In Vivo Stimulation of De Novo Collagen Production Caused by Cross-linked Hyaluronic Acid Dermal Filler Injections in Photodamaged Human Skin

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Objective: To determine whether endogenous synthesis of new extracellular matrix may contribute to the degree and duration of clinical benefits derived from cross-linked hyaluronic acid dermal filler injections.

Design: In vivo biochemical analyses after filler injections.

Setting: Academic referral center.

Participants: Eleven healthy volunteers (mean age, 74 years) with photodamaged forearm skin.

Interventions: Filler and vehicle (isotonic sodium chloride) injected into forearm skin and skin biopsy specimens taken 4 and 13 weeks later.

Main Outcome Measures: De novo synthesis of collagen, the major structural protein of dermal extracellular matrix, was assessed using immunohistochemical analysis, quantitative polymerase chain reaction, and electron microscopy.

Results: Compared with controls, immunostaining in skin receiving cross-linked hyaluronic acid injections revealed increased collagen deposition around the filler. Staining for prolyl-4-hydroxylase and the C-terminal and N-terminal epitopes of type I procollagen was enhanced at 4 and 13 weeks after treatment \((P<.05)\). Gene expression for types I and III procollagen as well as several profibrotic growth factors was also up-regulated at 4 and 13 weeks compared with controls \((P<.05)\). Fibroblasts in filler-injected skin demonstrated a mechanically stretched appearance and a biosynthetic phenotype. In vitro, fibroblasts did not bind the filler, suggesting that cross-linked hyaluronic acid is not directly stimulatory.

Conclusions: Injection of cross-linked hyaluronic acid stimulates collagen synthesis, partially restoring dermal matrix components that are lost in photodamaged skin. We hypothesize that this stimulatory effect may be induced by mechanical stretching of the dermis, which in turn leads to stretching and activation of dermal fibroblasts. These findings imply that cross-linked hyaluronic acid may be useful for stimulating collagen production therapeutically, particularly in the setting of atrophic skin conditions.

Arch Dermatol. 2007;143:155-163

Injectable dermal fillers are becoming increasingly popular for improving skin contour defects related to aging (wrinkles and lines), depressed acne scars, and other traumatic or congenital conditions. Among the most widely used temporary fillers in the United States is cross-linked hyaluronic acid. The first filler of this type was approved by the Food and Drug Administration in December 2003, and now, several cross-linked hyaluronic acid dermal fillers are commercially available.\(^1\) Of the 12 million cosmetic procedures performed annually in the United States, approximately 1 million currently involve this class of injectable fillers.\(^1\)

Hyaluronic acid is an endogenous polysaccharide found in highest concentrations in the skin and connective tissue.\(^2,3\) In the skin, polymers of hyaluronic acid can bind water, forming a viscous substance that assists in hydration and turgor.\(^3,4\) Accordingly, loss of hyaluronic acid with aging is associated with increased dehydration and wrinkling of the skin.\(^5\)

Since hyaluronic acid is rapidly degraded in the skin,\(^3,5\) chemical cross-linking of individual polymers provides increased stability.\(^3,6\) In the United States, one
form of cross-linked hyaluronic acid is available under the trade name Restylane (Medicis Aesthetics Inc, Scottsdale, Ariz), also known as nonanimal stabilized hyaluronic acid (NASHA). Nonanimal stabilized hyaluronic acid is one of the most widely used dermal fillers in the United States. It is purportedly long lasting because, in addition to the stabilizing effect of cross-linking, it absorbs increasing amounts of water while being slowly degraded.1,6 It as such, it has been suggested that hydration helps treated skin maintain volume, even while the implanted material is broken down. Clinically, the benefits of NASHA have been reported to last 4 to 12 months.1,6,7 This is at least twice as long as injectable collagen, the gold standard of dermal fillers.8

Because NASHA is relatively new, its biochemical effects in the skin are unknown. We surmised that changes in skin biology might occur in response to this filler. Normal skin is composed of an outer epidermis supported by an underlying dermis. The dermis consists mostly of secreted proteins, which collectively provide structural support for the skin and are known as the extracellular matrix. The major structural protein in the dermis is type I collagen, which comprises 90% of the dry weight of skin and diminishes with normal aging.1,12,13 We found that NASHA injections stimulate de novo production of type I collagen. Additionally, we found that this induction may be mediated by mechanical stretching and consequent activation of collagen-producing cells (fibroblasts) in the dermis.

