The spectrum of complications of immunosuppression: Is the time right for hand transplantation?

Michael J. Brenner
Washington University School of Medicine in St. Louis

Thomas H. Tung
Washington University School of Medicine in St. Louis

John N. Jensen
Washington University School of Medicine in St. Louis

Susan E. Mackinnon
Washington University School of Medicine in St. Louis

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The Spectrum of Complications of Immunosuppression: Is the Time Right for Hand Transplantation?

BY MICHAEL J. BRENNER, MD, THOMAS H. TUNG, MD, JOHN N. JENSEN, MD, AND SUSAN E. MACKINNON, MD

Investigation performed at the Division of Plastic and Reconstructive Surgery, Washington University School of Medicine, St. Louis, Missouri

- Life-threatening complications of long-term immunosuppression include malignancy, infection, and metabolic disorders such as renal failure and diabetes.
- Up to three-fourths or more of patients on chronic immunosuppressive medications experience an infectious complication.
- The hand transplants to date have had multiple episodes of acute rejection.
- The frequency and timing of episodes of acute rejection, even if the episodes are easily treated, are predictive of chronic allograft dysfunction and failure.
- Chronic allograft rejection is not effectively treated with current immunosuppressive medications, and it has become a primary cause of long-term allograft failure.

The introduction of cyclosporine A in the early 1980s revolutionized solid organ transplantation. There were marked improvements not only in preserving graft function, but also in prolonging patient survival following solid organ transplantation. As the viability of transplanted organs improved, the indications for clinical transplantation expanded to include not only acutely life-threatening conditions, but also more chronic conditions that adversely affect longevity and quality of life.

Composite tissue allotransplantation involves the transplantation of nonvital tissues for reconstruction of deficits following trauma or tumor resection. If successful, composite tissue allotransplantation would facilitate the recovery of lost function through grafting of complex, disparate tissue types. However, composite tissue allotransplantation also poses unique challenges. Solid organs, such as the kidneys, may be more tolerant of rejection episodes than are composite tissues, for which the risk of rejection of one or more components is high. Parenchymal organs may have a tremendous functional reserve so that a substantial amount of tissue can be lost before organ function is compromised, but composite tissue allografts tend to have complex architecture with limited built-in redundancy. Thus, while the majority of kidney function may be lost before blood urea nitrogen or creatinine levels are elevated, comparable loss of the function of composite tissue allotransplants may have more profound consequences. In the hand, for example, many fine anatomical components must work together to achieve precise motor movements. Rejection episodes that only impair nerve regeneration or result in loss of muscle could result in irreversible loss of function.

Despite these obstacles, enthusiasm for composite tissue allotransplantation has grown. In 1991, a composite tissue transplantation workshop was held in Seattle, Washington, under the sponsorship of the Rehabilitation Research and Developmental Service of the Department of Veteran Affairs. Literature and scientific progress in this area were reviewed extensively by transplantation biologists and clinical transplantation surgeons. Ultimately, the participants at this conference concluded that more research and clinical progress were necessary before clinical trials could be undertaken. In 1997, the first International Symposium on Composite Tissue Allotransplantation was held at the Jewish Hospital in Louisville, Kentucky. The scientific literature was again reviewed, and the controversy of clinical application was extensively debated. llull suggested that a moratorium be placed on transplantation of the hand, but others thought that "the time [was] ripe to proceed with the first human cadaveric hand transplantation." Despite opposition from the majority of the hand surgery community, the first hand transplants were performed in Lyon, France, and Louisville, Kentucky, in 1998, and other transplants in China, including bilateral transplants, have followed.
Since 1998, hand transplantation has remained a divisive subject in the hand surgery community. The controversy centers on the need for indefinite high-dose immunosuppression for allograft survival. While many experts identify composite tissue allotransplantation as an important long-term goal of hand and reconstructive surgery, there is debate surrounding both the hand transplants already performed and the wisdom of proceeding with future clinical trials. The controversy initially focused on whether the performance of the clinical hand transplantations had been premature as demonstrated by existing experimental data that predicted early graft failure. With the success of several clinical hand transplants that have now lasted for more than two years, the debate has shifted to potential side effects of long-term immunosuppression and the likelihood and timing of chronic rejection and graft failure. The literature on solid organ transplantation provides insight into these issues.

