Plasma membrane ion channels and epithelial to mesenchymal transition in cancer cells

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Abstract

A variety of studies have suggested that epithelial to mesenchymal transition (EMT) may be important in the progression of cancer in patients through metastasis and/or therapeutic resistance. A number of pathways have been investigated in EMT in cancer cells. Recently, changes in plasma membrane ion channel expression as a consequence of EMT have been reported. Other studies have identified specific ion channels able to regulate aspects of EMT induction. The utility of plasma membrane ion channels as targets for pharmacological modulation make them attractive for therapeutic approaches to target EMT. In this review, we provide an overview of some of the key plasma membrane ion channel types and highlight some of the studies that are beginning to define changes in plasma membrane ion channels as a consequence of EMT and also their possible roles in EMT induction.
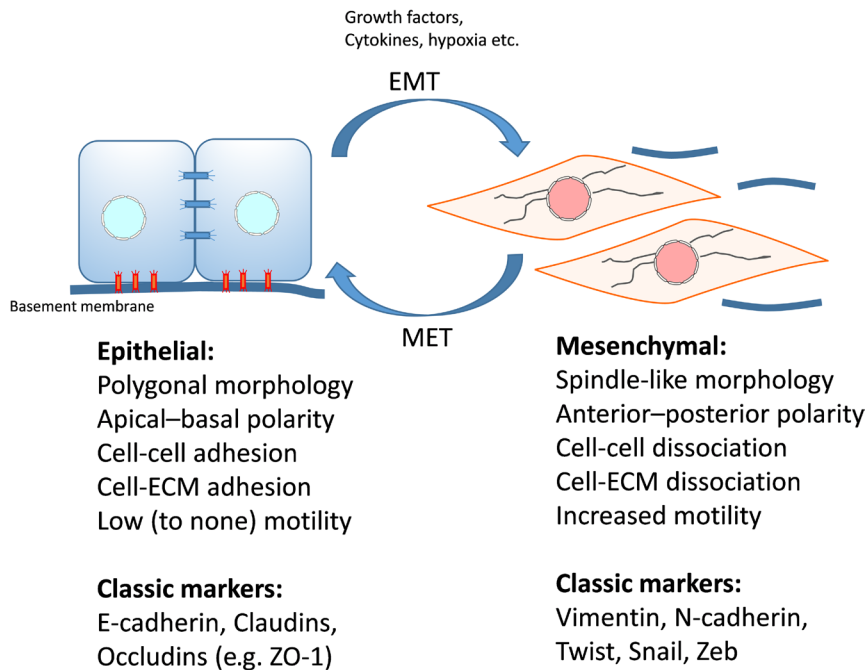
Introduction

Epithelial to mesenchymal transition (EMT) refers to the process whereby epithelial cells which typically exhibit features such as strong cell to cell adhesion and apical-basal polarity, lose these properties and acquire others such as greater motility and a spindle like morphology (Thiery *et al.* 2009, van Denderen & Thompson 2013) (Fig. 1). EMT is a key event in developmental processes including embryogenesis where it is associated with implantation and embryonic gastrulation (Kalluri & Weinberg 2009). EMT is also a feature of other aspects of normal physiology such as wound healing where it has an important role in tissue regeneration, and organ fibrosis (Kalluri & Weinberg 2009).

EMT in cancer

Metastasis is the cause of mortality in cancer types that originate from organs where surgical resection and/or treatment of the primary tumour are often feasible (e.g. breast and prostate). Metastasis is a highly regulated process whereby cells escape the primary tumour, enter the circulatory system and deposit at a metastatic site (Hanahan & Weinberg 2011). There is clear coordination of processes in metastasis and this is reflected in the propensity of different cancer subtypes to preferentially form metastatic lesions in specific sites. The loss of cell-to-cell adhesion, the acquisition of motility, the ability to degrade the surrounding extracellular matrix and to survive stresses such as that induced by entry into the circulation are all features that are required of cancer cells during metastasis. It is therefore not surprising that it is believed that as cells leave the primary tumour they may undergo processes similar to EMT (Heerboth *et al.* 2015). These include the expression of the specific transcription factors Snail and Twist, expression of mesenchymal

Growth factors,
Cytokines, hypoxia etc.

