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Mini Review

Maturation of function in dendritic cells for tolerance and immunity

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Abstract

The capacity of antigen presenting dendritic cells (DC) to function in both tolerance and immunity is now well documented. The function and characteristics of different DC subsets are reviewed here and their capacity to activate T cells under different conditions of maturation and activation is discussed. The immunogenic potential of exosomes produced by DC is also considered in light of evidence that the capacity of exosomes to activate T cells for tolerance or immunity appears to mirror that of the parent DC. A model is proposed whereby exosomes produced by immature DC can function to maintain peripheral tolerance, while exosomes produced by more mature DC can stimulate effector T cells.

Keywords: dendritic cells - immunity - tolerance - exosomes

Introduction

In 1973, Ralph M. Steinman and Zanvil A. Cohn reported the identification of a novel cell type in the peripheral lymphoid organs of mice [1]. These large plastic-adherent cells were initially identified structurally. Like other mononuclear leukocytes, they had numerous organelles including abundant mitochondria, endosomes of various structure and density and an irregular eccentric nucleus containing heterochromatin arranged along the nuclear envelope. However, these cells were distinct from other

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cells within lymphoid tissues by their unique cytoplasmic extensions arranged as dendrites of varying length, width, form and number. As a result of their distinct morphology the authors proposed that these cells be termed dendritic cells (DC).

Although initial studies differentiated DC from other leukocytes important in immune responses, like lymphocytes and mononuclear phagocytes, it was not long before their importance in immunity was predicted [1–3]. Within 5 years of their initial characterisation, spleen-derived DC were found to be 100 times more effective than lymphocytes and macrophages in stimulating primary allogeneic mixed leukocyte reactions (MLR) [4]. This finding was extended further by subsequent studies demonstrating that murine DC could cluster with T lymphocytes and initiate a primary syngeneic MLR albeit weaker than the allogeneic MLR response. This property was a function that separated DC from all other spleen cell populations [5]. With these investigations began the characterisation of what is now recognised as the most important antigen presenting cell (APC) in adaptive immunity. Nearly 25 years on, their unique capacity to stimulate naïve lymphocytes, in particular T lymphocytes, is still the most definitive functional characteristic DC can attain [6].

Tissue distribution, subtypes and ontogeny

Early studies on DC indicated they were of bone marrow origin [3]. Developing DC precursors are thought to migrate from bone marrow to blood [7], from where they supply the interstitial DC that can be observed throughout the non-lymphoid peripheral organs of the body [6]. DC have been found in heart, liver, thyroid, pancreas, bladder, kidney, ureter and skin, the latter of which contain the extensively characterised DC termed Langerhans cells (LC) [8, 9]. Fully developed DC have also been observed in the circulatory networks of the body, including blood [10] and afferent lymphatics where they are called veiled cells [11]. These represent DC emigrating from peripheral organs into lymphoid tissues [9]. Within lymphoid tissues, DC can be subdivided into a number of sub-populations based on their expression of cell surface markers.

Currently, the best marker for murine DC in lymphoid tissues is CD11c [12]. However, depending on their location within these organs, and/or their point in development, they can also express combinations of the 'lymphoid markers', CD4 and CD8α, the 'myeloid markers' CD11b and F4/80, and the markers DEC205 and 33D1 which are relatively restricted to DC populations [7, 12, 13]. DC which have a phenotype: $CD4^{+/-}CD8\alpha^{-}CD11b^{+}F4/80^{+}DEC205^{-/low}33D1^{+}$, are located mainly within the marginal zones of spleen, while $CD4^{-}CD8\alpha^{+}CD11b^{-}F4/80^{-}DEC205^{+}33D1^{-}$DC are located mainly in the T cell-rich paracortical areas of spleen and are termed interdigitating DC [7, 13–15]. $CD4^{-}CD8\alpha^{+}CD11b^{-}DEC205^{+}$DC also appear to be the dominant subtype in murine thymus and have also been found in lymph nodes [13]. In addition, lymph nodes contain a $CD4^{-}CD8\alpha^{-}CD11b^{+}DEC205^{low}$ subgroup of DC as well as $CD4^{-}CD8\alpha^{low}CD11b^{+}DEC205^{+}$DC which also express Langerin, a characteristic marker of LC. These are thought to be DC immigrants from skin [13].

