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# Magnetite Tattoos

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**Background and Objectives:** Tattoo removal is a significant problem. The extraction of magnetite ($Fe_3O_4$) ink tattoos by a magnetic field was investigated, with and without Q-switched laser treatment.
**Study Design/Materials and Methods:** Magnetite particles (1.4 μm) were used to make mature, black skin tattoos on hairless albino rats. A Q-switched ruby laser (QSRL) 3.5 J/cm$^2$, 6.5-mm spot size, 40-nanosecond pulse width was used for treatment. Permanent magnets (1.4 T, 6-mm diameter) were tested to extract the magnetite particles, alone and after QSRL. Lightening of treated tattoos was measured from digital photographs, and the amount and distribution of magnetite in skin biopsies was scored blindly.
**Results:** External application of magnets on mature magnetite tattoos without prior QSRL treatment, did not significantly extract, lighten, darken, or change their histologic appearance. A magnetic field applied immediately after QSRL treatment extracted some ink when epidermal injury was present, and caused significant redistribution of magnetite into the upper dermis with vertical banding along magnetic field lines. When applied for 3 weeks following QSRL, magnets caused darkening of tattoos.
**Conclusions:** Magnetite skin tattoos can be manipulated by external magnets, especially after Q-switched laser treatment. Magnetically-extractable tattoos may be feasible. Lasers Surg. Med. 31:121–128, 2002.
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**Key words:** ferric oxide; ink; magnet

## INTRODUCTION

Tattooing is an ancient art, dating back as early as 12000 BC [1], when ash was rubbed into skin incisions. Puncture tattooing later became popular and is practiced even today. Modern tattoo inks cover a wide pallet of colors and use different tattoo "inks." Today, about one in five young adults in the US have been injected with these substances, by people with little or no medical training.

The desire to remove tattoos is probably as old as their existence. The fraction of tattooed people who will seek tattoo removal is unknown, but substantial. The earliest report of tattoo removal was by Aetius, a Greek physician who described salabrasion in 543 AD [2]. Grossly destructive methods such as dermabrasion, Ar or $CO_2$ laser vaporization are still used [3–6], but they have a high risk of scarring. Leon Goldman first reported laser tattoo removal in 1965 and then in 1967 [7,8] using a Q-switched ruby laser (QSRL). Later cases reported by Reid et al. [9] revealed good results with QSRL, particularly in black and amateur tattoos. These results were further refined based on concepts of selective photothermolysis [10]. Because of the variety of tattoo ink colors, a variety of laser wavelengths are necessary. High-energy Q-switched ruby (694 nm), alexandrite (755 nm), Nd:YAG (1,064 nm), and frequency-doubled Nd:YAG (532 nm) lasers are now used, which emit visible and near-infrared light pulses ranging from about 10–100-nanosecond duration [11–14].

Before laser treatment, tattoo ink particles are found within dermal fibroblasts and mast cells, predominantly in a perivascular location [15]. The treatment mechanism for Q-switched lasers involves selective rupture of these cells, breakdown of tattoo ink particles, and ink removal by transepidermal elimination and/or lymphatic transport [16,17]. The risk of scarring after Q-switched laser treatment is substantially lower than after excision, dermabrasion, or $CO_2$ laser vaporization. However, much of the ink remains inside the body, either in regional lymph nodes or as a lightened, residual tattoo in the skin. The number of Q-switched laser treatments for tattoo "removal" depends on the type of tattoo ink, body location, and laser. Amateur tattoos made with carbon (ash, graphite, India ink) respond best, typically clearing in most patients after four to six treatments. Multicolored tattoos on the extremities tend to respond poorly. In our experience, less than half of these tattoos can be cleared in less than ten treatments, regardless of the Q-switched lasers used.

Tattoo inks are the least-regulated substance routinely injected into people in our society. The purity, pharmacology, biodistribution, and identity of most inks are unknown. None are approved by the Food and Drug Adminstration (FDA) [18]. New bright-colored inks are being introduced at an unknown rate, and are often those most difficult to remove by laser treatment. Although most tattoos appear to be well tolerated, there are reports of infection, photosensitivity, acute, and chronic hypersensitivity reactions [19–22]. Tattoo ink is permanently taken up in lymph nodes in addition to the intended target organ, skin. The long-term health risk of tattooing is unknown. The present situation may eventually lead to significant problems, when luck runs out.

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In view of the history, popularity, limited safety data, and limited treatment options for tattoos, it is remarkable that no efforts to develop safe, removable tattoo inks have been reported. Theoretically, tattoo inks could be made, which are sterile, non-toxic, and designed to be easily removed. Several approaches for the planned removal of tattoo ink particles from the skin have recently been suggested [23]. We report here a small animal study of a novel candidate "ink" and removal method. Magnetite ($Fe_3O_4$) is a non-toxic, insoluble, stable, jet-black compound, which can be manipulated by both lasers and external magnetic fields.