EMT

MET

Basement membrane

Epithelial:
Polygonal morphology
Apical–basal polarity
Cell-cell adhesion
Cell-ECM adhesion
Low (to none) motility

Classic markers:
E-cadherin, Claudins,
Occludins (e.g. ZO-1)

Mesenchymal:
Spindle-like morphology
Anterior–posterior polarity
Cell-cell dissociation
Cell-ECM dissociation
Increased motility

Classic markers:
Vimentin, N-cadherin,
Twist, Snail, Zeb

Figure 1
Epithelial to mesenchymal transition (EMT). EMT is a reversible process whereby epithelial cells with polygonal morphology, apical–basal polarity, and high cell–cell/cell–ECM adhesion, and stationary position acquire mesenchymal features including spindle-like morphology, anterior–posterior polarity, cell–cell/cell–ECM dissociation and enhanced motility. EMT can be induced by microenvironmental factors including growth factors, cytokines and hypoxia. The reverse process of EMT is called mesenchymal to epithelial transition (MET).

markers such as vimentin and N-cadherin, and loss of epithelial markers such as E-cadherin (Tsai & Yang 2013). Indeed, the consequences of EMT have been reported as increased motility and a remodelling of cellular adhesion (Lamouille *et al*. 2014). EMT in cancer cells is also associated with the acquisition of therapeutic resistance (Singh & Settleman 2010). Although some very recent studies indicate that in some cancers EMT may be more important in the acquisition of therapeutic resistance than metastasis (Fischer *et al*. 2015, Zheng *et al*. 2015), understanding the induction of EMT and the properties of the mesenchymal state would clearly help identify novel therapeutic targets.

A number of factors in the tumour microenvironment have been identified as inducers of EMT in cancer cells. In breast cancer cells, growth factors such as epidermal growth factor (EGF), and hypoxia have been shown to induce EMT in a variety of *in vitro* models, such as MDA-MB-468 breast cancer cells and ZR-75-1 breast cancer cells (Lester *et al*. 2007, Davis *et al*. 2014*a*). In prostate cancer cells, EMT is induced by epidermal growth factor (EGF) (Zhang *et al*. 2013*b*) and Growth and differentiation factor 9 (GDF-9) (Bokobza *et al*. 2011). Studies in lung cancer cells have demonstrated that hypoxia induces EMT through protein kinase A (PKA) activity in a hypoxia-inducible factor 1-alpha (HIF1-α) dependent manner (Shaikh *et al*. 2012). A variety of druggable targets have been identified as potential mechanisms to control EMT induction and/or target the mesenchymal phenotype

which is a consequence of EMT (Davis *et al*. 2014*b*). One class of proteins that are the target of existing drugs and many drug development programs are ion channels. Plasmalemmal ion channels in particular are often amenable to pharmacological modulation due to their extracellular domains. The availability of selective inhibitors to specific ion channel isoforms also allows chemogenomic and other methods to develop new therapeutics.

Ion channels as regulators of cellular processes

The presence of ion gradients across the plasma membrane is a defining feature of mammalian cells. The sodium ion gradient is maintained by Na^+/K^+-ATPases that actively pump Na^+ ions from the cytoplasm to maintain a lower intracellular free Na^+ level compared to those of the extracellular space (Castillo *et al*. 2015). Changes in this gradient can lead to rapid changes in membrane potential and drive action potentials in excitable cells. Similarly, changes in cytosolic free Ca^{2+} ($[Ca^{2+}]_{CYT}$) levels can be mediated by activation of Ca^{2+} permeable ion channels and such changes have important roles in an array of cellular processes including fertilization, muscle contraction, hormone secretion, gene transcription and cell death (Berridge *et al*. 2003). The diversity of processes influenced by changes in Na^+, Ca^{2+} and K^+ and other ions through the opening of ion channels, requires the