METHODS

TISSUE SAMPLES

All subjects signed informed consents, and the University of Michigan institutional review board approved this study. All subjects were volunteers and in good general health. The study was performed in the University of Michigan Clinical Research Program in the Department of Dermatology. Exclusion criteria included use of immunosuppressive medications, active infection of the skin, history of herpes simplex infection or connective tissue disease, and pregnancy. In an initial study (June 2004 through November 2004), a single NASHA injection in photodamaged forearm skin increased type I procollagen secretion by an underlying dermis. The dermis consists mostly of secreted proteins, which collectively provide structural support for the skin and are known as the extracellular matrix. The major structural protein in the dermis is type I collagen, which comprises 90% of the dry weight of skin and diminishes with normal aging.1,12,13 We found that NASHA injections stimulate de novo production of type I collagen. Additionally, we found that this induction may be mediated by mechanical stretching and consequent activation of collagen-producing cells (fibroblasts) in the dermis.

The paired t test was used with 2-tailed P values and significance accepted as P < .05. Data are presented as average fold change ± 1 SE.

RESULTS

SUBJECTS

All 11 subjects had lightly pigmented skin, and on a 4-point clinical severity scale (none, mild, moderate, or severe), 8 had moderate photodamage on their forearms (eg, brown spots, lax skin, wrinkles, and/or uneven pigmentation),
while 3 had mild-moderate photodamage. Following injections of NASHA and the saline vehicle into forearm skin, subjects experienced no adverse events except mild injection site tenderness for 24 to 48 hours.

Immediately following injections, intradermal saline and NASHA were visualized on each patient’s arms as small bumps approximately 1.0 to 1.5 cm in diameter. After 4 and 13 weeks, we reliably located all saline and NASHA injection sites. Some NASHA-injected sites were still visible as small bumps (<1 cm), but the remaining NASHA- and saline-injected sites appeared flat.

INCREASED COLLAGEN SYNTHESIS IN NASHA-INJECTED SKIN

To begin assessing NASHA’s biological effects, we stained tissue samples for hyaluronic acid. Saline-injected samples appeared normal and stained positively for endogenous hyaluronic acid (Figure 1A). In contrast, NASHA-injected skin at 4 and 13 weeks demonstrated well-circumscribed spaces in the middle and lower dermis. These spaces contained residual filler material that stained positively for hyaluronic acid (Figure 1B). This staining was abolished when samples were pretreated with a hyaluronic acid–degrading enzyme (hyaluronidase), thus verifying the specificity of our staining procedure (Figure 1C).

Next, we stained tissue for markers of newly synthesized type I collagen. Since collagen is initially produced as a soluble precursor (called procollagen), we first used an antibody against the C-terminal domain of type I procollagen. This antibody stains intracellular and extracellular epitopes, and accordingly, we found increased intracellular and extracellular dermal staining in NASHA-treated samples compared with controls (Figure 2A). At 4 and 13 weeks, staining occurred particularly in areas surrounding the filler.

Similar to the C-terminal marker, we found increased staining in NASHA-injected samples at 4 and 13 weeks using an antibody against the N-terminal domain of type I procollagen. This antibody binds an intracellular epitope, and correspondingly, we observed increased intracellular staining, especially in cells embedded within connective tissue fibers surrounding the filler (Figure 2B). Intracellular staining also occurred in cells more proximal (adjacent) to the filler, but no staining occurred inside spaces containing the filler.

Finally, we stained for prolyl-4-hydroxylase, an enzyme that modifies proline residues in procollagen to allow stable assembly of mature type I collagen. This enzyme level is elevated within fibroblasts that are actively producing procollagen.20 In NASHA-treated skin at 4 and 13 weeks, staining for this marker was increased compared with controls and appeared similar to staining for the N-terminal antibody (Figure 2C).

To further evaluate these findings, we used real-time reverse-transcriptase polymerase chain reaction technology to quantify gene expression (mRNA) for types I and III procollagen. Type III procollagen associates with type I procollagen, and both are coordinately regulated in the skin.21,22 At 4 and 13 weeks, respectively, expression was increased a mean±SE of 10.5±2.4-fold (P = .003) and 17.6±6.9-fold (P = .04) for type I procollagen, and 7.9±1.8-fold (P = .004) and 11.6±4.6-fold (P = .045) for type III procollagen (data not shown).

EXPRESSION OF GROWTH FACTORS AND MATRIX METALLOPROTEINASES WITH NASHA TREATMENT

To investigate potential mechanisms underlying collagen induction following NASHA injections, we measured gene expression of growth factors known to stimulate cutaneous collagen deposition.16,21 Compared with controls, we found that expression for connective tissue growth factor and all 3 isoforms of transforming growth factor β was increased with NASHA injections.
At 4 weeks, each gene was significantly induced ($P < .05$), while at 13 weeks transforming growth factors β2 and β3 remained significantly upregulated.