## MATERIALS AND METHODS

Magnetite $Fe_3O_4$, (Pea Ridge Iron Ore Company, Inc.; item code M-25; Sullivan, MO) particles 1.4 μm in diameter were mixed in glycerin (20% w/w), which provides sufficient viscosity for a suspension. The particle size was choosen to be within the .5–4 μm range typical skin tattoos [16]. The suspension was used to make magnetite tattoos. A standard oscillating tattoo machine with needle array for commercial tattooing was used (Spaulding and Rogers, Albany, NY), set to a puncture depth of ~1 mm. Fifteen hairless, albino rats were used for the study. The animals were anesthetized by a combination of ketamine, 45–75 mg/kg and xylazine 10–20 mg/kg, given intramuscularly. A total of 72 tattoos, each 1 cm × 3 cm, were made on the backs of the rats, and allowed to mature for 4 months before any treatment was done. A QSRL (QSRL, described below) and permanent magnets were investigated as agents for potentially clearing the tattoos, alone and in combination.

The tattoos were divided into six groups. Twelve tattoos per group were studied grossly and histologically after the following manipulations: tattoos alone (no treatment, control); 1 hour post QSRL alone; 1 hour post QSRL and magnet; 3 weeks post QSRL alone; 3 weeks post QSRL and magnet applied for 3 weeks; short-term (1 hour) application of magnet alone. The QSRL (Spectrum RD1100; Palomar Medical Products, Inc., Burlington MA) had a nominal pulse duration of 30 nanoseconds and wavelength of 694 nm. Treatment exposure fluence was 4.5 J/cm$^2$ with a 6.5-mm spot size, and partial overlapping of the pulses to avoid skip areas of treatment. Permanent magnets of 1.4 T (Neodymium alloy, a gift from J. Dallarosa, Coherent, Inc., Santa Clara, CA) 600 mg and 6-mm diameter were also used, applied to the skin surface overlying the tattoos alone, and in combination with prior laser treatment. These are among the most powerful small permanent magnets that are readily available. A thin layer of tegaderm tape was applied between the magnet and the tattooed skin, to avoid direct contact of the skin with the magnet.

Short-term application of magnets (1 hour) was achieved by directly placing the magnet on the skin with tegaderm tape in between, while the animal was still anesthetized. Attractive force between the magnets and tattooed skin was easily perceived, and were sufficient to "stick" the magnets to the skin surface (Fig 1c). Long-term application of magnets (3 weeks) was achieved by adhering the magnet to a thin plastic disc 1 cm in diameter, and suturing the disc to the skin surrounding the magnetite tattoo (Fig 1e). Wound care after placing tattoos and after laser treatment consisted of cleansing and daily application of bacitracin ointment for 7 days, after which any epidermal injury had healed.

## DATA ANALYSIS

### Photographic Analysis

Nikon Digital camera (Nikon Digital, Channel RGB, E950, 6V, 0.8 A NTSC, Japan) was used to take pictures before treatment, 1 hour after treatment, 1 week post treatment, 2 weeks post treatment, and 3 weeks post laser treatment. As a measure of relative lightening or darkening, a pixel histogram analysis (Corel Photo Paint 8, Channel RGB, Windows NT) was performed from the digital images. Relative lightening or darkening was measured by the mean pixel value in photographs within the region of interest (ROI) defined by the tattooed area of skin. Pixel values ranged from 0 to 255 because of the standard 8-bit digitization, with 0 being the maximum dark value and 255 being the maximum bright value. Pixel values were used for statistical analysis (see below).

### Histologic Analysis

Six millimeters punch biopsies were obtained from treated and control sites at the following time points: before treatment; 1 hour post treatment; 1 week post treatment; 2 weeks post treatment; and 3 weeks post treatment. The biopsy wounds were closed with 4-0 silk sutures, which were removed after 1 week. Biopsy samples were immediately fixed in 10% formalin, then processed routinely and embedded in paraffin. Vertical sections were obtained and stained lightly with eosin only, in order to easily see the magnetite tattoo ink particles. Standard H&E staining of sections were also performed. The sections were blindly analyzed by three histopathologists for the following features: amount of ink in the papillary dermis on a scale of 0–5, with 5 being a maximum; the presence of alignment and vertical streaking pattern of magnetite particles on a scale of 0–5, with 0 being no streaking and 5 being the most obvious streaking pattern.