The discussion that follows will address the following questions: What are the possible benefits of hand transplantation? What are the associated risks? In particular, what are the sequelae of chronic immunosuppression? Can acute rejection episodes predict chronic rejection and graft failure? What criteria can be used to determine whether there have been sufficient preliminary studies of composite tissue allotransplantation to justify its experimental use in patients?

**Benefits of Composite Tissue Allotransplantation**

Much of the argument for composite tissue allotransplantation is based on the success of reconstruction of major defects of the extremities with autologous tissue. The most relevant literature concerns the replantation of amputated digits and limbs and the free transfer of analogous tissue components (for example, toe-to-thumb transfers). While autologous reconstruction is a well-accepted option for the treatment of anatomical functional deficiencies of the hand, an unfavorable amputation site or a lack of suitable tissue for replantation may render this option impractical or impossible. In this setting, allotransplantation is likely to offer the best prospect for functional recovery and restoration of body image. Composite tissue allotransplantation could allow reconstruction of several specialized tissues other than the extremities, such as the larynx, the tongue, and potentially other maxillofacial components.

There are several theoretical benefits of hand transplantation. The anatomy of the hand is complex, and there are few satisfactory alternatives to reconstruction with autologous tissue when replantation is not possible. With transplantation of a cadaveric hand, the desired tissue can be procured without donor-site morbidity and can be adapted to the needs of the host environment. For example, an allograft can be fashioned to make productive use of the damaged nerves, vessels, tendons, and joints proximal to the amputation level. Although imperfect, a hand allograft would more closely replace the appearance, anatomy, and function of a native hand than would any other available reconstruction. In addition, from a psychological standpoint, a hand transplant might counter the devastating effects on body image that can occur with loss of a hand.

**Risks of Immunosuppression**

The possible benefits of composite tissue allotransplantation, particularly hand transplantation, must be weighed carefully against the risks of indefinite immunosuppression. On the basis of clinical experience with solid organ transplantation, it can be anticipated that the major risks include the possibility of graft-versus-host disease and the morbidity resulting from episodes of graft rejection. To this list should be added certain considerations that are unique to composite tissue allotransplantation. For example, what are the psychological and emotional ramifications of having a hand transplant that deteriorates in appearance or function, or both? The recipient of the world’s first “successful” hand transplant, which was recently amputated because of rejection, stated that he had no normal sensation in the hand and experienced pain and burning sensations. Signs of rejection are grossly evident as skin erythema progresses to epidermolysis and eschar formation. The patient became emotionally detached from the allograft and “realized that it wasn’t my hand after all.” Perhaps a more important question is: Should a hand transplant fail, what does it mean to a patient to lose a hand not once, but twice?

The complications of lifelong immunosuppression are well defined and some are potentially life-threatening. Nonspecific immunosuppression is the only established clinical method currently available for sustaining an allotransplant. Because composite tissue allotransplantation involves multiple heterogeneous tissue types, some of which are highly antigenic, not
only must immunosuppression be chronic, but it also must be maintained at a high level. The outcomes associated with such a regimen are not fully known, but a large body of literature addresses the prevalence of complications observed during treatment with immunosuppressive drugs (Table I).

