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Role of HOX Genes in Stem Cell Differentiation and Cancer

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Received 1 March 2018; Revised 8 May 2018; Accepted 15 May 2018; Published 22 July 2018

1. HOX Genes

HOX genes are master transcriptional regulators that have diverse roles from embryogenesis to carcinogenesis. The HOX genes are an evolutionary conserved family of genes that control anterior-posterior axis and dorsal-ventral anatomic development during embryogenesis. In humans there are a total of 39 HOX genes situated in clusters on four different chromosomes (7p15, 17q21.2, 12q13, and 2q31). These clusters are named as four HOX families: HOXA, HOXB, HOXC, and HOXD. Each family consists of 13 paralog groups with nine to eleven numbers assigned based on their sequence similarity and position within the cluster (Figure 1(a)). HOX genes contain two exons and a single intron. Exon 2 contains a 120-nucleotide sequence, known as homeobox. This homeobox encodes a 61 amino acid helix-turn-helix motif known as a homeodomain (Figure 1(b)). The protein products of the HOX genes are transcription factors that are capable of binding to specific nucleotide sequences on the DNA.

1.1. HOX Genes and Stem Cell Differentiation. SCs are multipotent cells that have the ability to self-renew or to differentiate along multiple lineages. HOX genes have been shown to play crucial roles during SC differentiation from embryonic stages of development to tissue-specific SC functions. Of the 39 HOX genes, mutations in 10 HOX genes (HOX1, HOX2, HOX4, HOX5, HOX6, HOX7, HOX8, HOX9, HOX10, and HOX11) have been found to cause human disorders with variations in their inheritance patterns, penetrance, expressivity, and mechanisms of pathogenesis [1]. Congenital defects caused by mutations in HOX genes support the concept that HOX gene function is crucial for SCs during development and differentiation.
Therefore, we reviewed the published literature for the role of HOX genes during differentiation of three main types of SC, namely, (i) embryonic SCs, (ii) adult SCs (hematopoietic SCs, colonic SCs, and mesenchymal SCs), and (iii) induced pluripotent SCs.

1.1.1. HOX Genes and Embryonic Stem Cell Differentiation. Embryonic stem cells (ESCs) are obtained from the inner cell mass of the blastocyst. ESCs are pluripotent cells that can give rise to most cell types except the placenta and umbilical cord. Retinoic acid (RA) signaling regulates HOX gene expression in ESCs during embryonic development. In adult neurogenesis, ESCs treated with RA almost exclusively differentiate into neurons and develop a HOX-related expression profile [2]. Retinoid acid response elements (RAREs) are found in regulatory regions of many HOX genes [3, 4]. In mice, RAREs are found in Hoxa1, Hoxa4, Hoxb1, Hoxb4, and Hoxd4 [5–14]. Several HOX genes have been found to be strongly upregulated during differentiation in the presence of RA [15]. RA receptor γ (RARγ) was found to be essential for RA-induced HOX gene transcriptional activation in ESCs. Deletion of its binding site in the Hoxa1 enhancer attenuates transcriptional and epigenomic activation of both Hoxa and Hoxb gene clusters. It was reported that RA/RARγ signaling is critical for the removal of histone methylation occurring on the amino terminal tail core of the core histone H3 (H3K27me3) from activated Hox genes during ESC differentiation [16]. The entire Hox cluster is actively repressed occurring on the amino terminal tail core of the core histone H3 (H3K27me3) from activated Hox genes during ESC differentiation [16]. The entire Hox cluster is actively repressed by ESC-derived hematopoietic stem cells (HSCs). Furthermore, Hoxb4 acts as a master regulator of ESC differentiation into HSCs by directly targeting multiple essential hematopoietic transcription factors and epigenetic factors [20]. Overall, these results show that complex regulatory mechanisms exist through which Hox genes are expressed in ESCs and function during differentiation.

1.1.2. HOX Genes and Adult Stem Cells. Adult SCs, also referred to as somatic or tissue-specific SCs, give rise to different cell types that are specific to each tissue type or organ in which they reside. HOX genes are crucial for the maintenance and functioning of adult SCs. Here, we focus on three types of adult SCs: hematopoietic SCs that generate entire blood cell lineages, colonic SCs that reside at the base of the normal crypt and are responsible for colonic tissue renewal and proper functioning of the colon, and mesenchymal SCs isolated from the stroma and that generate various differentiated cell types from bone, cartilage, and fat cells.

