Published in final edited form as:

Lancet. 1992 June 27; 339(8809): 1579–1582.

Cell migration, chimerism, and graft acceptance

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The chimeric nature of the transplanted liver was first shown in our long-surviving human recipients of orthotopic hepatic allografts in 1969.¹ When liver grafts were obtained from cadaveric donors of the opposite sex, karyotyping studies showed that hepatocytes and endothelium of major blood vessels retained their donor specificity, whereas the entire macrophage system, including Kupffer cells, was replaced with recipient cells.² Where donor cells that had left the liver had gone was unknown, but their continued presence was confirmed by the acquisition and maintenance in recipient blood of new donor-specific immunoglobulin (Gm) types^{1,3} and red-blood-cell alloantibodies, if donors with ABO non-identity were used.⁴ Davies et al⁵ attributed the secretion of new soluble HLA class I antigens of donor type to transplanted hepatocytes. However, these HLA molecules come from bone-marrow-derived macrophages and/or dendritic cells,⁶ and probably have the same origin from migrated donor cells as the additional Gm types and red-cell antibodies.

Although this early evidence of systemic mixed allogeneic chimerism was circumstantial, we have recently shown with both anatomical and molecular techniques the presence, in clinically stable patients, of peripherally located donor cells many years after liver replacement. For instance, in patients with type IV glycogen storage disease, a disorder in which an insoluble amylopectin-like polysaccharide accumulates throughout the body because of a deficiency in a branching enzyme, we found resorption of extrahepatic amylopectin after liver replacement.⁷ This process could not be explained until the migrated donor cells, which had acted as enzyme couriers, were identified by both HLA monoclonal antibodies (fig 1) and polymerase chain reaction (PCR) studies (fig 2) in the biopsied myocardium and skin of 2 patients, 33 and 91 months after hepatic transplantation.

Recent experiments in rats have shown the timing and extent of seeding from the hepatic allograft to both non-lymphoid and lymphoid organs (fig 3).⁸ A similar pattern of distribution was found after successful rat-to-mouse bone-marrow transplantation.⁹ This similarity between liver transplantation and bone-marrow transplantation has not been reported before. The prompt development, and then the persistence, of this systemic chimerism may help to explain the resistance of the liver to cellular¹⁰ and humoral¹¹ rejection, as well as its tolerogenicity to other organs from the same donor.¹²

The chimeric structure of the transplanted liver was thought to be a unique feature of this organ for many years until we identified lymphoid and dendritic cell replacement under FK 506 immunosuppression in rat¹³ and human¹⁴ intestinal allografts; a similar finding has been reported in swine.¹⁵ In our experiments with rats, the two-way traffic was the same, irrespective of whether bowel was transplanted alone or as a part of a multivisceral graft that also contained

liver, stomach, and pancreas.¹³ Replaced donor lymphoid and dendritic cells spread through vascular routes to host lymphoid tissues, creating a state of mixed allogeneic chimerism—free of lethal or even clinically detectable graft-versus-host disease (GVHD) except in special strain combinations in which there is a poorly understood imbalance between the graft and recipient immune systems.^{16,17}

In addition, GVHD has been only a minor difficulty in human beings after cadaveric small bowel or multivisceral allotransplantation,^{14,18,19} despite the use of histoincompatible donors and the routine development (as with the liver) of mixed allogeneic chimerism. Resistance to GVHD has also been described with mixed allogeneic or xenogeneic chimerism after bone-marrow transplantation.²⁰ This might be explained by responses of coexisting donor and recipient immune cells, each to the other, causing reciprocal clonal expansion followed by peripheral clonal deletion (fig 4). If these or similar²¹ events do take place, then the deliberate “unbalancing” of the donor-recipient axis by cytoablation (or cytoablation), which is normally part of bone-marrow transplantation, should be re-examined because it restricts acceptable marrow donors (perhaps unnecessarily) to those with major histocompatibility complex (MHC) concordance.

The abundance of lymphoreticular cells in the liver and intestine, plus the development of phenotyping techniques,^{8,14,22} have contributed to the discovery of cell migration and repopulation that follows organ transplantation. We believe that cell migration takes place to some degree with all successful transplantations, irrespective of the organ, with rapid seeding through the blood stream. As far back as 1962-63, we found evidence that cells migrated from kidney allografts into recipients treated with azathioprine and prednisone.²³ After renal transplantation, previously negative tuberculin, histoplasmin, and other skin tests among recipients always became positive to antigens that had been shown to provoke positive reactions in their donors. These results were interpreted as showing adoptive transfer of donor cellular immunity “by leukocytes in the renal vasculature and hilar lymphoid tissue”.²⁴

At the time, alteration of graft antigenicity was suggested as an explanation for the reversal of kidney rejection in these patients when prednisone was added to baseline therapy with azathioprine, and for the ability later to reduce maintenance immunosuppression.²³ More than 28 years later, chimerism as a reason for diminished antigenicity was demonstrated with immunocytochemical and PCR techniques in biopsy samples from the renal allograft, skin, and lymph nodes of several of these same patients (unpublished observations). Such reductions in antigenicity of free thyroid grafts, when located in the anterior chamber of the guinea pig eye before subcutaneous engraftment, had been observed by Woodruff and Woodruff²⁵ who called this process “adaptation”.