When the complications are considered collectively, lifelong immunosuppression can be thought of as a chronic disease characterized by its own set of risks. Much as chronic hypertension increases one’s risk of stroke or myocardial infarction, prolonged immunosuppression increases the risk of infection, fracture, neoplasia, drug toxicity, and metabolic derangement. Unlike hypertension, however, chronic immunosuppression is usually symptomatic. Patients on immunosuppressive regimens frequently experience undesirable changes in appearance or behavior. Patients may also have nausea, diarrhea, or a variety of other side effects. The morbidity of this new disease profoundly affects the quality of life, alters the risk profile of composite tissue allotransplantation, and therefore must figure prominently in the balance of risks versus benefits when determining whether to initiate treatment.

Infection
The majority of patients who have had a transplant have an infection as a result of immunosuppression. In one study, a major infection developed in up to 88% (107) of 122 patients who had undergone kidney, heart, or liver transplantation. Infections account for a major part of postoperative morbidity after solid organ transplants (Table II). The etiology may be bacterial, viral (cytomegalovirus, herpes simplex virus, or varicella zoster virus) or fungal, and the prevalence of these infections varies with the type of transplant and the degree of immunosuppression. Bacterial infections are the most common and have been reported in 21% to 68% of transplant recipients, and cytomegalovirus and herpes simplex virus may occur in up to 50% (or more) of patients. In the early postoperative period, infections are surgical complications and include wound infections; pneumonia; urinary tract infection; *Clostridium difficile* colitis; infection at the site of a drain, an indwelling central catheter, or another type of catheter; and a hematoma or lymphocele surrounding the graft. Opportunistic pathogens that are characteristic of patients who have had a transplant include cytomegalovirus, *Pneumocystis carinii*, Aspergillus species, *Nocardia* species, *Listeria monocytogenes*, and Toxoplasma, and they usually appear after the first month. Pathogens already present in the transplant recipient may be reactivated by immunosuppression; these include *Mycobacterium tuberculosis*, *Histoplasma capsulatum*, *Coccidioides immitis*, and occult bacterial or viral infections. Chronic or latent infections that may be transmitted through the allograft include human immuno-
deficiency virus, hepatitis B and C, and fungal or mycobacterial infection.

Hypertension and Nephrotoxicity

The neurohormonal mechanisms that lead to hypertension and nephrotoxicity following transplantation are thought to be similar. Factors that contribute to hypertension include altered renal vascular reactivity and vasoconstriction, increased sympathetic tone, and sodium retention. The development of hypertension after cardiac or liver transplantation has been reported in 60% to 90% of patients treated with cyclosporine A, with prevalences of fifty-two of eighty-five patients after two years and thirty-four times higher in women twenty-five to forty-four years of age and eighteen times higher in men forty-five to sixty-four years of age. The development of hypertension after cardiac or liver transplantation is cumulative tubulointerstitial damage and fibrosis associated with arteriopathy. In a review of the cases of forty-nine children followed for a mean of only twenty-nine months after a heart transplant, renal toxicity (defined with use of the same criterion as described above) was noted in 37% (fourteen) of thirty-eight patients taking tacrolimus as the initial primary agent and in ten of eleven patients who had initially been treated with cyclosporine A and then switched to tacrolimus because of persistent side effects or rejection.

Metabolic Disorders

The metabolic derangements associated with chronic immunosuppression take a variety of forms. Among the best studied are the increased risk of fracture due to loss of bone density (Table IV) and the increased prevalence of hyperlipidemia and diabetes (Table V). The specific abnormalities vary depending on the immunosuppressive regimen, with cyclosporine A, tacrolimus, and steroids being the most commonly implicated agents. In a review of 600 patients who underwent abdominal organ and heart transplantation, the prevalence of fractures was increased by as much as 9% in men and 25% in women and the prevalence was as high as 100% (five of five) in postmenopausal women. Overall, the relative risk, compared with National Health Interview Survey data on fracture prevalence in the United States population, was thirteen times higher in men forty-five to sixty-four years of age and eighteen and thirty-four times higher in women twenty-five to forty-four years of age and those forty-five to sixty-four years of age,
Skin cancer was found to occur in 43% of patients (cumulatively 764 patients) in a Dutch study of lung transplant recipients. The prevalence after lung transplantation (as determined on the basis of the Registry of the International Society for Heart and Lung Transplantation of 38,943 heart transplant and 2855 heart-lung transplant recipients) and 29% after renal transplantation. The mechanisms of these metabolic derangements have been reviewed in detail elsewhere.