### Statistical Analysis

Measures included the pixel values from each tattoo image, ratings of ink in the papillary dermis, and ratings of vertical streaking pattern in the papillary dermis. The mean, standard deviation, and median of pixel values for each treatment condition were calculated. To compare the non-parametric data, Kruskal–Wallis tests were used. After Kruskal–Wallis tests, we performed post-hoc Mann–Whitney test, and the global $P$ value was corrected by Bonferroni test ($p < 0.05$).

## RESULTS

### Tattoos Alone

The magnetite made dark black or blue-black skin tattoos, which healed easily and were stable. No evidence

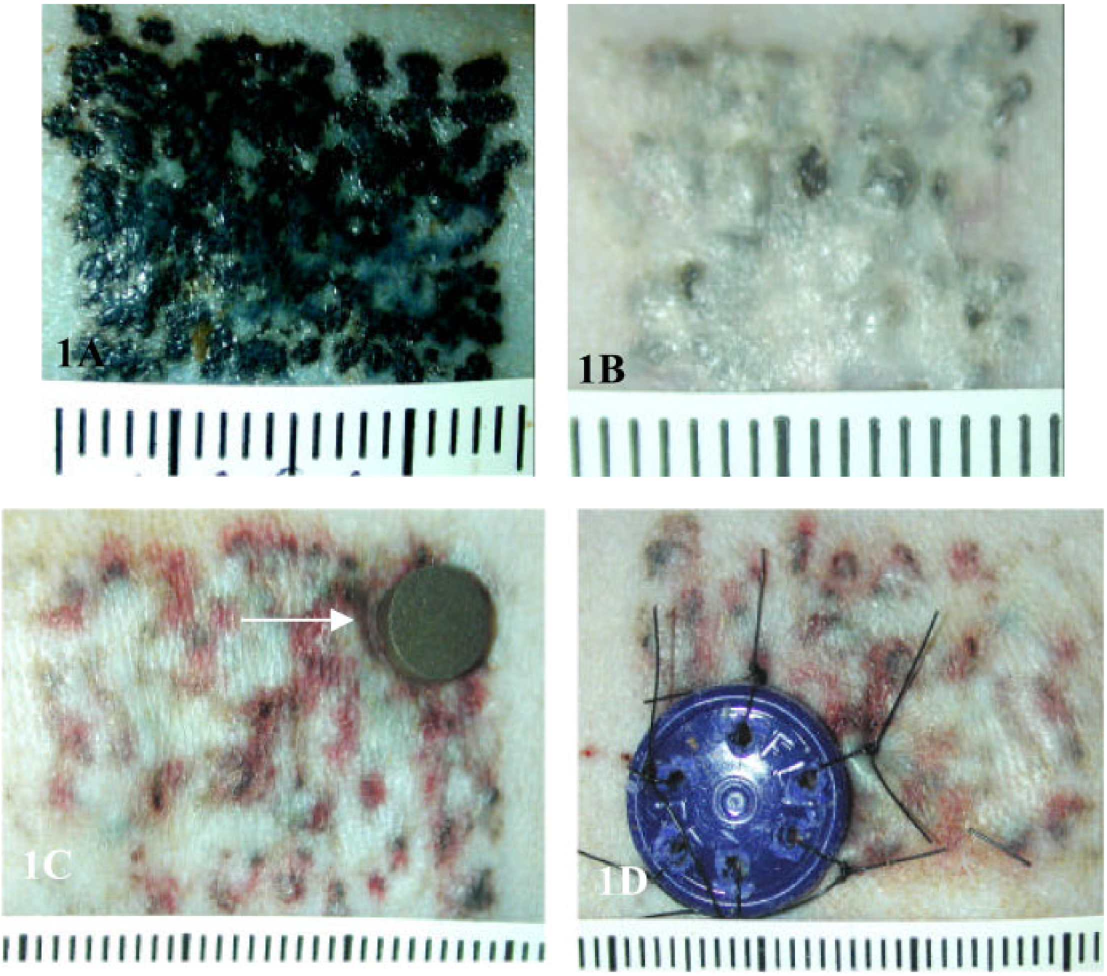

Fig. 1. **Appearance of the magnetite tattoos.** **A**: Untreated mature tattoo. **B**: Immediately after QSRL treatment, showing immediate whitening. **C**: Magnet affixed to a magnetite tattoo, by magnetic attraction. **D**: Magnet sutured in place after laser treatment, for 3-week application.

of inflammation or scarring was noted at 4 month follow-up after making the magnetite tattoos. The average brightness as determined by pixel value of untreated tattoos, was 97 (Fig. 1A). Histological analysis showed ink predominantly in the mid to deep reticular dermis, where the ink particles were in small clusters without any particular alignment (Fig. 2).