cell to selectively control such changes and the way such changes are decoded to alter cellular processes. Hence, it is not surprising that there are a plethora of ion channels in cells. For example there are over 20 genes that encode for just one specific class of ion channel – transient receptor potential (TRP) channels in humans. The next section provides an outline of the general properties of ion channels relevant to this review. We then provide a specific overview of studies that have identified roles of ion channels in EMT induction and/or remodelling.

Plasma membrane ion channels

There are a variety of ion channels with different permeability and selectivity for cations or anions. A comprehensive review of all ion channels even just those of the plasma membrane is well beyond the scope of this review. Hence, readers are directed to sources of comprehensive lists and review of ion channels such as the IUPHAR/BPS guide to pharmacology (Southan et al. 2016), which includes other channels not discussed in this review such as acid-sensing (proton-gated) ion channels (ASICs) and some ligand gated Ca^{2+} channels such as ionotropic glutamate receptors. Arguably, the most extensively studied plasma membrane ion channels are those depicted in Fig. 2 – which include calcium channels, sodium channels, potassium channels and chloride

channels. Examination of each of these channel types provides insight into their diversity. These channels can differ dramatically in their properties from ion selectivity to their mechanism of activation.

The diversity in ion channel properties is clear in the plasma membrane Ca^{2+} channels presented in Fig. 2 – Orai, TRP, P2X and voltage gated Ca^{2+} channels (VGCC). These classes have clear differences in their mechanism of activation. For example the Orai1 protein is part of a complex whereby Ca^{2+} influx is activated by the depletion of endoplasmic reticulum Ca^{2+} stores (Azimi et al. 2014). In contrast, TRP channels have been described as sensors, as exemplified by TRPV1 a Ca^{2+} permeable ion channel activated by heat and the hot chilli component, capsaicin (Azimi et al. 2014). Other ligand gated calcium channels include ionotropic glutamate receptors and also P2X channels that are activated by some nucleosides (e.g. ATP) whereas VGCCs are activated by changes in membrane potential (Azimi et al. 2014). Even within classes of Ca^{2+} channels there is great diversity of activators (e.g. TRPV1 is activated by capsaicin whereas TRPM8 is activated by menthol) and ion selectivity (e.g. TRPV6 is highly selective for Ca^{2+} ions whereas TRPV1 is also permeable to Na^+ ions) (Azimi et al. 2014). The remodelling of Ca^{2+} channel expression has been defined in some cancers and some have been identified as potential therapeutic targets in some cancer subtypes as reviewed elsewhere
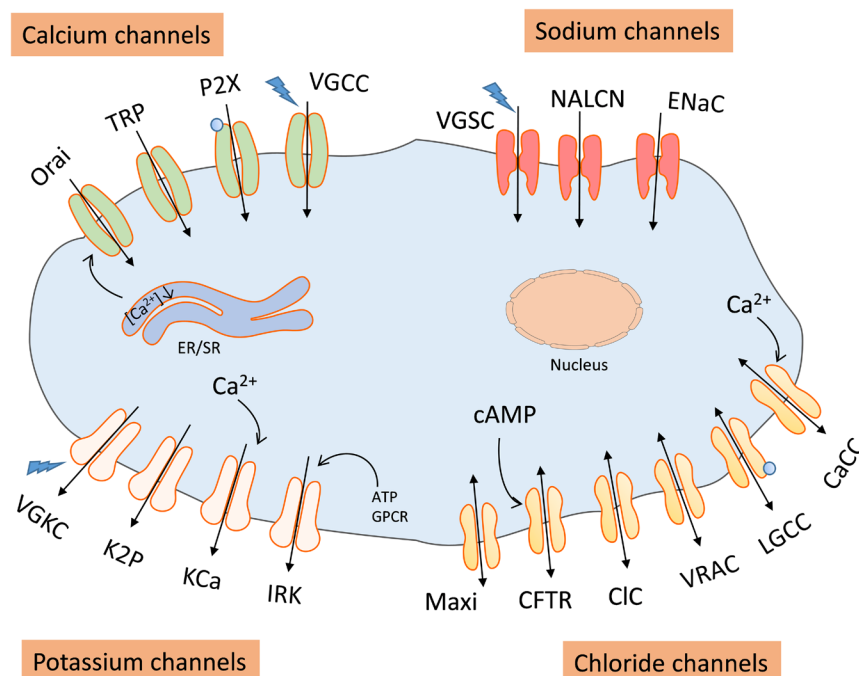