We then measured gene expression of matrix metalloproteinases. These enzymes play an important role in balancing collagen production vs breakdown.24 For instance, collagenase 1 and collagenase 3 cleave mature collagen, while stromelysin 1 and gelatinase B further cleave collagen fragments.24,25 Altogether, these 4 enzymes are capable of degrading all components of dermal extracellular matrix. Compared with vehicle, we observed no statistically significant changes ($P > .05$) in mRNA levels for collagenase 1, collagenase 3, and stromelysin 1 at 4 or 13 weeks after NASHA treatment (data not shown). Gelatinase B mRNA expression was not significantly changed at 4 weeks ($P = .07$) but exhibited a statistically significant elevation of mean±SE 8.9±3.3-fold at 13 weeks ($P = .04$). However, immunostaining did not demonstrate significant changes ($P = .09$) in gelatinase B protein expression at 13 weeks (data not shown).

We also examined gene expression of tissue inhibitors of matrix metalloproteinases, which are endogenous proteins that prevent excessive extracellular matrix breakdown.24 In NASHA-treated skin, we observed increased expression of tissue inhibitor of matrix metalloproteinases 1, 2, and 3 at 4 weeks ($P < .05$ for each) (Figure 3B).

**FIBROBLASTS DEMONSTRATE A BIOSYNTHETIC PHENOTYPE WITH NASHA INJECTIONS**

To further investigate mechanisms for collagen induction by NASHA treatment, we examined fibroblast morphologic characteristics for stretching, a finding that correlates with increased collagen synthesis.19,26,27 To identify dermal fibroblasts, tissue sections were stained for the C-terminus of type I procollagen (as first depicted in Figure 2A). At 4 weeks, each gene was significantly induced ($P < .05$), while at 13 weeks transforming growth factors β2 and β3 remained significantly upregulated.

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Figure 2A). In NASHA-treated skin at 4 and 13 weeks, we observed many stretched fibroblasts embedded in connective tissue fibers surrounding spaces that contained NASHA (Figure 4A). Some cells were directly adjacent to these spaces, but none were inside. Many stretched fibroblasts contained abundant rough endoplasmic reticulum, indicating a heightened state of protein synthesis (Figure 4B). Compared with controls, these cells also had more surface area contacting nearby collagen fibers. In saline-treated skin, dermal fibroblasts did not possess stretched shapes or conspicuous rough endoplasmic reticulum (Figure 4).

Given these observations, we cultured fibroblasts with and without NASHA added to collagen films that mimic dermal extracellular matrix (data not shown). In the presence of collagen alone, fibroblasts were distributed evenly. In cultures containing NASHA, the filler material was localized to scattered pockets (as seen in vivo), and fibroblasts were found surrounding the filler. No cells were identified within the filler, suggesting that fibroblasts do not preferentially populate or bind the filler.

It is generally assumed that many dermal fillers improve the appearance of skin by occupying physical volume. Indeed, we visualized the presence of injected NASHA in skin, suggesting that this filler’s effects are derived in part from space filling. To further investigate potential mechanisms for this filler’s long-lasting cosmetic benefits, we assessed the biological response of skin to NASHA. We found that NASHA injections induce type I collagen production in photodamaged forearm skin. Currently, there is no evidence to suggest that biological responses fundamentally differ in skin from various anatomic sites. As such, it is likely that induction of type I collagen enhances NASHA’s clinical duration in facial skin, where the filler is most commonly injected.

We observed increased intracellular and extracellular immunostaining for type I procollagen synthesis in NASHA-treated skin. This pattern is consistent with the production of type I collagen, a protein that is synthesized inside cells and secreted into the surrounding