**TABLE VI Cancer in Transplant Recipients**

<table>
<thead>
<tr>
<th>Prevalence of Cancer (%)</th>
<th>Liver Transplant (Overall)</th>
<th>Kidney Transplant (Overall)</th>
<th>Heart Transplant (At 1 Yr)</th>
<th>Heart Transplant (at 5-10 Yr)</th>
<th>Lung Transplant (at 1 Yr)</th>
<th>Lung Transplant (at 5 Yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Post-Transplant lymphoproliferative disorder</td>
<td>1.7-13</td>
<td>1.0</td>
<td>1.0-13</td>
<td>1.16</td>
<td>1.8-20</td>
<td>1.4</td>
</tr>
<tr>
<td>Skin</td>
<td>2.2</td>
<td>2.65</td>
<td>1.3</td>
<td>3.43</td>
<td>0.6</td>
<td>3.2</td>
</tr>
<tr>
<td>Other</td>
<td>5</td>
<td>3</td>
<td>1.2</td>
<td>3.2</td>
<td>1.4</td>
<td>1.6</td>
</tr>
<tr>
<td>Total</td>
<td>12</td>
<td>2.2-20</td>
<td>3.5</td>
<td>8.8</td>
<td>4.4</td>
<td>5.8</td>
</tr>
</tbody>
</table>

**Malignant Lesions**

Recipients of organ transplants are at substantially increased risk for the development of cancer. The relative risk of certain types of malignant disease has been estimated to be up to 400 times that in the general population. The prevalences of different malignant lesions, organized by type of transplant, are shown in Table VI. The most common malignant lesions seen in transplant recipients are skin cancers, which account for 37% of post-transplant tumors (4305 of 11,483) and 29% after renal transplantation. The mechanisms of these metabolic derangements have been reviewed in detail elsewhere.

**Chronic Allograft Dysfunction and Rejection**

The frequency and timing of acute rejections predict chronic rejection and allograft failure. Chronic rejection is the most prevalent cause of long-term failure of allograft organ transplantation, and its prevalence has remained unchanged despite two decades of progress in immunosuppressive therapy and perioperative care. Chronic rejection with loss of the allograft is seen in 52% of patients (thirteen of twenty-five) by five years after cardiac and lung transplants and in >50% (as determined on the basis of multcenter data from the United Network for Organ Sharing [UNOS] and Eurotransplant) seven to eight years after renal allograft transplantation. The literature on renal transplantation indicates that the risk of chronic rejection increases threefold with one acute rejection episode, twofold with two or more acute episodes, and twenty-six-fold with late rejection episodes (those occurring more than eight weeks after transplantation). Experience with the first hand transplants performed in Lyon, France, and Louisville, Kentucky, suggests that preventing chronic rejection of composite tissue allografts will not be easy. Acute rejection episodes were noted at eight, fifty-five, and seventy-four weeks in Lyon and at four to six, eighteen to twenty, and seventy-seven weeks in Louisville. These frequent and late acute rejection episodes suggest a substantial risk of chronic allograft rejection.
While the principal risk of hand transplantation results from immunosuppression, the principal obstacle to functional recovery is rejection. Because of the risk of rejection, the results of hand transplantation may be poorer than those of hand reimplantation. Function must be restored for limb transplantation to be considered a success\(^4\). The factors limiting recovery of function are impaired nerve regeneration and loss of motor units and sensory receptors. Composite tissue allotransplantation involves transplantation of composite tissues containing highly antigenic properties. Nerve regeneration could theoretically be impaired in the setting of a large antigen load. In primate studies conducted in our laboratory, nerve allografts treated with anti-CD40 ligand, an agent that blocks the costimulatory pathway between T-cells and antigen-presenting cells, showed robust regeneration. However, addition of a skin graft led to rejection in the same model, suggesting that one antigenic tissue component may predispose other tissue components to rejection\(^6\). Patients treated with nerve allotransplantation alone require immunosuppression only for the time necessary for host axons to traverse the allograft and reach host motor and sensory targets. Similarly, experimental studies on acute rejection of nerve allografts have demonstrated only a very short window of time during which immunosuppression can rescue a nerve allograft undergoing acute rejection\(^7\). If there is an episode of acute rejection, it is only a matter of days before the nerve allograft can no longer be rescued.