Figure 2
Plasma membrane ion channels. Plasma membrane calcium channels include Orai (activated by Ca^{2+} store depletion), transient receptor potential (TRP), P2X (activated by ligands such as ATP), and voltage gated Ca^{2+} channels (VGCC). Plasma membrane sodium channels include voltage-gated sodium channels (VGSC), sodium leak channel (NALCN) and epithelial sodium channel (ENaC). Plasma membrane potassium channels include voltage gated channels (VGKC two-pore domain (K2P) channels, Ca^{2+}-activated channels (KCa) and inwardly rectifying channels (IRK). Plasma membrane chloride channels include maxi channels, cystic fibrosis transmembrane conductance regulator (CFTR), Ca^{2+}-activated channels (CaCC), ligand-gated channels (LGCC), volume-regulated anion channels (VRAC), and the chloride channel superfamily (ClC).

(Azimi *et al*. 2014, Stewart *et al*. 2015). Indeed, SOR-C13, a TRPV6 inhibitor has been recently assessed in clinical trials of ovarian cancer (www.clinicaltrials.gov, NCT01578564).

Although the association between Na+ influx and action potentials has seen a focus on Na+ channel in neuroscience and cardiovascular research, Na+ channels are in fact expressed in a variety of cell types. For example voltage gated sodium channels (VGSC) are expressed in excitable cells including neurons and muscle cells, where they are responsible for action potential and conduction (Southan *et al*. 2016); NALCN has been described as a sodium leak channel which regulates the resting membrane potential and excitability in neurons (Cochet-Bissuel *et al*. 2014); and epithelial sodium channels (ENaC) play pivotal roles in the regulation of extracellular fluid (ECF) volume and blood pressure in kidney tubules (Hanukoglu & Hanukoglu 2016). Potassium channels are equally as complex and diverse and include those that are voltage gated (VGKC), those that are two-pore domain (K2P), those that play roles in Ca²⁺-activated K⁺ transport (KCa channels) and Inwardly rectifying K⁺ (IRK) channels (Hibino *et al*. 2010).

Chloride channels include channels that when defective due to hereditary mutation can alter the fluid transport in epithelial cells resulting in cystic fibrosis (Cystic Fibrosis Transmembrane conductance Regulator (CFTR)), channels activated by intracellular Ca²⁺ (CaCC), those which are ligand activated (LGCC), or volume regulated (VRAC) or the chloride channel superfamily (CIC) (Southan *et al*. 2016).

The outline of plasmalemmal ion channels presented above highlighted the diversity of ion channels and their roles in mammalian cells. As discussed below, some of these ion channels have recently been shown to be remodelled as a consequence of EMT in cancer cells or play roles in the induction of EMT markers induced by some stimuli.

Plasma membrane ion channels and EMT in cancer cells

This review is focused on the remodelling and in some cases roles of ion channels in EMT in cancer cells. It should be noted that other studies have investigated ion channels in EMT in the context of other EMT relevant processes many of which intersect with disease states such as airway remodelling (Arthur *et al*. 2015) and renal fibrosis (Mai *et al*. 2016).