### Short-Term Application of Magnets Alone

Magnets applied for 1 hour did not significantly affect tattoo brightness ($p = 0.285$) compared to untreated tattoos. Biopsies taken 1 hour after the application of magnets on mature tattoos without laser treatment, revealed

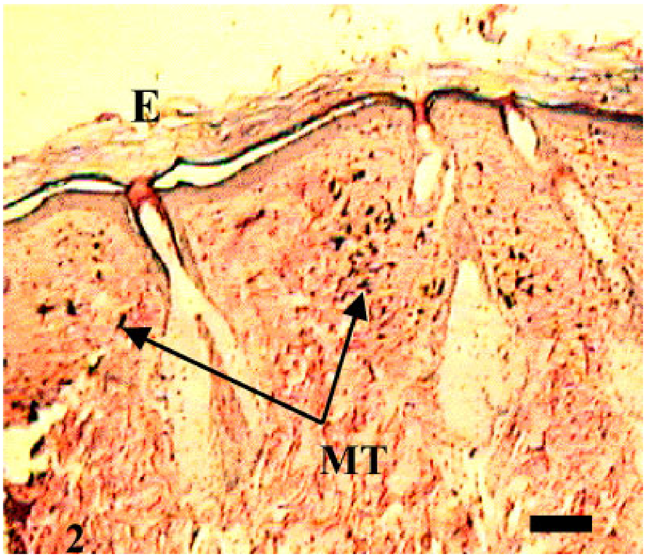

Fig. 2. **Histological appearance of a 4 month old magnetite ink tattoo.** There is a predominance of ink (*arrows*) in the middle and deep reticular dermis, without a streaking pattern. *Scale bar* 100 µm, 4*x*, eosin stained. MT, Magnetite tattoo ink.

no significant change in particle distribution ($p = 0.133$) compared with untreated stable tattoos (Fig. 3A). In 4 out of 12 biopsy samples, magnets produced a minor degree of vertical streaking pattern, which was not statistically different from untreated tattoos ($p = 0.071$; see Fig. 7).

### Short-Term Application of Magnets Post QSRL Treatment

Immediate whitening of the area was seen upon treatment with QSRL (Fig. 1B). However, in small areas of the tattoos, QSRL treatment caused local epidermal damage, for example, epidermal erosions with a small amount of blood or serous fluid appearing at the skin surface. External application of magnets for 1 hour following a QSRL treatment, did not significantly affect the brightness of tattoos ($p = 0.33$; Fig. 5) compared with laser alone. At sites with epidermal damage, magnetite ink particles were extracted (removed) from the skin by magnet application. This was evident by the appearance of ink on the under surface of the tegaderm tape, which occurred only where the magnet was applied. Epidermal damage was necessary for ink to be extracted by magnets. Histologically, magnet application for 1 hour after QSRL caused a significant upward migration of magnetite ink in the papillary dermis. Compared with control, there was a predominance of ink particles in the papillary dermis ($p < 0.0001$; Fig. 5) at or close to the dermo–epidermal junction in 11 out of 12 samples (Fig. 3B). Coarse dermal spaces similar to those previously described after QSRL treatment of tattoos [16] and a sparse dermal infiltrate were also present. Areas with epidermal damage showed ink extending to the surface of the skin (Fig. 3C). A