1.1.3. HOXA5. HOXA5 overexpression in bone marrow CD34+ SCs and cord blood CD34+ CD38− cells resulted in
a significant shift in myeloid differentiation [25]. When HOXA5 was overexpressed in HSCs, erythroid progenitors (burst-forming unit-erythroid BFU-E) were significantly decreased in frequency among all progenitors, with no reduction in total colony-forming unit (CFU) numbers [25]. Similarly, the overexpression of HOXA5 inhibited erythroid differentiation of K562 cells [26]. In contrast, the knockdown of HOXA5 in human bone marrow cells resulted in the inhibition of granulocytic/monocytic hematopoiesis and increased erythroid progenitors [26]. Overall, these studies showed that HOXA5 is crucial for the balance between myeloid and erythroid differentiation.

1.1.4. HOXA7. Hoxa7 knockout mice showed reduced megakaryocytic/erythroid progenitors (MEP) and exhibited reticulocytosis and thrombocytopenia without anemia [27], suggesting that HOXA7 is required for MEP differentiation.

1.1.5. HOXA9. HOXA9 is one of the most abundant HOX genes in HSCs. HOXA9 is downregulated during HSC differentiation [24, 28]. Hoxa9 knockout mice displayed marked lymphopenia (low levels of lymphocytes in the blood) and substantial reductions of common lymphoid progenitors (CLPs) and lymphoid precursors. In addition, significant reduction of common myeloid progenitors (CMPs) and granulocyte/monocyte progenitors (GMPs) was observed upon Hoxa9 knockout in vivo [27]. Hoxa9 knockout mice also showed a reduction in the number of total leukocytes [29], and the loss of expression of Hoxa9 impaired the proliferating and repopulating ability of HSCs [30]. HOXA9 thus appears to regulate HSC proliferation, self-renewal, and myeloid and lymphoid differentiation.

1.1.6. HOXA10. HOXA10 overexpression in human cord blood and fetal liver CD34+ cells resulted in a significant
production of blast cells (undifferentiated blood cells, commonly seen in acute leukemia) and myelopoiesis concomitant with a complete block of erythroid differentiation and a severe reduction in B cell development [31]. Thus, these findings suggest that the regulation of HOXA10 expression is crucial for preventing abnormal development and differentiation of HSCs.

1.1.7. HOXB3. In mice, the overexpression of Hoxb3 blocked B and T cell differentiation and caused a delay in myeloid precursor proliferation [32], whereas the knockout of Hoxb3 in mice at 6 months of age caused significant impairment of B cell development in the bone marrow [33].

1.1.8. HOXB4. HOXB4 is known to enhance primitive hematopoietic cell growth by increasing self-renewal without affecting homeostatic control of HSC population size or of the rate of HSC production. The retention of full lymphomyeloid repopulating potential and enhanced in vivo regenerative potential demonstrates the feasibility of achieving significant ex vivo expansion of HSCs without functional impairment [34–39]. Hoxb3 and Hoxb4 double-knockout mice showed defects in endogenous hematopoiesis with reduced cellularity of HSC regeneration. Hoxb3−/Hoxb4− mice showed reduction in hematopoietic progenitor numbers without perturbing lineage commitment [40].

1.1.9. HOXB6. Hoxb6 overexpression in mice resulted in HSC and myeloid progenitor cell expansion but inhibited erythropoiesis and lymphopoiesis [41]. Urogenital HOXB6 is often seen in acute myeloid leukemia (AML). Cytogenetic analysis of a subset of HOXB6-induced AMLs revealed recurrent deletions of chromosome band 2D-E4, a region frequently deleted in HOXA9-induced AMLs. The biologic effects of HOXB6 were seen to be largely dependent on DNA binding but they were independent of direct interaction of PBX1 [41]. The knockout of Hoxb6 resulted in an increase in early erythroid progenitors in murine bone marrow and fetal liver cells [42]. Thus, HOXB6 is critical not only for HSC self-renewal and maintenance but also for regulatory balance between lymphoid and myeloid differentiation.

1.1.10. HOXC3. An antisense oligonucleotide against Hoxc3 inhibited the formation of colony-forming units (CFUs) of erythroid-derived colonies without any changes in size or degree of hemoglobinization. Early erythroid burst-forming unit colonies or myeloid colonies were not affected, demonstrating that Hoxc3 is involved in an early step in proliferation of the erythroid colony-forming unit subset of progenitor cells [43].

1.1.11. HOXC4. The enforced expression of HOXC4 in human CD34+ cells induced a significant increase in the number of erythroid colonies compared with granulocyte/macrophage colony-forming units (CFU-GM), without perturbing, at least in vitro, the maturation program of these cells. On the other hand, HOXC4 overexpression did not induce any skewing in the colony types derived from the myeloid lineage [44].