The very different properties of cancer cells such as the acquisition of therapeutic resistance and the major

changes in the expression of specific proteins (e.g. vimentin) and transcription factors (e.g. twist and Snail) as a consequence of EMT means that changes in ion influx should not have been surprising. The change in phenotype of cancer cells that have undergone EMT and the very specific roles of specific ion channels in different cell types suggests that the mesenchymal phenotype will exploit different ion channels to achieve different cellular functions. In the section below we will provide an overview of studies that have now shown such changes and in some cases implicated specific ion channels in EMT induction. Many of these studies are summarised in Table 1.

Sodium channels and EMT in cancer cells

Hypotheses have been proposed and an intellectual case made for the potential of voltage-gated sodium channels to regulate EMT induction in cancer cells (Eren & Oyan 2014, Eren *et al*. 2015). The repositioning of clinically used voltage-gated sodium channel blockers to attenuate metastatic progression and/or chemotherapy resistance through inhibition of EMT induction has also been highlighted (Eren *et al*. 2015). However, this area has yet to be fully assessed experimentally with models of EMT in cancer cells, and this represents an opportunity for future research.

Potassium channels and EMT in cancer cells

The association between changes in the potassium gradient and EMT was suggested in early studies of potassium chloride co-transporter 3 (KCC3) (Hsu *et al*. 2007). KCC3 is not an ion channel, but its ability to cotransport K⁺ and Cl⁻ ions makes it an important regulator of the flux of these ions across the plasma membranes of many cell types where it can play an important role in the regulation of cell volume (Hsu *et al*. 2007, Kahle *et al*. 2015). Forced overexpression of KCC3 in cervical cancer SiHa cells is associated with the adoption of a more mesenchymal-like morphology, the down regulation of the epithelial marker E-cadherin and the upregulation of the mesenchymal marker vimentin (Hsu *et al*. 2007). Subsequent to these studies an association with the EAG1 potassium channel and EMT in lung cancer cells has been implicated, because of an increase in Eag1 mRNA levels in A549 lung cancer cells treated with transforming growth factor beta 1 (TGFβ1), an EMT inducer in this model (Restrepo-Angulo *et al*. 2011). In context of colorectal cancer, studies of phosphatase of regenerating liver-3 (PRL-3) induced EMT in LoVo cells

Table 1 Ion channels with roles in EMT in cancer cells. List of ion channels that have been identified to be remodelled during EMT and/or have roles in the induction of EMT in cancer cells, including the target they affect and any characterised consequential effects.

Channel	EMT induced by	Cancer	Cell line	Mechanism/affected target	Reference
TRPM7	EGF	Breast	MDA-MB-468	Vimentin protein-possibly via STAT3	Davis et al. (2014a)
Orai1/STIM1	Oct4 silencing	Breast	MCF7	E-cadherin and α-smooth muscle actin (α-SMA)-possible mechanism via enhancement in SOCE	Hu et al. (2011)
TRPM8	Basal (not induced)	Breast	MDA-MB-231	Activating AKT/glycogen synthase kinase-3 beta (GSK-3β)	Liu et al. (2014)
TRPC6	Doxorubicin	Hepatocellular carcinoma	Huh7 and HepG2	E-cadherin-regulation of calcium-dependant multi-drug resistance (MDR)	Wen et al. (2016)
KCNN4	PRL-3	Colorectal	LoVo	Snail and E-cadherin. Mechanism via CaM-kinase II GSK-3β	Lai et al. (2013)
EAG1	TGFβ1	Lung	A549	TGFβ1-induced EMT upregulates EAG1 mRNA and protein expression-consequence was not explained	Restrepo-Angulo et al. (2011)
CLCA2	Basal (not induced)	Breast	HMLE	Loss of CLCA2 promotes EMT, migration and invasion	Walia et al. (2012)
CLCA4	TGFβ	Breast	HMLE	Via upregulating N-cadherin, vimentin, and fibronectin, and downregulating E-cadherin	Yu et al. (2013)
CFTR	TGF-β1	Breast	MCF7MDA-MB-231	Downregulation of CFTR promotes EMT, migration and invasion	Zhang et al. (2013a)
TMEM16A	Basal (not induced)	Head and neck	T24	Silencing promotes EMT by regulation of snail and E-cadherin	Shiwarski et al. (2014)