Murine DC expressing the lymphoid-associated marker, CD8α, were initially defined as a lymphoid subtype derived from lymphoid precursors based on reports indicating that they could be propagated from $CD4^{low}$ thymic T cell progenitors [16]. DC lacking CD8α were initially defined as myeloid DC derived from myeloid precursors based on reports demonstrating that they could be propagated efficiently from myeloid progenitors [17]. However, $CD8\alpha^{+}$ and $CD8\alpha^{-}$ DC have now been derived from both common myeloid and common lymphoid progenitors [18, 19] and it has been shown that $CD8\alpha^{-}$ DC can develop into $CD8\alpha^{+}$ DC *in vivo* [7]. Furthermore, a common DC precursor has recently been identified in blood, which has a $CD11c^{+}CD11b^{+}B220^{+}$MHC-II^{-} phenotype and is committed to the production of $CD8\alpha^{+}$ and $CD8\alpha^{-}$ DC as well as a newly identified DC subset bearing B220 which corresponds to the plasmacytoid DC present in humans [7]. The emerging view of DC development in mice appears to be that bone marrow-derived hemopoietic stem cells can differentiate into many of the DC subsets through either a committed blood $CD11c^{+}CD11b^{+}B220^{+}$MHC-II^{-} DC precursor, a common myeloid progenitor and/or a common lymphoid progenitor [7].

For those in the field, the study of DC development and the definition of lineage relationships between phenotypically distinct DC subsets has been more difficult than anticipated. In retrospect, the reason for this appears to relate to plasticity in DC development, uncharacteristic of other hematopoietic lineages [20]. Theories on the myeloid or lymphoid lineage relationships between DC subsets have been disputed and corrected over time (see for example ref [21]). The current thinking is that under steady-state or non-inflammatory conditions, there are three main classes of immature DC resident in peripheral lymphoid tissues of mice: the myeloid-like $CD11c^+CD11b^+CD8\alpha^-$DC and the lymphoid-like $CD11c^+CD11b^-CD8\alpha^+$DC making up the 'conventional' DC, and the $CD11c^{low}B220^+$ plasmacytoid (p) precursor DC which express CD8α upon activation [22]. Cells of the p-DC lineage express lymphoid markers including pTα and early D-J rearrangement at the IgH locus [23]. In contrast, monocyte-derived DC develop *in vivo* under inflammatory conditions which drive them from blood into lymph nodes for antigen presentation [24].

In vivo studies have now confirmed that conventional DC and p-DC derive from the $Flt3^+$ subset of both common lymphoid and common myeloid progenitors [25, 26]. It is also possible to derive these different DC types by culture of $Flt3^+$ bone marrow cells in the presence of different defined cocktails of growth factors including Flt3L [27, 28]. These studies indicate that DC development mediated by Flt3L can occur via multiple pathways from $Flt3^+$ bone marrow precursors. However, Flt3L is not specific for DC, and can stimulate expansion of hematopoietic cells of other lineages [29]. *In vivo* evidence in support of this plasticity was obtained after lymphocytic choriomeningitis infection of mice which showed transdifferentiation of p-DC into myeloid-like DC [30]. This plasticity was first detected as an increase in the number of myeloid DC over p-DC but subsequently p-DC derived from infected bone marrow were shown to differentiate into myeloid-like DC after *in vitro* culture with Flt3L [30]. In the least, these two DC subsets must share an immediate common precursor which is responsive to Flt3L. No further committed DC progenitor has been identified other than the $Flt3^+$ subsets in bone marrow.