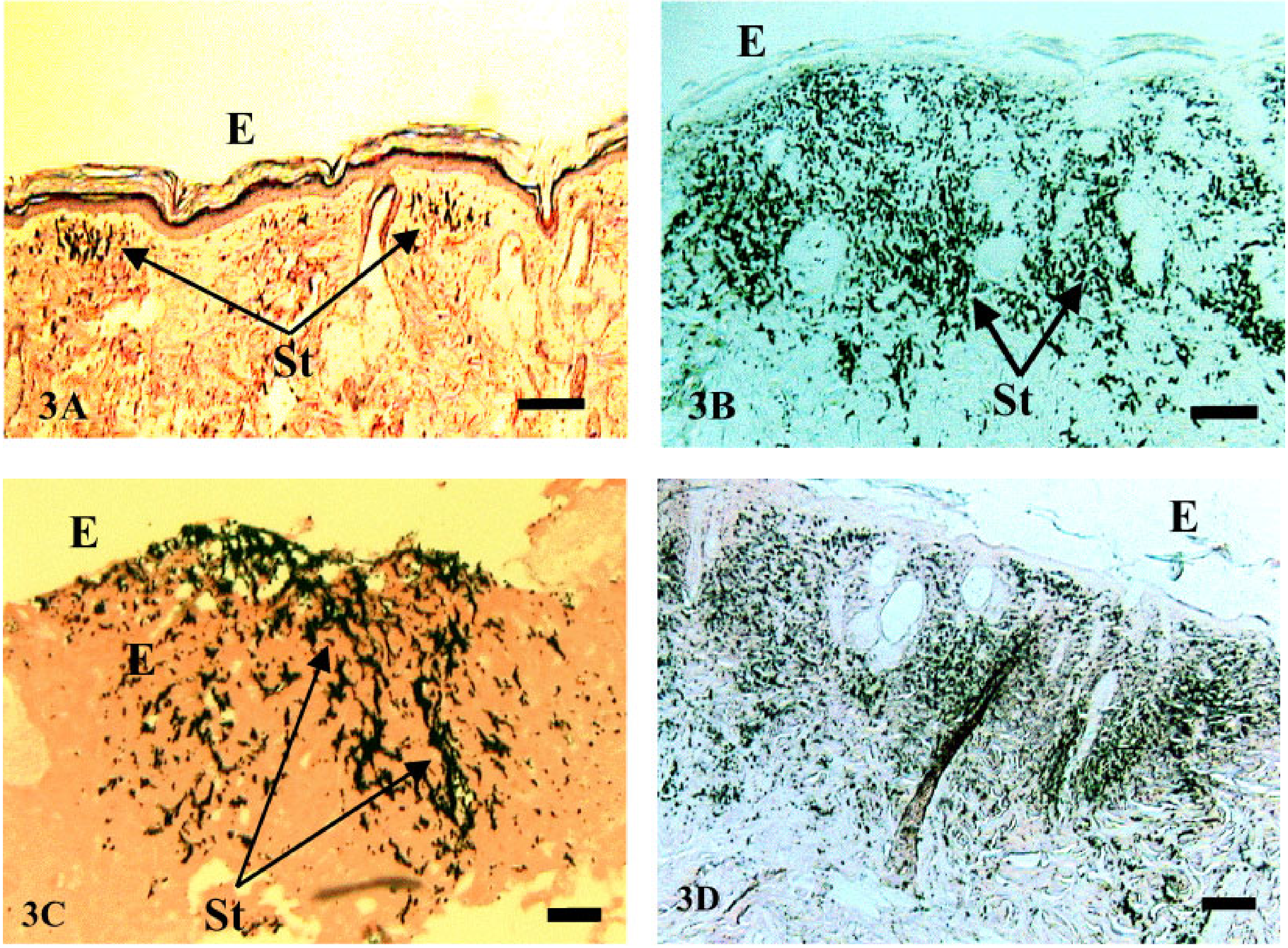

Fig. 3. **Histological appearance of tattoos treated with QSRL and magnets. A**: Mature magnetite ink tattoo treated with magnets alone. There is no significant difference in the amount and distribution of ink compared to Figure 2, however, some streaking characteristic of magnet application is seen (*arrows*). **B**: One hour after QSRL treatment followed by magnet application, showing increased ink in the papillary dermis under an intact epidermis. **C**: One hour post QSRL treatment followed by magnet application without an intact epidermis. The ink particles are streaked and extend to the tissue surface. **D**: Three weeks post QSRL treatment and magnet application for 3 weeks. Ink is significantly retained in the papillary dermis close to the DEJ, compared with controls. *Eosin stain*, *scale bar* 100 µm, 4*x*. E, epidermis; St, streaking.

characteristic vertical streaking pattern of the ink particles was seen in the dermis only after magnet application, apparently along magnetic field lines (Fig. 3B, 3C). This streaking pattern was not seen in the tattoos treated with laser alone ($p < 0.0001$; Fig. 6).

### QSRL Treatment Alone

One hour after QSRL treatment of tattoos, there was cellular debris, but no magnetite particles on the under surface of the tegaderm tape. Biopsies revealed predominance of ink particles mostly in the reticular dermis with obvious focal disruptions of dermis and epidermis, and an inflammatory infiltrate (Fig. 4A). Laser treatment caused local dispersion of ink clusters compared with the untreated tattoos, but unlike sites after magnet application, there was no streaking pattern or vertical alignment of the particles. Three weeks after QSRL treatment alone, tattoos appeared slightly lighter (Fig. 1D). However, by statistical analysis of the pixel values, the lightening was not significant ($p = 0.214$). Complete healing of the treated area was seen, without any evidence of scarring, infection, granulation tissue formation, or skin textural changes. Biopsies taken 3 weeks after QSRL treatment, showed distribution of the ink particles throughout the reticular dermis similar to untreated tattoos. No streaking pattern was seen (Figs. 4B and 6).