(a colon cancer cell line), has shown that a pharmacological inhibitor of the Ca^{2+} activated potassium channel KCNN4 – TRAM-34, supresses the mesenchymal markers vimentin and Snail, and increases the expression of the epithelial marker E-cadherin (Lai et al. 2013). Although the concentrations of TRAM-34 used may have inhibited other ion channels, siRNA to KCNN4 phenocopied the effects of TRAM-34 (Lai et al. 2013). Moreover, KCNN4 expression was positively correlated with tumour stage in clinical cohort of 86 patient colorectal tumour samples (Lai et al. 2013). Very recent studies have now shown that silencing of KCNN4 in MDA-MB-231 (a breast cancer cell line with features of the mesenchymal phenotype) appeared to reduce the expression of the mesenchymal markers vimentin and Snail (Zhang et al. 2016).

Collectively, the studies described above are beginning to define associations between specific potassium channels and EMT in cancer cells. Further studies of other potassium channels in the context of changes in expression as

a consequence of EMT as well as the induction of EMT and/or maintenance of the mesenchymal phenotype now seem appropriate. Given the diversity of EMT models in cancer cells and the variety of inducers of EMT, it is also important that the roles of specific potassium channels be investigated across a variety of models and inducers of EMT.

Chloride channels and EMT in cancer cells

An increasing number of studies have identified the remodelling of expression of chloride channel components as a consequence of EMT in cancer cells. Examples of such remodelling include isoforms of chloride channel accessory proteins, namely CLCA2 and CLCA4. CLCA2 mRNA levels are reduced in breast cancer cell lines associated with the mesenchymal phenotype (e.g. MDA-MB-231 and BT549) compared to those often enriched in epithelial markers (e.g. MCF-7). Indeed, expression of the EMT

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transcription factor Snail supresses CLCA2 protein in the human breast cell line MCF10A, and CLCA2 levels are reduced in subpopulations of cells from the human mammary epithelial (HMLE) cell line that are enriched in mesenchymal markers (Walia *et al.* 2012). Moreover, CLCA2 levels are reduced during EMT induced by TGFβ (Yu *et al.* 2013). Similarly, reduced levels of the related isoform CLCA4 is a feature of subpopulations of cells from the HMLE cell line that are enriched in mesenchymal markers and a consequence of TGFβ-induced EMT (Yu *et al.* 2013). Consistent with the loss of CLCA2 and CLCA4 in the mesenchymal phenotype, low levels of CLCA2 and CLCA4 appear likely to be associated with an increased incidence of metastasis (as assessed through metastasis or relapse free survival) using specific cohorts of breast cancer patients (Walia *et al.* 2012, Yu *et al.* 2013). In addition to their remodelling as a consequence of EMT, CLCA2 and CLCA4 have also been implicated in the regulation of the transition of breast cancer cells towards a more mesenchymal state. Knockdown of CLCA2 or CLCA4 is sufficient in HMLE cells to induce the expression of the mesenchymal marker vimentin and supress the epithelial marker E-Cadherin (Walia *et al.* 2012, Yu *et al.* 2013). In the case of CLCA2, the regulation of EMT may at least in part be through interactions with the cell junctional protein EVA1 (Ramena *et al.* 2016). Future studies are now required to define the relative importance in changes in chloride flux in these events, and the ability of the loss of CLCA2 or CLCA4 to induce a mesenchymal phenotype in other models of EMT, including those not of breast cancer origin.