In our hands, splenic stromal cells which support DC development do not express Flt3L transcripts and produce only immature myeloid-like DC [31, 32]. This raises the possibility that a more committed progenitor of myeloid DC is maintained in spleen. Consistent with this hypothesis is evidence that spleen contains a majority of endogenous, immature DC [33] which are thought to be involved in the induction and maintenance of peripheral tolerance [34, 35]. Similarly, the major population of DC in thymus is a $CD8\alpha^+$ population which arises from an endogenous $CD4^{low}$ lymphoid precursor population [36]. These DC are thought to play a major role in the induction of self tolerance through negative selection.

Functions of dendritic cells and the role of maturation

The paradigm for DC function is to classify DC residing in non-lymphoid peripheral tissues in the immune steady-state as immature. These cells are primarily involved in antigen recognition and uptake. DC that have attained both the capacity to migrate to secondary lymphoid tissues and the capacity to stimulate T cells have been defined as mature. This terminology reflects the functional development of DC.

Immature dendritic cells

The DC located in peripheral tissues in the immune steady-state have characteristics which make them ideally suited to monitor their environment for pathogens and to facilitate their uptake [6]. They are said to be 'immature' and express a large array of receptors that can specifically recognise pathogen-related molecules. These include Toll-like receptor (TLR)-2, TLR-3, TLR-4, TLR-5, TLR-8 and TLR-9 [37], which have specific recognition for a range of molecules including prokaryote-derived lipoproteins, glycolipids, flagellin, CpG DNA and lipopolysaccharides (LPS) [38]. Immature DC, also express several C-type lectins, like the mannose receptor, DEC205 and DC-SIGN, which recognise carbohydrate structures on pathogens [39]. Once in contact with antigen,

immature DC use several pathways to facilitate uptake. These include receptor-mediated endocytosis through C-type lectins and FcγII/IIIR [6, 40]. They also have high capacity to non-specifically endocytose particulates and solutes through phagocytosis and macropinocytosis. Although many of these pathways appear to be utilised for uptake of pathogen-related molecules they may also be utilised for uptake of self antigens [41]. Indeed, immature DC also express $\alpha_v\beta_3$-integrins, $\alpha_v\beta_5$-integrins and CD36, which help to facilitate continuous uptake of apoptotic material in the immune steady state [42]. These may be important in DC-mediated maintenance of peripheral self tolerance [41].

Once in the endocytic pathway of DC, internalised antigens must be processed before they can be displayed to lymphocytes in association with Major Histocompatibility Complex (MHC) molecules. The endosomes in which this process occurs are present late in the endocytic pathway. They are mildly acidic and contain lysosomal proteins, including lysosome-associated membrane protein (LAMP)-1 and LAMP-2 and the tetraspanins CD63 and CD82 [43]. The acidic nature of these endosomes and an abundance of cysteine proteases (cathepsins B, H, S and L) and aspartic hydrolases (cathepsins D and E) with acidic pH optima, allows them to degrade a variety of exogenous antigens [44–46]. These endosomes also accumulate newly synthesised MHC Class-II (MHC-II) αβ heterodimers due to their association with the invariant chain, which has endosomal sorting, leucine-rich N-terminal motifs [47]. Due to their high expression of MHC-II, these specialised antigen processing compartments have been termed MHC-II-rich compartments (MIIC) [43]. These appear to be particularly prevalent in immature DC [48].

Recent studies have shown that proteins sequestered into the MIIC of immature DC can be transported directly into the cytosol where they follow the pathway for MHC Class-I (MHC-I) presentation [49]. Normally, newly synthesised MHC-I molecules within the endoplasmic reticulum (ER) associate with peptides derived from cytosol proteins [50]. This process is mediated by the ER resident transporter associated with antigen processing (TAP) which facilitates the trafficking of proteasome-processed peptides from the cytosol into the ER. MHC-I/peptide complexes are then thought to directly traffic to the plasma membrane (PM) without intersecting the endosomal pathway, allowing presentation of antigen peptides from intracellular pathogens to $CD8^+$ T cells [50]. However, several reports have demonstrated that DC can present extracellular antigens *via* MHC-I molecules in a process termed 'cross presentation' [51-53]. This occurs primarily through a TAP-dependent pathway, where proteins from MIIC are transported to the cytosol, and processed by proteasomes before being complexed with MHC-I in the ER [49, 52, 53]. In addition, recent studies have demonstrated that DC can 'cross present' through TAP-independent pathways, where processed antigens within MIIC appear to complex with resident MHC-I molecules present in the MIIC of maturing DC [54–56]. However, before DC can complex processed peptide antigen to MHC molecules and display them at the cell surface, they must first undergo a process of functional maturation.

