather than by immune complex, other factors might contribute to this observation. However, it is likely that SHP-1 is recruited by IRp60, because syk phosphorylation was observed. We are currently using biotinylated ITIMs as described (16) to clarify this issue.

IRp60 represents an allelic isoform of CMRF-35H (39). Although no in vivo function has been attributed to IRp60 in humans yet, a murine CMRF-35H family member (termed CMRF-like molecule 1 (CLM-1)) has been shown to inhibit osteoclast formation in vivo through SHP-1 recruitment (40). It has been recently reported that murine mast cells express an Ig-superfamily receptor termed LMIR1 (25), which is \( \sim 70\% \) identical with human IRp60, with the important functional residues in the V-type Ig-fold and ITIM sequences well conserved, and is able to recruit SHP-1 and SHP-2 via tyrosine phosphorylation. We have conducted a functional bioinformatics comparison between LMIR1 and IRp60 (data not shown) and concluded that there is a very high probability that LMIR1 actually represents a murine homolog of the human IRp60. Neutralization of LMIR1 enhanced mast cell activation and consequent eosinophilic infiltration in the peritoneal lavage of these mice. This indicates that LMIR1 and its yet-undefined ligand have a key role in regulation of allergy.

The gene encoding for IRp60, IRCl, is located on chromosome 17q24.25 (41) in close linkage with a recently identified locus dictating susceptibility to psoriasis (41), arthritis, and atopic dermatitis (42). The possibility that IRp60 is the actual gene responsible for these diseases is strengthened by the observation that neutralizing its activity in vivo augments the allergen-dependent response in murine allergic peritonitis. It is therefore conceivable that IRp60 represents an important family of immune negative regulators that has long been overlooked.

In conclusion, this work demonstrates a novel pathway for the negative regulation of human mast cell function. This issue is important not just academically, because the ability to target IRp60 and consequently inhibit mast cell inflammatory functions opens the potential for novel therapeutic strategies for the management of mast cell-dependent pathologies.

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Disclosures
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