Cutting Edge: Humanized Nano-Proresolving Medicines Mimic Inflammation-Resolution and Enhance Wound Healing

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Endogenous microparticles (MPs) were systematically profiled during the time course of self-limited inflammation. Precursors for specialized proresolving lipid mediators were identified in MPs from inflammatory exudates using liquid chromatography tandem mass spectrometry-based metabolomics. Hence, we postulated that formation of anti-inflammatory and proresolving lipid mediators could underlie beneficial effects attributed to MPs and that this process could serve as a basis for biomimicry. Using human neutrophil-derived MPs, we constructed novel nanoparticles (NPs) containing aspirin-triggered resolvin D1 or a lipoxin A4 analog. Enriched NPs dramatically reduced polymorphonuclear cell influx in murine peritonitis, short-ened resolution intervals, and exhibited proresolving actions accelerating keratinocyte healing. The enriched NPs protected against inflammation in the temporomandibular joint. These findings indicate that humanized NPs, termed nano-proresolving medicines, are mimetics of endogenous resolving mechanisms, possess potent beneficial bioactions, can reduce nanotoxicity, and offer new therapeutic approaches.

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Uncontrolled inflammation is a fundamental etiology of many pathologies, including cardiovascular diseases, arthritis, and temporomandibular joint (TMJ) disorders (TMDs) (1, 2). Prevalence of TMDs is high, with at least one symptom afflicting a third of United States adults. However, there is an unmet need for effective treatments, as options are limited and often involve behavioral or physical therapies or acute administration of nonsteroidal anti-inflammatory drugs or acute administration of nonsteroidal anti-inflammatory drugs (3). Timely resolution of an inflammatory insult is pertinent for restoration of tissue homeostasis and essential for ongoing health (3). Thus, endogenous control mechanisms of inflammation and its resolution are of considerable interest. Recently, potent specialized chemical mediators derived from essential fatty acids were identified that actively promote inflammation resolution via novel proresolving and anti-inflammatory cascades (4). Originally, microparticles (MPs) were thought to be inert empty vesicles; however, their multiple roles and functional significance during inflammation is now being appreciated. MPs are detected in physiologic conditions, with increased numbers disseminated in multiple diseases including rheumatoid arthritis (5). Along these lines, anti-inflammatory properties of MPs shed from polymorphonuclear cells (PMNs) were uncovered (6, 7).

In this study, we investigated the temporal generation and properties of endogenous MPs produced in evolving self-limited inflammatory exudates in vivo and constructed a novel biomimetic system using human PMN-derived MPs to stimulate resolution of inflammation as demonstrated in TMJ disease. This biomimetic construction is highly advantageous as compared with other synthetic nanoparticle (NP) drug delivery systems that have adverse immunotoxic effects (8).

Materials and Methods

Endogenous MPs

Peritonitis was initiated in male FVB mice (6–8 wk; Charles River Laboratories) with zymosan A (1 mg i.p.), and peritoneal lavages were collected at indicated times. Exudate MPs were isolated by removal of leucocytes (4000 × g, 15 min) followed by ultracen trifugation (100,000 × g, 1 h) and quantified by flow cytometry. MPs were characterized with anti-CD11b (M1/70), CD54 (YN1), isotype control Abs (eBioscience), or CD45 (30-F11) (BD Biosciences) and Annexin A5 (BD Biosciences) for external phosphatidylinerine. For solid-phase extraction and liquid chromatography tandem mass spectrometry (LC-MS/MS)-based analyses, cold methanol was added to MPs (9).