Mature dendritic cells

One of the first properties attained by 'maturing DC' is the capacity to migrate from non-lymphoid peripheral organs through afferent lymph to the T cell-rich paracortical areas of the proximal secondary lymphoid tissue [57, 58]. This is shown diagrammatically in Fig. 1. This has been well studied in LC where upon maturation there is downregulation of the adhesion molecule, E-cadherin, which acts through homotropic interactions to keep LC within the keratinocytes of the skin [59]. Maturing LC also downregulate the chemokine receptor (CCR)-6, whose ligand CCL20 (MIP3α) helps localise these cells to dermal tissues [60]. Concomitantly, maturing LC also upregulate CD44 and the integrin $\alpha_v\beta_3$. Both are receptors for osteopontin, a factor important in LC migration to lymph nodes [61]. Maturing LC also upregulate CCR-7 [62]. Ligands for CCR-7 include secondary lymphoid tissue chemokine (SLC: CCL21) which is expressed by lymphatic endothelium and cells in the T cell-rich paracortical areas of secondary lymphoid tissues. Cells in the T cell-rich areas also express CCL19 (MIP3β) another CCR-7 ligand [60]. Expression of CCR-7 is thought to enable maturing DC to migrate towards lymphatic

endothelium and to concentrate within T cell-rich areas. DC located within these areas amplify this chemotatic signal since they also express CCL21 and CCL19 [60].

The maturing DC is also characterised by tight control over the formation of MHC/peptide complexes and their expression on the cell surface along with costimulatory molecules. Internalised protein antigen can accumulate in MIIC for up to 60hr in immature DC [55]. However, within 3–4hr after induction of maturation of DC, antigen rapidly begins to complex with MHC-II within MIIC. This process involves downregulation of cystatin C, an inhibitor of cathepsin S. Cathepsin S degrades the invariant chain, leaving its MHC-II-associated invariant chain peptide fragment (CLIP) in the peptide binding groove of MHC-II [63]. MHC-II are then released from the endosomal sorting motifs of the invariant chain and CLIP is thought to be replaced with antigen peptide by the action of the resident catalyst H-2M [64, 65]. MHC-II/peptide complexes then separate from the bulk of unprocessed antigen and accumulate in LAMP$^-$H-2M$^-$ compartments designated Class-II vesicles (CIIV), which are located in the periphery of the cell [55]. CIIV appear to emanate from MIIC as extensive tubules that separate off and move towards the cell periphery in a microtubule-dependent manner upon DC maturation [66, 67]. Maturation of DC also triggers neo-biosynthesis of MHC-I [53]. MHC-I, along with CD86 molecules, appear to accumulate in CIIV directly from the ER/trans-Golgi network [55, 67]. CIIV can fuse with the PM resulting in expression of MHC-II, CD86 and MHC-I at the cell surface [55, 67]. Concomitantly, maturing DC downregulate their endocytic capacity, thereby preventing reabsorption and degradation of MHC-II/peptide complexes and promoting their stable expression at the cell surface [68].

Functional maturation culminates with DC residing in T cell-rich areas of lymphoid tissues presenting peptide antigens acquired in the periphery in the context of MHC to passing T cells. MHC molecules are expressed 10–100 fold higher on mature DC than on B cells and monocytes [69]. Mature DC also upregulate expression of several costimulatory molecules including CD80, CD86 and CD40 [70] and also begin expression of a novel chemokine, DC-CK1, that preferentially attracts naïve (CD45RA$^+$) T cells [71]. They also