### Long-Term Application of Magnets Post QSRL Treatment

Application of magnets for 3 weeks after laser treatment, caused significant darkening of the tattoo under the magnet ($p < 0.0001$), compared to tattoos treated with laser alone. No particles were detected on the under surface of the magnet. Histological analysis showed ink predominance in the papillary dermis and close to the dermo–epidermal junction in 10 out of 12 samples, with some vertical streaking pattern (Figs. 3D, 6). Consistent with the gross appearance of healing without scar, there was no residual inflammation or fibrosis.

## DISCUSSION

This study produced several novel findings, with interesting implications. We have shown that magnetite tattoos can be grossly and microscopically manipulated *in vivo* by external magnetic fields. After a Q-switched laser treatment, which “frees” the particles from cells in the dermis [16,17,24], the ink particles were dragged through the dermis toward a magnet at the skin surface. In the dermis, they lined up along what appear to be magnetic field lines. Some ink was physically extracted within an hour, if the epidermis was not intact. Therefore, magnetite particles appear to traverse the dermis until they reach an intact dermo–epidermal junction, which acts as a barrier. Magnets applied for several weeks after laser treatment caused a darker tattoo, by bringing more of the ink into the upper dermis.

These findings point to the remarkable fact that micrometer-sized particles can be rather easily forced to traverse the dermis. The broad implication for tattoo removal, is that a Q-switched laser treatment followed by any adjunctive treatment, which enhances and/or forces particle motion, could provide a better way to remove tattoos. While magnetic fields were convenient and effective for our experiment, this is not the only means for forcing particle motion. For example, it may be possible to employ massage and/or to wash particles through the dermis by directed flow of extracellular fluid. We are presently trying this approach because it may work with essentially any tattoo ink. In our study, the epidermis or dermo–epidermal junction apparently blocked extraction of tattoo ink. Therefore, intentional removal of the epidermis followed by forced-ink extraction may also be especially effective. Ort et al. [25] recently reported that

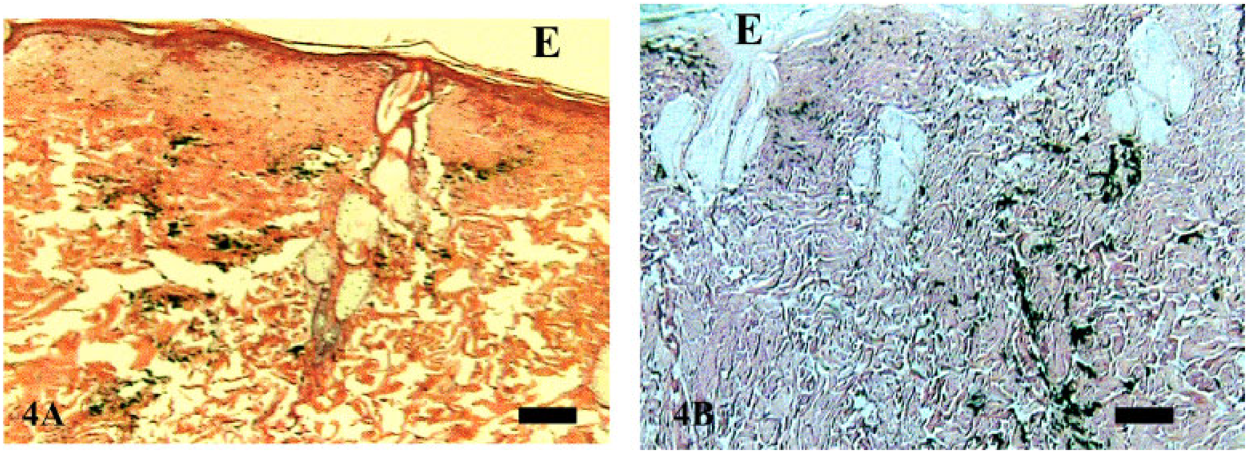

Fig. 4. **Histological appearance of tattoos treated with QSRL alone. A**: One hour post QSRL treatment, ink particles are dispersed throughout the reticular dermis and there is no streaking pattern. **B**: 3-weeks post QSRL treatment, there is significant clearing of ink from the papillary and reticular dermis. *Eosin stain, scale bar* 100 μm, 4*x*. E, epidermis.