Thus, episodes of acute rejection in hand transplant recipients are more than just temporary setbacks. Even though these acute episodes have been controlled relatively easily, the fact that they have been frequent and that some have occurred late predicts chronic rejection and ultimate failure of the allograft.

### Balancing Risks and Benefits

Risks that are considered to be acceptable in association with composite tissue allotransplantation. The benefits of each type of transplant surgery must be weighed against the concomitant risks. Table VII shows one scheme for classifying different types of transplant surgery. In the first group are lifesaving transplants—for example, heart, lung, or liver transplants. In the second group are transplants that, although not immediately lifesaving, alleviate chronic disease and offer the prospect of improved longevity and quality of life. Composite tissue allotransplantations are a third group. These transplants offer the possibility of functional improvement alone. The expected outcomes of surgery and subsequent immunosuppression differ for each of these groups, as shown in Table VIII. While all share the morbidity of a new disease (immunosuppression), the benefits of transplantation lie along a continuum. Cardiac, lung, and liver transplantations are lifesaving. A pancreas transplant to a diabetic patient or a kidney transplant to a patient with end-stage renal disease may prolong life. Recipients of kidney transplants from living relatives have been shown to survive longer than patients on dialysis\(^8\). In each of these examples, solid organ transplantation has transcended the biological limits of end-organ failure. Since composite tissue transplantation does not replace essential organs and remains experimental, a lower level of morbidity is acceptable. Also, unlike solid organ transplantation, which has an established track record of clinical success, composite tissue allotransplantation is still experimental.

### Ethical Considerations in Determining Whether to Perform Experimental Surgery

What criteria can be used to determine whether to perform experimental surgery? Siegler\(^8\) suggested that the six criteria originally proposed by Moore\(^8\) be used for evaluating how innovative surgical techniques might be applied to hand transplantation. The criteria include (1) the scientific background of the innovation, (2) the skill and experience of the
team (so-called field strength), (3) the ethical climate of the institution, (4) open display, (5) public evaluation, and (6) public and professional discussion.

These criteria address many aspects of experimental surgery—not only the scientific underpinnings and the ethical backdrop of the surgery, but also the practical issues of who will perform the surgery, how and where it will be done, and how it will be evaluated. Siegler concluded that the teams working on clinical hand transplantation had satisfactorily met these criteria, and he recommended proceeding with cadaveric hand transplant surgery in humans. However, it bears mention that these criteria were designed as ethical standards for the use of innovative surgery for life-threatening, otherwise untreatable conditions, specifically the use of innovative liver transplantation at the University of Chicago.

While criteria 2 through 6 can reasonably be extrapolated from liver transplantation to hand transplantation and other types of composite tissue transplantation, the same does not hold for criterion 1. The central concept in criterion 1 is the equipoise consideration. Equipoise refers to a clinical setting in which the prospects for benefiting the patient are favorably balanced against the risk of causing unintended harm. The threshold for undertaking innovative surgery is necessarily much higher for hand transplantation, the goal of which is restoration of function, than for liver transplantation for the treatment of a life-threatening condition. For hand transplantation to meet equipoise conditions, the benefits in terms of functional improvement and enhanced quality of life from the patient’s perspective must equal or exceed the risks of the surgery and subsequent immunosuppression.