Figure 3. Cross-linked hyaluronic acid injections induce gene expression of profibrotic growth factors and tissue inhibitors of matrix metalloproteinases in human skin in vivo. Total messenger RNA was extracted from skin injected with nonanimal stabilized hyaluronic acid (NASHA) or vehicle, and transcripts for the indicated genes were quantified using real-time reverse-transcriptase polymerase chain reaction. A, Expression for profibrotic growth factors, including connective tissue growth factor (CTGF) and the 3 isoforms of transforming growth factor β (TGF-β1, TGF-β2, and TGF-β3). B, Expression for 3 tissue inhibitors of matrix metalloproteinases (TIMP-1, TIMP-2, and TIMP-3). Data at 4 and 13 weeks are presented. Data for controls (skin treated with isotonic sodium chloride vehicle) are normalized to 1, and data for NASHA-injected skin are depicted as mean ± SE–fold. *P<.05.
Figure 4. Fibroblasts exhibit a stretched morphologic shape and synthetically active phenotype in skin treated with nonanimal stabilized hyaluronic acid (NASHA). Fibroblasts were visualized in skin injected with isotonic sodium chloride vehicle (left images) or NASHA (right images). Shown are representative tissue sections at 4 weeks after treatment. Open spaces (asterisks) in the NASHA images are consistent with areas that contained filler material. A, Tissue sections were stained for the C-terminus of type I procollagen (as first depicted in Figure 2A), and positively stained fibroblasts (arrows) appear dark red. Cell nuclei were counterstained with hematoxylin (blue) (original magnification ×40). B, Fibroblasts were examined with transmission electron microscopy. Daggers denote collagen fibers/fibrils in the extracellular matrix. Arrows denote rough endoplasmic reticulum, which are intracellular structures involved in synthesizing proteins, including collagen. These are shown at higher power in the insets (main panels original magnification ×2200; insets ×5300).
extracellular matrix. The shape and localization of positively stained cells were consistent with fibroblasts, the major producer of collagen in skin. We also found that gene and protein expression for procollagen remained elevated at least 13 weeks, suggesting that NASHA continually activated collagen synthesis pathways in the skin.

We considered that receptor-mediated interaction with injected NASHA may be able to stimulate fibroblasts. Fibroblasts can bind endogenous hyaluronic acid through various receptors, including CD44, the receptor for hyaluronan-mediated motility, intercellular adhesion molecule, and others. Binding to hyaluronic acid has been implicated in cellular activation, migration, inflammatory activity, and other processes. In vivo and in vitro, we observed that fibroblasts preferentially adhered to collagen matrix rather than to NASHA. While these observations do not completely rule out a direct stimulatory role for injected NASHA, they suggest that cellular binding to NASHA does not occur to an appreciable degree and, therefore, is not likely involved in inducing collagen production.

Our findings instead suggest that mechanical tension may play a critical role in stimulating collagen synthesis. We found mechanically stretched fibroblasts in extracellular matrix areas surrounding spaces occupied by NASHA. In vivo, these stretched cells were localized near the filler, but not always directly contacting the material (Figure 2 and Figure 4). This observation, together with our in vitro findings, suggests that NASHA injections alter cellular production of collagen by stretching existing collagen fibers. This stretching, in turn, may impose mechanical tension on nearby fibroblasts, which interact with collagen fibers through cell surface integrin receptors.

Indeed, increased mechanical tension in extracellular matrix has been shown to induce morphologic stretching of fibroblasts and initiation of collagen synthesis. In contrast to cells in relaxed substrates, fibroblasts cultured in mechanically tense collagen lattices assume a stretched, spindlelike shape rather than appearing short and round. These fibroblasts reorganize their actin cytoskeleton so as to align themselves along lines of tension. Furthermore, stretched fibroblasts increase the production of connective tissue components such as types I and III collagen. It is thought that this reflects a dynamic cellular response for counteracting extrinsically applied tension.

Similarly, mechanical tension is maintained in younger skin because intact collagen fibers provide a stable scaffold to which fibroblasts can bind. In contrast, photodamaged older skin contains a greater proportion of fragmented collagen. Fragmentation reduces the structural integrity of the extracellular matrix, resulting in less mechanical tension on fibroblasts and, hence, the appearance of “collapsed” (spherical) fibroblasts and reduction of collagen production. Since NASHA was localized to discrete areas within photodamaged skin, we believe that NASHA may preferentially flow into areas containing fragmented fibers, since these regions may be more accommodating. The introduction of NASHA may “push” on existing fibers and thereby create a more rigid scaffold that approximates younger dermis. This provides increased mechanical tension, stimulating fibroblasts to produce new, intact collagen (Figure 5).

In addition, we found that NASHA injections may promote collagen synthesis by inducing connective tissue growth factor and transforming growth factor β. These profibrotic growth factors stimulate collagen production in fibroblasts and play a key role in connective tissue production during wound repair. Although the magnitude of induction was relatively modest, small amounts of growth factors often produce biologically significant effects. As such, production of growth fac-
tors likely contributes to new extracellular matrix synthesis in NASHA-treated skin.