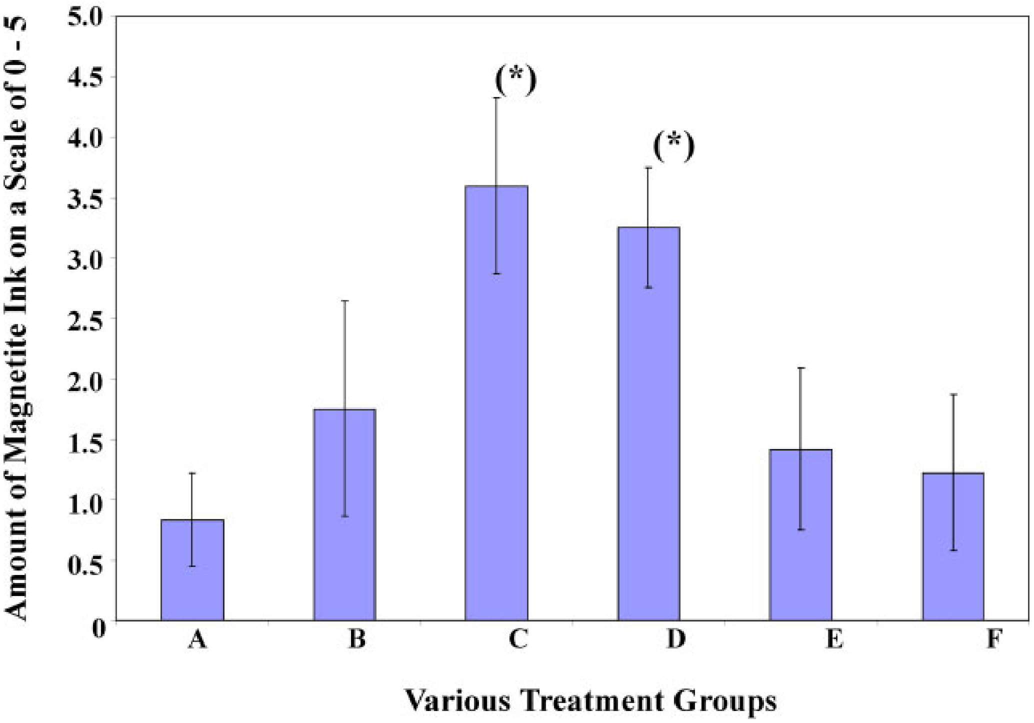

Fig. 5. **Amount of tattoo ink in the papillary dermis.** Tattoos treated with QSRL and magnets had significantly greater ink in the papillary dermis (*).

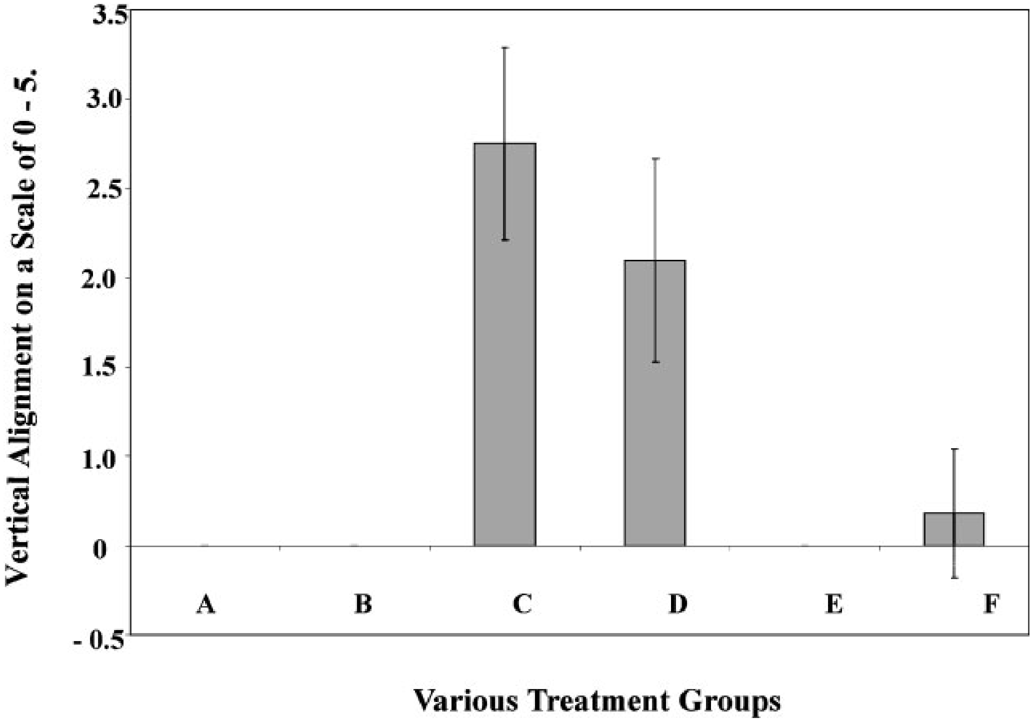

Fig. 6. **Degree of vertical streaking pattern.** Application of magnets after QSRL causes streaking pattern in the dermis, apparently along magnetic field lines. **Key for Figures 5 and 6**: **A**: Tattoos alone; **B**: One hour post QSRL alone; **C**: One hour post QSRL and magnet; **D**: Three weeks post QSRL and magnet; **E**: Three weeks post QSRL alone; **F**: One hour post magnet alone.

removal of the epidermis by $CO_2$ laser did not enhance tattoo removal after Q-switched laser treatment, but in that study nothing was used to force ink from the dermis. An interesting alternative to ink extraction would be to force ink in the opposite direction—to the bottom of the dermis and "out of sight." In our experiment, we found that long-term application of a magnet to intact skin after laser treatment produced the opposite effect, darkening the tattoo by moving ink into the upper dermis. Had the magnet been placed under the skin, one might expect that the tattoo would have lightened.