Siegler’s assessment of the equipoise criterion here warrants scrutiny:

“It is ethically acceptable to allow a patient to balance an improvement in quality of life (such as may be obtained from hand transplant) against the potential risk of morbidity and mortality. . . . Specifically, is improving the patient’s quality of life (as determined by the patient) sufficient grounds to allow patients to risk morbidity and mortality? The answer is clearly ‘yes’ because such trade-offs are inevitable and are not unique to hand transplantation.”

The answer is “clearly ‘yes,’” only when benefits clearly exceed risks. Physicians and surgeons regularly accept risk as the necessary price of conferring future benefits. Although an experimental treatment may provide benefit from the patient’s perspective, it is the surgeon’s responsibility to make sure that such benefit does not exact an unacceptable cost. Before undertaking experimental surgery, it behooves us to reflect on the tenet “primum non nocere” (“first, do no harm”).

The Principle-Based Approach to Human Experimentation

Several incentives may drive surgeons to move forward with new techniques faster than is appropriate. Among these are desperate patients, the patient’s or surgeon’s desire for notoriety, and institutional interest in market share. As Selzer wrote: “In the act of surgery, the scalpel must be restrained rather than given its head. Holding back is the primary mode of surgery.” The ethical precepts derived from the Declaration of Helsinki and from the Nuremberg trials can help to steady our hand. The Nuremberg Code advises in part:

(2) The experiment should be such as to yield fruitful results for the good of society, unprocurable by other methods or means of study. . . .
(3) The experiment should be so designed and based on the results of animal experimentation. . . .
(10) During the course of the experiment the scientist in charge must be prepared to terminate the experiment at any stage, if he has probable cause to believe, in the exercise of the good faith, superior skill and careful judgment required of him that a continuation of the experiment is likely to result in injury, disability, or death to the experimental subject.

The following excerpts from the Helsinki Declaration are also particularly relevant:

(1) Biomedical research involving human subjects . . . should be based on adequately performed laboratory and animal experimentation. . . .
(3) . . . The responsibility for the human subject must always rest with a medically qualified person and never rest on the subject of the research, even though the subject has given his or her consent.
(5) . . . Concern for the interests of the subject must always prevail over the interests of science and society.

Based on the principles from both Nuremberg and Helsinki, several aspects of hand transplantation raise concerns. Both sets of principles place special emphasis on conducting thorough animal research prior to human experimentation. While some animal models of composite tissue allotransplantation do exist, they have shown varying levels of success. Specifically, the pooled data from three primate studies indicated that rejection had occurred in eighteen of twenty-four animals. Sepsis or malignant disease developed in fifteen of those animals, and only two of the twenty-four animals survived beyond 200 days. As Lee and Mathes pointed out, no animal studies have successfully demonstrated return of function following limb allotransplantation.

Both the Nuremberg Code and the Helsinki Declaration instruct us to safeguard the welfare of the individual patient, a responsibility that begins before surgery takes place. Principle 3 of the Helsinki Declaration suggests that the surgeon is obliged to balance thoughtful guidance with careful attention to the patient’s needs. While it is inappropriate to impose personal values on patients, it is equally unacceptable to offer patients an innovative treatment and then sit back in silence as he or she agonizes, alone, over a final decision. Principle 10 of the Nuremberg Code emphasizes the need to terminate an experiment once there is indication that it may be injurious to the patient.

As Principle 5 of the Helsinki Declaration emphasizes, human experimentation that purports to serve the “greater
good” at the expense of the individual is not justifiable. The long-term success of clinical hand transplantation remains uncertain. While hand replantation sometimes results in durable recovery of function17, hand transplantation has not yet been shown to provide such favorable outcomes. This must be taken into account when determining whether surgery is in the patient’s best interest.