Preparation of humanized nano-proresolving medicines

Human MPs were prepared (6) and added to thin lipid films in glass flasks (after organic solvent removal by rotary evaporation; 10 min, 25°C) containing fluorescein 1,2-dioleoyl-sn-glycero-3-phospho-1-serine-N-7-nitro-2-
1,3-benzonitril-4-yl (100 µg; Avanti Polar Lipids) and 7S, 8R, 17R-tri-hydroxy-docosa-4Z,9E,11E,13Z,15E,19Z-hexaenoic acid (aspirin-triggered resolvin D1 [AT-RvD1, 1 µg; Cayman Chemical] or e-[9,12]-benzo-oct-9-enoic acid (LXA4) (1 µg) (10) prepared for these studies by custom synthesis. Intercalation of AT-RvD1 or LXA4 analog and fluorescent phospholipid was performed by aqueous energy dissemination using a sonic dismembrator (output power 15 W, 15 min, 25°C; Fisher Scientific). Humanized NPs were layered on Sephadex G50 columns (Sigma-Aldrich) and fractions collected in 0.2 µm filtered PBS. Incorporation of AT-RvD1 and LXA4 analog was determined using LC-MS/MS and fluorescent phospholipid content confirmed by flow cytometry (BD FACSCanto II; BD Biosciences). NPs and MPs were sized using calibration beads (Corpuscular) by flow cytometry and conventional electron microscopy following negative staining (Tecnai G² Spirit BioTWIN; Harvard Medical School core facility).

Mediator lipomics

LC-UV/MS/MS-based mediator lipomics analysis was performed with an HPLC (Shimadzu LC20AD; Shimadzu)-UV (Agilent 1100; Agilent Technologies) coupled to a quadrupole ion-trap mass spectrometer (QTrap3200; Applied Biosystems) equipped with a C18 column (Agilent Eclipse Plus, 4.6 mm × 50 mm × 1.8 µm; Agilent Technologies). Acquisition was conducted in negative ionization mode, and lipid mediators (LMs) were profiled using scheduled multiple reaction monitoring (MRM) and identified using retention time, at least five to six diagnostic ions, and matching criteria (9). Esterified monohydroxy products were assessed in endogenous MPs following methanol/chloroform extraction of phospholipids and overnight saponification with 1 N potassium hydroxide in 90% ethanol. Samples were acidified and extracted with added internal standard d5-17-hydroxy-docosaheaxaenoic acid (HDHA; 1 ng) for LC-MS/MS–based lipomics as above.

For MP phosphatidylcholine analyses, LC-UV/MS/MS–based mediator lipomics analysis was performed with an HPLC (Shimadzu LC20AD; Shimadzu)-UV (Agilent 1100; Agilent Technologies) coupled to a hybrid quadrupole triple mass spectrometer (QStar XL; Applied Biosystems) equipped with a Phenomenex Luna C18(2) column (2 mm × 150 mm × 3 µm; Phenomenex). Mobile phase consisted of 0.5% ammonium hydroxide in methanol/acetonitrile and 0.1 M ammonium acetate (97:2:1, v/v/v) at 200 µL/min. Operating parameters and collision energies were optimized individually.

Peritonitis and wound healing

Human MPs or nano-proresolving medicines (NPRMs) (1 × 10^2–3 × 10^3) were given i.v. (or i.p. as indicated) prior to zymosan A (0.1 mg i.p.), and peritoneal leukocytes were assessed at 2, 4, or 12 h. In some experiments, mice were given d5-DHA (1 µg i.v.) prior to zymosan A (1 mg), and peritoneal MPs were collected at 4 h. Wound healing was assessed using an Electric Cell-Substrate Impedance Sensing 1600R system (Applied Biophysics) (11). Human epidermal keratinocytes (Lanza) were cultured on SW1E electrode arrays and, once confluent (∼8000 Ω, using 16 kHz), were wounded (64 kHz, 30 s). Cells were treated with buffer, AT-RvD1 NPRMs (10 nM), AT-RvD1 (10 nM), or the equivalent NP number.