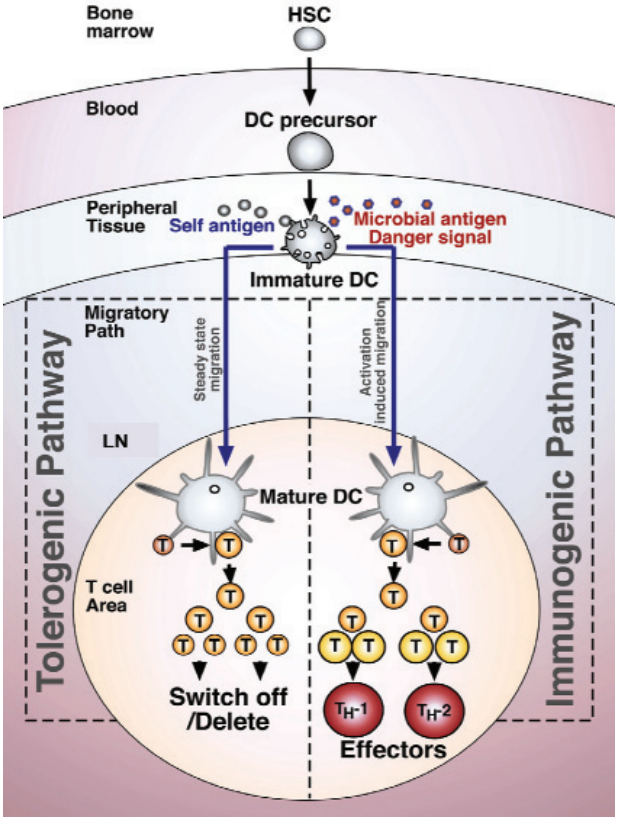

Fig. 1 A dual role for DC in immunity and tolerance. Hemopoietic stem cells (HSC) in bone marrow seed DC precursors in blood, which supply peripheral tissues with immature DC. Immature DC constitutively take up surrounding antigens, both self and foreign. In the immune steady-state, DC would commonly take up self antigens, mature and follow a tolerogenic pathway of development. They migrate with self antigens to T cell areas of lymphoid tissues where they present self antigen in the context of MHC and promote unresponsiveness in T cells specific for self antigens. Upon exposure to 'danger' signals, immature DC undergo activation during their maturation leading acquisition of immunogenic characteristics. They migrate to lymph nodes (LN) and present foreign antigen in the context of MHC and costimulatory molecules to T cells which are driven to differentiate into effector cells. The type of effector T cells generated, either T_H-1 or T_H-2, is influenced by the DC, and is dependent on the activating antigen. It is currently not known what signals lead to maturation of DC for T cell tolerance or how activationwith 'danger' signals leads to maturation and T cell immunity.

express several adhesion molecules including CD2, CD11a, CD54 (ICAM-1), CD58 (LFA-3), and the integrins β1 and β2 [6, 9]. These properties are thought to enable mature DC to attract and cluster with naïve T lymphocytes as has been observed *in vivo* [72]. MHC-II molecules in maturing DC have been observed to traffic in CIIV-like compartments directly toward the PM adjacent to interacting T cells in an antigen-dependent manner [66]. This culminates in MHC/antigen complex expression at the PM and selection of clustered antigen-specific T cells and their subsequent stimulation through costimulatory molecules. $CD4^+$ T cells respond by increasing surface expression of CD40L, which can in turn interact with CD40 on mature DC empowering them to directly stimulate naïve $CD8^+$ T cells [73, 74]. This bypasses the need for direct spatial interaction of $CD8^+$ T cells with T helper (T_H)-1 cells [73, 74].