Assessment with use of quality-adjusted life-years could theoretically assist in decision-making regarding hand transplantation. This method provides a quantitative interpretation of the subjective risks and benefits of a treatment. Unfortunately, in the case of hand transplantation, the principal benefits are not certain since, as Lee and Mathes18 pointed out, long-term survival of limb allografts has not been achieved. Whether functional recovery can be sustained long-term after human hand transplantation is unknown. Furthermore, the psychological repercussions of a favorable or unfavorable outcome are difficult to quantify. The world’s first “successful” hand transplant was amputated on February 3, 2001. Among the patient’s complaints were the adverse effects of the treatment regimen, poor hand function, deterioration of the hand’s physical appearance, and a sense of both physical and psychic detachment from the transplanted hand. In the wake of this treatment failure, the impact of rejection on quality of life must not be taken lightly34.

Given the morbidity associated with chronic immunosuppression and the lack of evidence supporting durable recovery of function, it would seem that additional research and reflection are warranted before proceeding with additional hand transplants. It seems doubtful that hand transplantation in its current state serves the best interests of the individual transplant recipient. How many members of the hand or transplant surgery community would be willing to undergo a hand transplant were they to lose one of their hands?

Future Directions

Composite tissue allotransplantation has become a source of not only tremendous enthusiasm, but also considerable controversy. Nonetheless, composite tissue allotransplantation remains one of the great frontiers in hand and reconstructive surgery. Progress in developing models of immune tolerance suggests that a more promising paradigm for composite tissue allotransplantation may be forthcoming. Immune tolerance is a state of donor-specific immune unresponsiveness leading to the indefinite engraftment of transplanted tissue without the need for ongoing therapy. Strategies of tolerance induction include irradiation, donor-bone-marrow transfusion, intrathy- mic injection of donor cells, and antibody-based therapies. Among the promising antibody-based therapies are T-cell depletion, blockade of antigen recognition, blockade of adhesion molecules, and costimulation blockade. Currently, several tolerance-inducing strategies, including donor-bone-marrow transfusion with immunosuppression, anti-ICAM (intercellular adhesion molecule)-1 antibody, anti-LFA (lymphocyte function-associated)-1 monoclonal antibody, anti-CD25 monoclonal antibody, and anti-CD40 ligand monoclonal antibody, are being studied in clinical trials35.

Blockade of the CD40 costimulatory pathway appears to be one of the most promising approaches and has produced long-term donor-specific allograft survival in many experimental models with minimal toxicity36,37. Its role in the future of transplantation seems to be as part of a combined regimen that includes other modalities such as T-cell depletion and bone-marrow transfusion38,39. However, the enthusiasm resulting from the efficacy of CD40L blockade in models of limb40 and nerve allotransplantation41 must be tempered with the possibility that the potent neuroregenerative effects of tacrolimus cannot be used in combination with costimulation blockade. When used simultaneously, calcineurin inhibitors such as tacrolimus and cyclosporine A have been shown to abrogate the effects of costimulation blockade in numerous models of skin and solid organ transplantation42.

The universal acceptance of composite tissue allotransplantation as a safe and viable therapeutic option rests with the reduction or elimination of the adverse effects of immune modulation. The successful induction of donor-specific tolerance would circumvent the toxicity associated with nonspecific immunosuppression and may eliminate the potential for chronic rejection. The result would be the safe transfer of composite tissue allografts leading to improved functional outcomes and reduced morbidity.

Michael J. Brenner, MD
Thomas H. Tung, MD
John N. Jensen, MD
Susan E. Mackinnon, MD
Division of Plastic and Reconstructive Surgery, Washington University School of Medicine, One Barnes-Jewish Hospital Plaza, Suite 17424, East Pavilion, St. Louis, MO 63110. E-mail address for T.H. Tung: tungt@msnotes.wustl.edu. E-mail address for S.E. Mackinnon: mackinnons@msnotes.wustl.edu

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