TMJ inflammation

Mice were anesthetized (O₂: 1 L/min, isoflurane: 2.5%), and CFA was administered (10 µg; 20 µL) into the periarticular space of the left TMJ and 0.9% sterile saline (20 µL) into the right TMJ space (as in Ref. 12). Treatments were then delivered i.v. with buffer (100 µL PBS), AT-RvD1 (10 ng) NPRMs, or e-[9,12]-benzo-oct-9-enoic acid (10 ng) NPRMs. After 12 h, PMN infiltration was assessed in the TMJ by myeloperoxidase (MPO) activity by ELISA (Hycult Biotechnology).

Statistics

Data are mean ± SEM. Multiple group comparisons were made using one-way ANOVA followed by Dunnett’s or Bonferroni post hoc analysis. The p values < 0.05 were considered significant.

Results and Discussion

First, we profiled the time course of MP generation in self-limited acute inflammation (i.e., zymosan-induced peritonitis). The endogenous leukocyte-derived MPs were temporally generated in vivo in inflammatory exudates, with maximum MPs identified within the initiation phase, which gradually declined during the resolution phase corresponding with neutrophilic loss (Fig. 1A). Further characterization of these MPs followed by aqueous energy dissemination using a sonic dismembrator (output power 15 W, 15 min, 25°C; Fisher Scientific). Humanized NPs were layered on Sephadex G50 columns (Sigma-Aldrich) and fractions collected in 0.2 µm filtered PBS. Incorporation of AT-RvD1 and LXA4 analog was determined using LC-MS/MS and fluorescent phospholipid content confirmed by flow cytometry (BD FACSCanto II; BD Biosciences). NPs and MPs were sized using calibration beads (Corpuscular) by flow cytometry and conventional electron microscopy following negative staining (Tecnai G² Spirit BioTWIN; Harvard Medical School core facility).

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Annexin A5+ MPs by surface molecule expression demonstrated these were CD11b+, CD45+, and CD54+ (Fig. 1B). For identification criteria denoted, including mass/charge ratio (m/z) 245 and 273. Notably, endogenous MPs from exudates at indicated time points. Results are mean ± SEM (n = 3–7 per time point).

TO systematically address the LM profiles carried by endogenous MPs, LC-MS/MS–based metabolomics were performed. We discovered that endogenous MPs formed in inflammatory exudates contain esterified biosynthetic precursors of novel specialized proresolving mediators (Fig. 2A). For example, the levels of MP-associated hydroxydocosaheaxaenoic acids, namely 14-HDHA and 17-HDHA, were high during the initiation phase of acute inflammatory response, decreased during the peak of inflammation, and accumulated in resolution, the phase in which potent anti-inflammatory and proresolving LMs are biosynthesized (13). Fig. 2B shows a representative mass spectrum of 17-HDHA, with the diagnostic ions used for identification criteria denoted, including mass/charge ratio (m/z) 245 and 273. Notably, endogenous MPs were devoid of unesterified monohydroxy fatty acids, suggesting that once liberated from MP membranes, they are made available to leukocytes within the exudate.

Following i.v administration of deuterium-labeled d5-DHA for tracking, circulating d5-DHA is made rapidly available to exudates (14) and was incorporated into endogenous MPs generated during the onset of acute inflammation. Additionally, these MPs also contained enzymatic metabolites of d5-DHA, namely d5-17-HDHA and d5-14-HDHA, deuterated biosynthetic pathway biomarkers for D-series resolvins and maresins biosynthesis, respectively, which reflects activation of these new pathways and their H(p)DHA intermediates (Fig. 2C). These results implicate endogenous MPs as intercellular communicators that can deliver proresolving LM
precursors to inflammatory loci. Further experiments were performed to assess whether exogenous DHA was stored within MP phospholipids. When human PMNs were incubated with d₅-DHA, MPs were generated containing both d₅-DHA and d₅-HDHA esterified into phosphatidylcholine (Supplemental Fig. 1A, 1B). Noteworthy, both cytosolic and secretory phospholipase A₂ are induced during the resolution phase of inflammation (15). Secretory phospholipase A₂ added to resolving MPs liberated esterified precursors from MPs (Supplemental Table I).