Outcome of dendritic cell-T cell interactions

Although DC maturation can result in generation of effector T cells which facilitate immunity, functional maturation also appears to be required by DC which switch off T cell reactions. Two different pathways of DC development and functional maturation can lead to production of DC which can function in either tolerance or immunity. These are shown diagrammatically in Fig.1. The capacity to induce tolerance is important in the maintenance of peripheral self tolerance in the immune steady state [75]. A role for thymic DC in the central tolerisation of T cells to self antigens is well established [76]. More recently, a role for DC in the peripheral tolerisation of $CD4^+$ T cells and $CD8^+$ T cells *in vivo* has also been demonstrated in murine models and was thought to be mediated by immature DC [77, 78]. However, in the immune steady state, DC are continually taking up self antigens including apoptotic material and acquiring some properties of mature DC [75]. These include the capacity to migrate carrying self antigens to the draining lymph nodes [79–82]. Migration coincides with upregulation of MHC and costimulatory molecules and downregulation of endocytic capacity, classic features associated with DC maturation [83–85]. DC with these characteristics in lymph nodes draining an antigen source have been found to induce antigen-specific T cell tolerance [83]. Recent studies have also demonstrated that mature DC can induce $CD8^+$ T cell tolerance by inducing transient cell proliferation and apoptosis, while immature DC produce $CD8^+$ T cell ignorance [86]. Thus, in the immune steady state DC appear able to induce peripheral T cell tolerance that requires some functional maturation of DC.

A variety of 'danger' signals can lead to activation as well as maturation of DC [87]. These include, pathogen components like LPS, CpG DNA and double-stranded viral RNA, cytokines released during inflammation like tumour necrosis factor (TNF)-α, interleukin (IL)-1 and IL-4 and T cell ligands including CD40L and RANKL [6, 62]. However, depending on the type of danger signal, the DC subset receiving them and/or the cytokine profile present during T cell activation, DC can become activated in different ways leading to a diversity in the effector T cell responses generated [88–90]. For instance, $CD8^+$ murine DC can produce high levels of IL-12 and prime naïve $CD4^+$ T cells to secrete TH1 cytokines, while $CD8^-$ murine DC once activated prime naïve $CD4^+$ T cells to secrete T_H-0/T_H-2 cytokines [91]. While LPS derived from *E. coli* has been found to stimulate IL-12 production in $CD8^+$ DC resulting in T_H-1 effector responses, LPS derived from P. gingivalis does not induce IL-12 production by $CD8^+$ DC but induces a T_H-2 response [88]. Similarly, the yeast stage of the fungus *C. albicans* stimulates DC to produce IL-12 and a T_H-1 response, while the hyphae stage of *C. albicans* stimulates DC to produce IL-4 and a T_H-2 response [92]. Furthermore, DC in the presence of T_H cells producing IL-4 preferentially induce T_H-2 responses, while DC in the presence of interferon (IFN)-γ and IL-12 producing T_H cells, preferentially induce T_H-1 responses [90]. It is thought that a range of different activation states amongst the DC population allows generation of effector lymphocytes appropriate to deal with the pathogen at hand.

A role for dendritic cell-derived exosomes

Recent studies have shown that another defining property of DC is their capacity to secrete membrane vesicles called exosomes which can induce antigen-specific T cell responses [93–96]. Exosomes are