Breast cancer cells have also been the focus of investigators exploring the relationship between CFTR and EMT. The EMT inducer TGFβ1 causes a down regulation of CFTR in MCF-7 cells, which is also associated with a down regulation of the epithelial marker E-cadherin (Zhang *et al.* 2013*a*). A functional role for CFTR in EMT induction is suggested by the ability of CFTR silencing to induce the expression of a variety of mesenchymal markers in MCF-7 breast cancer cells. This proposed function of CFTR is further supported by the ability of CFTR overexpression in mesenchymal-like MDA-MB-231 breast cancer cells to suppress the expression of vimentin (a mesenchymal marker) and induce the expression of E-cadherin (an epithelial marker) (Zhang *et al.* 2013*a*). As would be predicted based on these results, reduced levels of CFTR are associated with poor prognosis in breast cancer patients (Zhang *et al.* 2013*a*). More recent studies have begun to explore chloride channels in the context of EMT in other cancer types, such as squamous cell carcinomas of the head and neck (Shiwarski *et al.* 2014). TMEM16A (also known as ANO1), is one of a reported subset (termed Anoctamins) of calcium activated chloride channels (Kunzelmann *et al.* 2011). Levels of TMEM16A are reduced in cancer cells in metastatic lymph nodes compared to those of the primary tumour in squamous cell carcinomas of the head and neck (Shiwarski *et al.* 2014). TMEM16A seems to be more than a potential marker of EMT, since silencing of TMEM16A in T24 cells (a human bladder carcinoma cell line), produces a mesenchymal-like phenotype (spindle morphology, lower E-cadherin, increased Snail) and overexpression of TMEM16A produces an epithelial-like phenotype (rounded packed morphology, increased E-cadherin, reduced vimentin and fibronectin) (Shiwarski *et al.* 2014).

The work described above, performed by a variety of investigators using an array of models and approaches has now helped define a remodelling of specific chloride channels (or components) in EMT and a role for these same channels in the induction of EMT and/or the maintenance of the epithelial-like phenotype.

Calcium channels and EMT in cancer cells

The calcium signal has been identified as or could be speculated to be a potential mechanism by which at least some of the aforementioned ion channels may immediate their effects on EMT. For example the mechanism by which KCNN4 may regulate EMT in colon cancer cells has been linked to effects on calcium signalling (Lai *et al.* 2013). Indeed, global chelation of intracellular free Ca^{2+} that attenuates increases in cytosolic free Ca^{2+}, suppresses both EGF and hypoxia induced increases in the mesenchymal markers vimentin, N-cadherin and CD44 (Davis *et al.* 2014*a*). Similar findings have now been reported in Huh7 and HepG2 hepatic cancer cell lines for EMT induced by doxorubicin (Wen *et al.* 2016). It is also now clear that a major remodelling in calcium signalling and the expression of specific calcium permeable ion channels is a feature of EMT and some calcium permeable ion channels are important in the induction of expression of some proteins associated with the mesenchymal phenotype.

Alterations in the responses to ATP, able to activate G-protein coupled purinergic receptors (P2Y family) and ligand gated Ca^{2+} channels (P2X family) is a feature of both EGF and hypoxia induced EMT in MDA-MB-468 breast cancer cells (Davis *et al.* 2011, Azimi *et al.* 2015).

EMT induced by hypoxia and EGF is associated with the attenuation of peak $[Ca^{2+}]_{CYT}$ and the sustained phase of Ca^{2+} influx induced by ATP. EMT is also associated with a reduction in the sensitivity to ATP with an increase the EC_{50} (Davis *et al.* 2011, Azimi *et al.* 2015). Such changes in the mesenchymal phenotype may be an adaption of breast cancer cells to the high ATP concentrations in some tumour microenvironments. However, despite this consistent change in ATP-mediated Ca^{2+} signalling, the nature of the remodelling of P2X receptors seems very different as the upregulation of P2X5 mRNA is a feature of EGF but not hypoxia associated ATP (Davis *et al.* 2011, Azimi *et al.* 2015). The attenuation of store operated Ca^{2+} entry (SOCE) and basal Ca^{2+} influx is also a feature of EGF induced EMT in MDA-MB-468 (Davis *et al.* 2012), however, assessment of such changes with hypoxia induced EMT has not been reported. Such studies are critical given that in MCF-7 cells, the EMT inducer TGF-β1 has been reported to be associated with enhancement of store operated Ca^{2+} entry (Hu *et al.* 2011).