We have also described cell repopulation of human heart-lung allografts from studies of necropsy samples of recipients treated with cyclosporin.²⁶ In untreated rats, Prop et al²⁷ showed that a lymphoid-poor heart is less vigorously rejected than a lung that contains rich bronchus-associated lymphoid tissue (BALT). However, this order of susceptibility to rejection was reversed with postoperative cyclosporin, which often induced permanent acceptance of the rat lung, but never of the heart. This paradox was explained by the greater volume and ease of migration of the lung's lymphoid and dendritic cell population. Permanent graft acceptance in rats after a brief induction course of FK 506 has also been shown to be more difficult to achieve with the heart than with the liver,²⁸ a difference that is reflected by the difficulty of maintenance of seeded peripheral donor cells after cardiac but not liver engraftment.⁸

Thus, cell traffic seems to be a striking event with all transplants. Donor cells leaving the solid organ graft and recipient cells entering it include passenger leucocytes that were shown by Steinmuller²⁹ to be the main cause of allograft immunogenicity. These cells are a distinct family

of bone-marrow derived antigen presenting dendritic leucocytes.³⁰ These dendritic leucocytes are distributed throughout the body, including organs once thought to be mostly devoid of immunologically active cells.^{30,31} The evidence implicating these antigen-presenting cells in primary T-cell alloimmunity^{22,30,32} has prompted efforts to eliminate them before transplantation.^{33,34}

Whether this reduction of graft antigenicity is beneficial remains uncertain. Our data show that migration of dendritic and lymphoid cells is associated with graft acceptance rather than rejection, depending on the quality of immunosuppression, the immunological substrate of the organs, donor-recipient histocompatibility, and perhaps other factors. The fine margin between graft rejection and acceptance was shown by Armstrong et al³⁵ who found an association between the increased rate of dendritic cell replacement and the survival of renal allografts transplanted to rats after they had been immunised by blood transfusion from the donor strain.

Thus, contrary to the dendritic cell deletion approach, the objective perhaps should be to promote, not prevent, two-way cell migration while at the same time giving treatment to avoid graft destruction or GVHD, which are the normal and inevitable consequences of migration. If so, improved treatment strategies might include perioperative infusion of bone-marrow or other immunocompetent cells.³⁶⁻³⁸ Antigen extracts or killed cells cannot substitute for living cells.^{38,39}

We have not attempted to distinguish between drug-free “classical tolerance”, as defined by Billingham, Brent, and Medawar,³⁶ the tolerance found after bone-marrow transplantation, and the ambiguous “graft acceptance” referred to by solid organ transplant surgeons. We believe that all are variants stages of the same cell migration process. Clinical success—tolerance or graft acceptance—means that a characteristic lymphoid and dendritic cell chimerism has been introduced, which may be stable either without further treatment or only when continued immunosuppression is provided; an unstable graft and its migrated cells may either be rejected or cause GVHD. Thus, our view of solid organ graft acceptance can be related easily to the Billingham-Brent-Medawar model of actively acquired tolerance,^{36,40} and accommodates Woodruff's suggestion about “replacement of certain elements of graft, for example connective tissue stroma and vascular endothelium”.⁴¹

Medawar was perplexed by the unexpected success of clinical renal transplantation and wrote that “. . . foreign kidneys do sometimes become acceptable to their hosts for a reason other than acquired tolerance in a technical sense . . . One possible explanation is the progressive and perhaps very extensive replacement of the vascular endothelium of the graft by endothelium of host origin, a process that might occur insidiously and imperceptibly during a homograft reaction weakened by immunosuppressive drugs”.⁴² He was unaware of the existence of cell migration and its possible association with transplant tolerance.

Since cell migration quickly transforms both the graft and the recipient into chimeras, both the importance of HIA matching for bone-marrow transplantation (an inherently immunologically unbalanced procedure) and its imperfection as a predictor for outcome of solid organ transplantation^{43,44} might now have an explanation. Although the dynamics of the chimeric state remain speculative, the reciprocal clonal deletion that was invoked to explain GVHD resistance (fig 4) can be thought of as immunosuppressive in proportion to the degree of MHC incompatibility. This process would be especially important with organs such as the liver and intestine, which have an important immunological component.

Cell migration, which we believe is an invariable early event in graft acceptance, could lead to self-perpetuating and presumably linked changes in the host immune response, which do not depend on the continued survival of seeded donor cells. Hypotheses such as these have

defined attempts at verification,⁴⁵ probably because the proposed elements of each theory are simply epiphenomena of the key event: cell migration and repopulation.

Acknowledgments

This work was supported by Project Grant DK 29961 from the National Institutes of Health, Bethesda, Maryland.

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Fig 1. Heart (upper) and skin (lower) biopsy samples 33 months after liver transplantation
Immunoperoxidase stain with monoclonal antibody GSP5.3 that reacts with HLA-B7, which was present in the donor and not the recipient. Rust-coloured cells (numerous in heart, sparse in skin) are from donor (magnification $\times 500$).

Fig 2. Chimerism after human liver transplantation

Southern blot analysis of polymerase chain reaction (PCR) products of liver (L), heart (H), and skin (S) 91 months after liver transplantation from HLA-DR1-specific and DRw52-associated amplification of the DRB1 gene in tissue biopsy samples. The presence of the donor DRB1 *0101 (donor-specific) allele in all three tissues was confirmed by hybridisation to a DRB-specific probe and by oligonucleotide probe subtyping of DR1-specific PCR products. M, molecular weight marker; N, PCR-negative control.

Fig 3. Result of traffic of donor and recipient lymphoreticular cell traffic after successful liver transplantation

White, recipient cells; black, donor cells.

Fig 4. Reciprocal clonal expansion and depletion by immune cells in graft and recipient
 HVG: host vs graft.