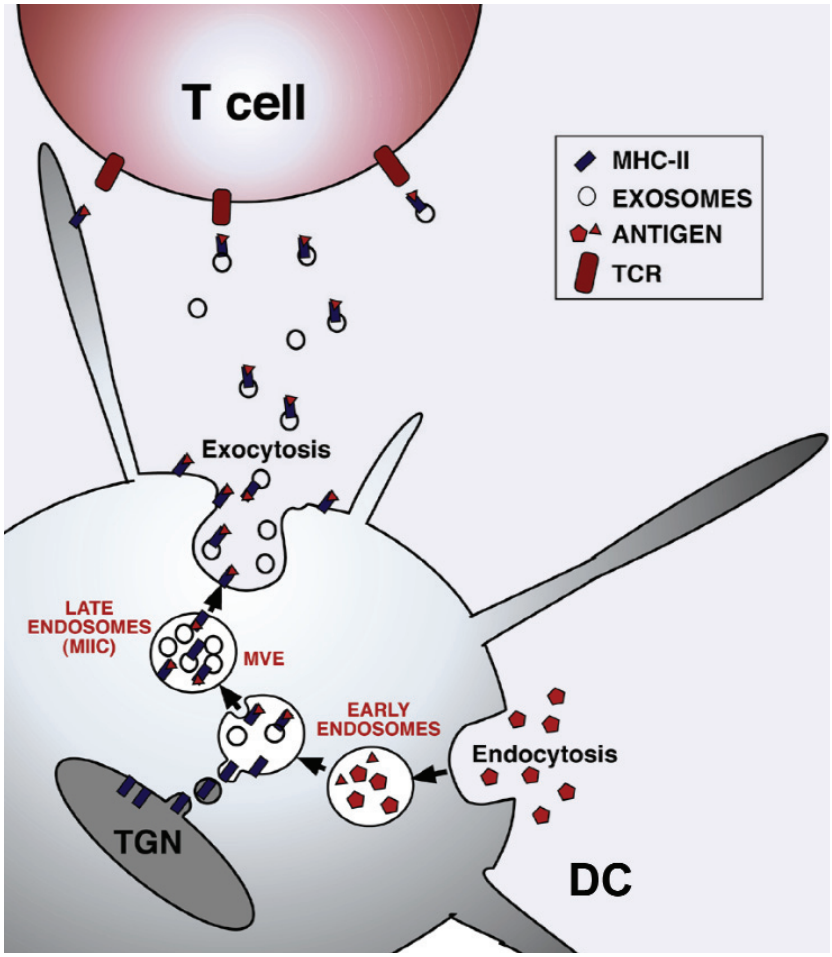

Fig. 2 Pathway for production of exosomes by DC. Antigens taken up by DC enter the endocytic pathway. Newly synthesised MHC-II molecules are transported from the trans-Golgi-network (TGN) to the endosomal pathway where they intercept with processed peptide antigens and form MHC-II rich compartments (MIIC). The limiting membrane of MHC-II rich compartments invaginate inwardly and bud off to give intraluminal vesicles. The multivesicular endosomes (MVE) formed by this process can fuse with the plasma membrane, thereby transporting their MHC-II/antigen complexes to the cell surface where internal vesicles or exosomes are released. Exosomes expressing MHC-II/antigen complexes can then trigger T cell activation. The mechanism of exosome-mediated T cell activation is not currently well understood. It could involve direct interaction with T cells (as shown), or indirect activation involving uptake of exosomes by functionally mature APC for antigen presentation.

thought to originate from intracellular compartments called multivesicular endosomes (MVE) by the inward invagination and budding from the limiting endosomal membrane. Exosomes isolated from antigen presenting cells like B cells and DC can express MIIC-specific markers like LAMP-1, MHC-II, CD63 and CD82 [56, 96]. When MVE fuse with the PM, exosomes are released into the extracellular environment. The process of production and release of exosomes by DC is shown in Fig. 2.

When B cell-derived exosomes were found to express MHC-II, including MHC-II in peptide-binding conformation [96], it was hypothesised that they could stimulate T cells. The response however was lower than that induced by parent B cells. Similarly, DC produced by *in vitro* culture of murine bone marrow precursors with GM-CSF and IL-4 were shown to produce immunostimulatory exosomes [56]. These DC-derived exosomes expressed MHC-I and CD86, and generated $CD8^+$ T cell responses *in vivo* against tumours [56]. In contrast, exosomes derived from steady state MHC-$II^{-/low}$ DC produced in long term stromal cultures express LAMP-1, a marker of MVE, but lack expression of the costimulator CD86 and MHC-II [95]. Isolated exosomes were found to be incapable of stimulating $CD4^+$ T cells *in vitro*. They could induce an anti-tumour response *in vivo* probably through exosome uptake by immunostimulatory DC [95]. Exosomes can therefore reflect the functional state and behaviour of antigen presenting cells that release them and not all DC-derived exosomes will be immunogenic. One extension of this hypothesis is that exosomes released by DC maturing in the steady state in the absence of 'danger' and activation signals, may be important mediators of peripheral tolerance. A further extension of the model is that foreign antigen taken up by DC in the steady state will induce tolerance to the antigen, and self antigens presented on DC in the presence of 'danger' signals could lead to an autoreactive response.