The potential for magnetite tattoos *per se* is speculative. Magnetic tattoo manipulation could almost certainly be improved over that achieved in this pilot study. Our choice of magnets, magnetic field strength, magnetic field gradient, time of application, magnetite particle size, and other factors was largely arbitrary. The motive force exerted by a magnetic field on a paramagnetic material, such as $Fe_3O_4$, is approximately proportional to the magnetic moment of the particle, and to the product of the magnetic field strength and the local magnetic field gradient. We did not optimize any of these factors. There are intrinsic limitations to the field strength and gradient of permanent magnets, such as those we used. Electromagnets could be constructed specifically for tattoo manipulation, which also offer the option of pulsing or switching the field polarity.

Magnetite is not new in biology and medicine. For example, Bees have evolved a magnetite-based sensor for navigation with respect to the earth's magnetic field. In medicine, magnetite is a biodegradable, biocompatible, non-toxic molecule that has been used as an MRI contrast agent [26–28] for studying cell trafficking [29–31] and for selectively targeting chemotherapy [32]. Cosmetics contain red and black iron oxides ($Fe_2O_3$, FeO, and $Fe_3O_4$) [33], and many of the tattoo inks already in use contain iron oxides. Unlike other tattoo inks, iron oxides have not been reported to cause hypersensitivity reactions. Patients with iron-containing tattoos have been reported to suffer skin burns during MR imaging [34,35]. A static magnetic field cannot account for tattoo heating, but the powerful radio-frequency source used with MRI can deposit energy into paramagnetic and superparamagnetic materials such as iron oxides.

The most common tattoo ink color is black, and magnetite makes black tattoos nicely. Potentially, a pure, sterile, optimized suspension of magnetite could be produced as an alternative to other black inks, which include carbon and FeO. Some unknown fraction of existing black tattoos probably contain magnetite, which could be determined non-invasively by noting the attraction between an external magnet and the tattoo. In our study, a palpable magnetic "tug" was easily felt as the magnet approached the tattooed skin surface. It is also conceivable that magnetite particles could be incorporated into other ink colors, for example, by coating them with a chromophoric substance.

Potentially, magnetic fields could be used to extract magnetite tattoos alone, i.e., without the need for laser treatment to free particles from within dermal cells. In our study, application of magnets for an hour without laser treatment did not cause significant ink particle movement by histological analysis ($p = 0.133$), although there was a suggestion of streaking along magnetic field lines (see Fig. 3a). Tattoo ink is contained in cells, mainly macrophages, fibroblasts, and mast cells. We conclude that the magnetic forces produced for 1 hour in this study were not sufficient to overcome cell-matrix adhesion in the dermis. However, we neither tested the effect of long-term application of magnets to tattoos, nor the effects of more powerful magnetic fields. These conditions will be examined in the future. Potentially, it may be possible to "drag" intact cells loaded with magnetite, through the dermis.

Vertical streaking of magnetite tattoos in the dermis was uniquely associated with magnet application. The streaking pattern is consistent with magnetic field lines, which can be seen in any setting where paramagnetic or superparamagnetic particles are free to move in response to a permanent magnet. The particles clump together and form an oriented streak because of particle–particle interactions. Within each particle, magnetic polarization occurs in response to the external magnetic field, such that each particle becomes a small magnet. Head-to-tail alignment of particles along the external magnetic field then occurs. In a stationary magnetic field, this alignment inhibits further particle motion. This suggests that a time-varying magnetic field might work better for extracting magnetite particles from the dermis. We further hypothesize that some particles may enter cul-de-sacs created by extracellular matrix proteins and various skin structures. A spatially-varying magnetic field would be expected to minimize this problem. Thus, one might expect a time- and spatially-varying magnetic field to be more optimal than the fields we tested.

In summary, we have shown that magnetite tattoos can be manipulated by a combination of Q-switched laser and external magnetic field. The safety and well-being of tens of millions of people who choose to be tattooed is a challenge that falls squarely into the realm of dermatology.

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