Human PMN-derived MPs display anti-inflammatory properties via ALX/formyl peptide receptor 2, the receptor for LXA₄, Annexin-A1, as well as RvD1 (6, 16). Additionally, we demonstrated in this study that MPs enhanced efferocytosis (Supplemental Fig. 2) and contain precursors for proresolving LM, thus likely contributing to the beneficial properties attributed to these MPs. Because many biomaterials used for NP drug delivery can activate the circulatory system and cause nanotoxicity (for example, by uptake and activation of dendritic cells) (8), we sought new means to locally administer and activate proresolving cascades in vivo based on the endogenous MP system. Thus, newly constructed nanomedicines should possess multipronged agonist actions in resolution, activating endogenous ALX, releasing precursors for local proresolving mediators, as well as delivering their cargo of uploaded LM.

Harnessing human neutrophil-derived MPs as scaffolds, we constructed NPs containing either AT-RvD1 (4) or a stable analog of LXA₄ (10). Following enrichment procedures and energy-induced conversion of MP to NPs, preparations were layered onto size-exclusion chromatography columns to separate free unincorporated lipids from MP-associated lipids, and eluate fractions were collected and taken for analyses including flow cytometry. Characteristically, enriched NPs (Fig. 3A, blue dot plot) were smaller than their MP counterparts (Fig. 3A, red dot plot) and also contained fluorescent phospholipid (Fig. 3B, blue histogram). NP sizing was accomplished by flow cytometry using nanosphere calibration beads (Fig. 3C, 3D). Sizing was further validated using negative stain electron microscopy of MPs (Fig. 3E) and NPRMs (Fig. 3F). Both methods showed smaller, more uniform sizing of NPs following enrichment procedures. Prior to each experiment, incorporation of AT-RvD1 or the LXA₄ analog was determined using LC-MS/MS. Representative tandem mass spectrum of NP-associated AT-RvD1 (m/z 375.2) is shown from scheduled MRM of the m/z 375/215 transition pair at 7.4 min (Fig. 3G).

These humanized NPs were inherently anti-inflammatory, even without enriching with LM, counterregulating PMN infiltration in acute zymosan (0.1 mg) peritonitis by ∼25% following i.v. administration of 1 × 10⁷ NPs (Fig. 4A). A similar reduction in PMN influx was observed with 300 ng stable LXA₄ analog consistent with earlier findings (17). Remarkably, when the LXA₄ analog was incorporated into human NPs, they drastically limited PMN numbers by ∼60%, showing they possess additional anti-inflammatory properties. Importantly, 1 × 10⁵ NPs equated to an incorporation of 5.0–8.8 ng LXA₄ analog, effectively demonstrating that much lower amounts were needed locally to reduce PMN infiltration than analog alone. This proved dose dependent, with maximal NPRMs greatly limiting PMN recruitment (Supplemental Fig. 3A). Noteworthy, we found an inhibitory action on PMN recruitment when NPRMs were administered directly into the peritoneum, suggesting a direct action on resident macrophages, dampening their inflammatory response to zymosan (Supplemental Fig. 3B). We also assessed bioactivity of AT-RvD1–enriched NPs in murine peritonitis. Leukocyte recruitment and differential analyses were assessed at three separate intervals to quantify acute inflammatory response using self-limited inflammation (Fig. 4B). Local microbial administration resulted in a rapid increase in PMN infiltration, which peaked at 4 h postchallenge corresponding to the onset of inflammation. By 12 h, PMNs had declined, and the resolution interval (Rₐ) was calculated (i.e., time taken for maximal PMN to decrease 50%). NPs carrying AT-RvD1 drastically reduced PMN recruitment in microbial peritonitis, reducing maximal PMN infiltration from 9.4 ± 0.7 × 10⁶ to 4.0 ± 0.8 × 10⁶ and also shortened Rₐ from 7 h to ∼4.5 h (Fig. 4B).