Despite poor capacity to stimulate T cell responses *in vitro*, DC-derived exosomes have been shown to have potent immunostimulatory potential *in vivo*, particularly in $CD8^+$ cytotoxic T cell responses against established tumours in mice [56, 95]. This finding applies to both MHC-II^+ DC generated *in vitro* by culture of precursors with cytokines like GM-CSF and IL-4 [56], as well as to non-immunogenic MHC-$II^{-/low}$ DC derived in long term stromal cultures in the absence of activating cytokines [95]. The increased immunogenicity of exosomes *in vivo* has been attributed to the uptake and representation of antigens by immunogenic DC in the animal. Exosomes are thought to be involved in the 'spreading' of MHC-II/peptide complexes between DC [97]. Indirect T cell stimulation *in vivo* by exosomes taken up by recipient DC has been well documented for both $CD8^+$ T cells [98, 99] and for $CD4^+$ T cells [100]. These *in vivo* findings suggest that exosomes may play an important immunoregulatory role in DC function and also in immune response development.

In the steady state in the absence of pathogenic invasion or inflammation, DC exist in an immature form [9]. It is not surprising, therefore, that exosomes produced by immature DC as opposed to more mature or activated DC express no CD86 [95] and may play a role in maintaining peripheral tolerance. In this situation, immature or maturing peripheral DC, would constantly process self antigens, and secrete exosomes bearing MHC/self antigen complexes. These exosomes could then disperse and arrive at draining lymph nodes where resident immature lymphoid DC could then endocytose or re-present exosomes. By displaying exosome-derived MHC/self antigen complexes, resident immature DC could maintain peripheral tolerance and so control autoreactive T cells. This would allow a constant source of peripheral self antigen to be presented to autoreactive T cells at the lymphoid tissues.

Upon pathogenic invasion however, exosomes could play a T cell sensitising role. In this situation, inflammatory mediators like TNF-α and products associated with pathogenic invasion like LPS, would trigger activation and maturation of DC, that had taken up and processed foreign antigen [53]. Activated DC, expressing high levels of MHC/foreign antigen complexes and costimulatory molecules, could migrate to the draining lymph node where they meet and stimulate T cells [9]. Activated DC still actively processing foreign antigen and expressing costimulatory molecules may secrete exosomes, incorporating costimulatory molecules, as well as MHC/peptide complexes. Exosomes rich in the ICAM-1 adhesion molecule as well as MHC/peptide and costimulatory molecules have recently been shown to be very effective in T cell activation [98]. Exosomes dispersing to the draining lymph node would then be presented on residential lymphoid DC for stimulation of T cells.

Exosomes playing the role of an antigen-bearing vector could allow transfer of large amounts of antigenic material from peripheral tissues to lymph nodes without the need for migration of large numbers of cells. This would also allow immunostimulatory DC which can no longer process antigen to present new foreign material from the periphery. Some evidence supporting a role for a soluble form of MHC/antigen complexes being transferred to the lymph node from peripheral tissues exists in the literature [101, 102].

Conclusions

Originally it was thought that different DC subsets may adopt specific roles in the immune response, however the dominant picture emerging shows less functional distinction between lineages of DC, so that each of the myeloid, lymphoid-like and plasmacytoid DC can function in both tolerance and immunity. The difficulties associated with *ex vivo* isolation of DC subsets, and particularly more immature DC, have impacted on our capacity to clearly delineate the function of DC in different states of maturation. The study of DC maturation of function is now complicated by evidence for plasticity amongst DC subsets. Tolerogenic DC appear to represent cells in a short-lived, immature or maturing state and so the properties of these cells are difficult to capture or immortalise in studies reliant on subset isolation. DC-derived exosomes can express immunostimulatory molecules and effectively mimick the immune potential of the parent DC. They have been shown to be very effective inducers of immunity following adoptive transfer. A role for DC-derived exosomes in tolerance induction is also proposed in light of the need for a migratory vector for efficiently moving antigen from the periphery into lymph nodes for tolerisation of T cells.

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