In addition to a remodelling of Ca^{2+} influx and/or the expression of some Ca^{2+} permeable ion channels in EMT in cancer cells, specific calcium permeable ion channels have also been identified as regulators of the induction of at least some hallmarks of EMT. A focused siRNA screen identified TRPM7 as a regulator of EGF-induced expression of the mesenchymal marker vimentin in MDA-MB-468 breast cancer cells (Davis *et al.* 2014*a*). A pharmacological inhibitor of TRPM7 replicated the consequences of TRPM7 silencing on EGF induced vimentin expression. These effects were not due to general inhibition of EGF receptor (EGFR) signalling since EGF-mediated EGFR and AKT phosphorylation were unaffected by TRPM7 silencing, however, EGF-mediated STAT3 and ERK1/2 phosphorylation were significantly reduced (Davis *et al.* 2014*a*). Although a Ca^{2+} permeable ion channel, the importance of TRPM7 in Mg^{2+} homeostasis and its ability to function as an atypical alpha kinase (Paravicini *et al.* 2012) require further attention into the nature of its contribution to EMT in some cancer models. Silencing of the cold sensor TRPM8 increases the expression of the epithelial marker E-cadherin in mesenchymal-like MDA-MB-231 cells and reduces levels of the mesenchymal marker vimentin (Liu *et al.* 2014). Consistent with a role for TRPM8 in the maintenance and/or induction of the mesenchymal phenotype in breast cancer cells, overexpression of TRPM8 in the more epithelial like MCF-7 cell line leads to EMT induction as indicated by down regulation of E-cadherin and induction of vimentin (Liu *et al.* 2014). In Huh7 and HepG2 hepatic cancer cells,

TRPC6 silencing attenuates changes in the expression of E-cadherin induced by doxorubicin suggesting that in the ability of TRPC6 silencing to increase sensitivity to doxorubicin through effects of resistance pathways may be due at least in part to effects on some aspects of EMT induction (Wen *et al.* 2016).

Hence, studies of calcium signalling and Ca^{2+} permeable ion channels in EMT from a variety of groups using an array of EMT inducers and models have helped define a critical role for the Ca^{2+} signal in EMT in cancer cells.

Conclusion

An increasing number of studies have reported the remodelling of plasma membrane ion channel expression as a characterizing feature of EMT in cancer cells. The identification of the role of specific ion channels in the induction of EMT and/or the maintenance of aspects of the epithelial or mesenchymal-like phenotype in cancer cells suggest that some ion channels may be therapeutic targets to control EMT and hence disease progression (e.g. therapeutic resistance). However, it is likely that different EMT inducers may engage different ion channels to regulate the properties of the mesenchymal phenotype and/or EMT induction itself. This issue and the study of the intersection between sex hormones and receptors that regulate EMT (Zuo *et al.* 2010, van der Horst *et al.* 2012, Sun *et al.* 2014, Kong *et al.* 2015, Jeon *et al.* 2016) and ion channels which themselves intersect with sex hormone pathways (Asuthkar *et al.* 2015, Hao *et al.* 2015, Mahmoodzadeh *et al.* 2016) are areas for future research. Which ion channels to pursue for therapeutic targeting requires careful consideration, and deciding factors will include the expression of targets in other cell types and the likely adverse systemic effects of channel inhibitors. However, the successful use of ion channel inhibitors for conditions as diverse as cardiovascular disease to pain demonstrated the need to continue research in this area.

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