Proresolving bioactions of these humanized nanomedicines were next evaluated in a keratinocyte wound-healing assay using in vitro epidermal abrasion (11). Following focal clearance of keratinocytes with an elevated electrical field pulse, keratinocyte healing from the perimeter into the clearance zone was assessed in real time by impedance sensing. This highly sensitive method indicated that AT-RvD1-containing
nanomedicines enhanced wound closure rates as compared with either nonenriched NPs or equimolar amounts of AT-RvD1 (10 nM), demonstrating their proresolving properties (Fig. 4C).

TMDs are a significant clinical problem, causing craniofacial pain (2). Effective treatment of pain arising from inflammation of joints and muscles remains an unmet medical need and is implicated not only in TMDs but also in many other human diseases. To this end, we evaluated whether these nanomedicines would confer protection against CFA-induced inflammation of the TMJ. Indeed, 10 ng AT-RvD1 NPRMs or ω-[9,12]-benzo-ω6-epi-LXA4 NPRMs drastically reduced the number of infiltrating PMNs into the inflamed TMJ 12 h after CFA-induced inflammation (Fig. 4D). Importantly, MPO levels in the contralateral TMJ were not elevated, and no significant differences were noted between buffer control and NPRM treatment groups (not shown). Of relevance, both RvD1 and RvE1 also attenuate inflammatory pain (18). Together, these results establish that biomimicking endogenous resolution mechanisms centered on anti-inflammatory and proresolving MPs, enhance the bioactions of potent LMs. NP delivery of AT-RvD1 or a stable analog of LXA4 prevented excessive neutrophilic infiltration to inflamed TMJs, thus circumventing ensuing granuloma formation and further joint destruction associated with overzealous leukocyte recruitment in this complex joint disease.

FIGURE 3. Humanized NPRMs: construction and characterization. A, Human PMN-derived MPs (red) were isolated and enriched with AT-RvD1 or ω-[9,12]-benzo-ω6-epi-LXA4 and fluorescent 1,2-dioleyl-glycerol-3-phospho-1-serine-N (7-nitro-2,1,3-benzoxadiazolo-4-yl). Enriched NPRMs were separated by size-exclusion chromatography and sized by flow cytometry (blue). B, Fluorescence incorporation into NPRM (blue histogram) was monitored by flow cytometry. C and D, NPRM sizing was determined using cytometry calibration beads. E and F, Sizing was also validated using electron microscopy of MPs and NPRMs following negative staining; calibration nanospheres are shown in the inset (F). G, Incorporation of AT-RvD1 into NPs was determined using LC-MS/MS with representative mass spectra.

FIGURE 4. NPRMs limit PMN infiltration to inflammatory sites, enhance wound healing, and are protective in TMJ. A, Peritoneal PMN infiltration was assessed 2 h after zymosan (100 μg i.p.). Mice were treated with vehicle, NPs (1 × 10⁶), LXA4 analog (300 ng), or LXA4 analog NPRMs (1 × 10⁷). B, Mice were given vehicle or AT-RvD1 NPRMs (1 × 10⁷ i.v.) before zymosan (100 μg i.p.), and the R₄ of acute inflammation was calculated. C, Wound healing of keratinocytes was assessed in vitro following treatment with vehicle, NPs, AT-RvD1 (10 nM), or AT-RvD1 (10 nM) NPRMs (n = 3). D, NPRMs limit PMN infiltration to CFA-inflamed TMJs. Mice administered CFA (10 μg, 20 μl, periaricular) to the left TMJ and saline (20 μl) into the right TMJ followed by i.v. treatment with buffer (100 μl PBS), AT-RvD1 (10 ng) NPRMs, or LXA4 analog (10 ng) NPRMs, and 12-h MPO tissue levels were assessed in CFA-inflamed TMJ (n = 3–7 per treatment group). Values are mean ± SEM. *p < 0.05, **p < 0.01.
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