Finally, we considered the possibility that NASHA injections may stimulate wound repair mechanisms in the skin. Several dermatologic cosmetic procedures, such as carbon dioxide laser resurfacing and microdermabrasion, stimulate collagen production by inducing wound healing. The early stages of wound healing are characterized by inflammation and dermal collagen degradation by matrix metalloproteinases. In later stages, breakdown of collagen is replaced by deposition of new collagen. This remodeling is associated with improved appearance of aged skin. In the present study, our earliest skin samples were taken at 4 weeks. Since this would correspond to later stages of wound healing, we cannot completely eliminate wound repair responses as contributing to collagen production in NASHA-treated skin. However, based on expression of matrix metalloproteinases and their regulators (tissue inhibitors of matrix metalloproteinases), collagen deposition in NASHA-treated skin may be promoted in part by reduced collagen breakdown after 4 weeks.

Overall, our findings indicate that NASHA injections induce robust collagen production through several potential mechanisms, including the mechanical stretching of fibroblasts, stimulation of growth factors, and inhibition of collagen breakdown. Of these, mechanical stretching may be the most important. This is because mechanical stretching has been shown to stimulate fibroblasts to produce growth factors and tissue inhibitors of matrix metalloproteinases while also inhibiting expression of matrix metalloproteinases. Thus, mechanical stretch may act as a proximal stimulus that accounts for many of our observations.

To our knowledge, NASHA is the first hyaluronic acid filler to clearly demonstrate substantial and sustained induction of collagen synthesis in the dermis. It remains to be seen whether other hyaluronic acid fillers, such as hylan B (sold as Hylaform and Hylaform Plus; Inamed Aesthetics, Santa Barbara, Calif), another form of NASHA (sold as Captique; Genzyme Corporation, Cambridge, Mass), or a recently approved version of cross-linked hyaluronic acid (sold as Juvederm; Allergan Inc, Irvine, Calif), can also stimulate collagen deposition in skin. Decreased collagen levels likely contribute to wrinkle formation, and as such, the stimulation of collagen production by NASHA may explain in part this filler’s cosmetic benefits.

Furthermore, histologic studies indicate that injected NASHA lasts 6 to 9 months in skin. This correlates well with NASHA’s clinical duration, suggesting a predominantly volume-derived effect during this time. However, as more NASHA injections are received in a particular area of skin over time, we predict that collagen will accumulate at that location. This is because the half-life of dermal collagen is estimated to be 15 years. Thus, although it is unclear whether a single NASHA injection stimulates enough collagen to create noticeable clinical changes, we hypothesize that collagen accumulation from multiple NASHA injections over time may yield durable cosmetic effects. Long-term studies correlating biochemical changes to observable clinical improvements may clarify this.

Finally, our findings suggest that cross-linked hyaluronic acid may have application as a stimulator of collagen in conditions of collagen deficiency, including atrophic skin disorders (eg, human immunodeficiency virus–related lipodystrophy or steroid-induced dermal atrophy). Additionally, in fibrotic conditions such as scleroderma or keloids, we suggest that mechanical stretch may be a potential pathologic mechanism worth investigating in future studies.

Accepted for Publication: August 9, 2006.
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Author Contributions: Drs Wang and Garza contributed equally to this article. Drs Wang and Fisher had full access to all of the data in the study and take responsibility for the integrity of the data and the accuracy of the data analysis. Study concept and design: Garza, Kang, Varani, Orringer, Fisher, and Voorhees. Acquisition of data: Wang, Garza, Kang, Varani, and Fisher. Analysis and interpretation of data: Wang, Garza, Kang, Varani, Orringer, Fisher, and Voorhees. Drafting of the manuscript: Wang. Critical revision of the manuscript for important intellectual content: Wang, Garza, Kang, Varani, and Fisher. Funding/support: Medicis Aesthetics donated cross-linked hyaluronic acid–containing syringes for research purposes but had no involvement in the design or conduct of the study or in the collection, management, analysis, and interpretation of the data. Medicis was not involved in the preparation or review of the manuscript. This study was supported by the University of Michigan Department of Dermatology Cosmetic Research Fund; grants 5T32 AR007197 (F.V.W.) and 1K24 AR01259 (S.K.) from the National Institutes of Health, Bethesda, Md; and the Babcock Research Endowment, University of Michigan, Ann Arbor.

Acknowledgment: We thank Laura VanGoor, BFA, for assistance with graphic material; Ted Hamilton, MS, for assistance with statistical analysis; and Craig Hammerberg, PhD, for technical assistance.

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