1.1.12. HOXC8. A significant reduction in the number of erythroid burst-forming units (BFU-E) and in CFU-GM occurred in Hoxc8 null mice, although the peripheral blood cell counts were normal [45] suggesting that HOXC8 plays a role during MEP (megakaryocyte-erythroid progenitor) differentiation into BFU-E and GMP differentiation into CFU-GM.

(1) HOX Genes and Colonic Stem Cells. We previously showed that normal colonic SCs are found at the base of the normal human colon crypt and can be isolated using SC markers such as aldehyde dehydrogenase (ALDH1), ALCAM (CD166), and LGR5 [46–48]. The overpopulation of colonic SCs drives colorectal cancer (CRC) development [47, 48]. We studied the expression of HOX genes in normal colonic SCs by microarray profiling. Our analysis showed that HOXA4, HOXA9, and HOXD10 are expressed more in colonic SCs than in proliferating cells or differentiating crypt cells [49]. Further studies showed that HOXA4 and HOXA9 are enriched in SCs during CRC development and that the dysregulation of HOXA4 and HOXA9 expression promotes self-renewal and proliferation of colonic SCs [50] (Figure 3). The siRNA knockdown of HOXA4 and HOXA9 in colon cancer cell lines SW480 and HT29 reduced proliferation and sphere-forming ability of colon SCs [50] thus suggesting regulatory roles of HOX genes during colon SC maintenance and differentiation.

(2) HOX Genes and Mesenchymal Stem Cells. Mesenchymal stem cells (MSCs) isolated from the umbilical cord blood express HOXA9, HOXB7, HOXC10, and HOXD6, whereas bone marrow-derived MSCs express HOXB7 and HOXD6 [51]. HOXC10 was found to be differentially expressed in amnion- and decidua-derived MSCs [51]. HOX genes, particularly HOXA9, HOXB7, HOXC10, and HOXD8, were used as biomarkers to distinguish between MSCs derived from unrestricted somatic stem cells and cord blood [51]. A study by Woo et al. [52] showed that the expression of HOXC13 increased whereas HOXD13 expression decreased as bone marrow-derived MSCs differentiated into osteoblasts during osteogenesis. Taken together, these findings indicate that distinct expression patterns of HOXA5, HOXA10, HOXB6, HOXB7, HOXC4, HOXC6, HOXC8, HOXC9, HOXC10, HOXD3, and HOXD8 exist in MSCs derived from different human sources [52]. Hoxb2, Hoxb5, Hoxb7, and Hoxc4 genes were found to regulate self-renewal and differentiation of murine MSCs [53].

HOX genes have been shown to play critical roles during osteogenesis of human MSCs. Histone demethylase KDM6B controlled HOX expression by removing histone 3K27 trimethylation (H3K27me3) and reduced KDM6B significantly by reducing osteogenic differentiation and increasing adipogenic differentiation [54]. The role of HOX genes during differentiation of human vascular wall-resident CD44+ multipotent stem cells (VW-MPSCs) was also studied [55]. VW-MPSCs are capable of differentiating into pericytes and smooth muscle cells. This study demonstrated that the expression of HOXB7, HOXC6, and HOXC8 is differentially expressed in VW-MPSCs as compared to terminally
differentiated human aortic smooth muscle cells, endothelial cells, and undifferentiated pluripotent ESCs. The knockdown of HOX genes in VW-MPSCs reduced their sprouting capacity and increased their levels of smooth muscle markers, transgelin and calponin, as well as histone H1. In addition, changes in methylation patterns of the TAGLN promoter were observed [55]. Overall, this study suggested a role for HOX genes in regulating differentiation of human VW-MPSC into smooth muscle cells via epigenetic mechanisms. The results of this study will help us understand VW-MPSC-dependent vascular disease processes such as neointima formation and tumor vascularization [55].

1.1.13. HOX Genes and Induced Pluripotent Stem Cells. Induced pluripotent stem cells (iPSCs) are cells that are engineered in the lab by converting tissue-specific adult SCs into cells that possess ESC-like properties. iPSCs, like ESCs, did not express HOX genes [56]. Although suppression of HOX gene expression was observed in iPSCs, transient WNT/β-catenin signaling triggered the activation of the CDX/HOX pathway, which in turn conferred a hematogenic posterior mesoderm phenotype to differentiating human iPSCs [57].

2. HOX Genes and Cancer

In recent years, it has been shown that HOX genes are not only responsible for proper embryonic development but they are also associated with cancer development [58]. In the next section of this review, we focus on the role of HOX genes in cancer development, particularly colorectal cancer (CRC) and acute myeloid leukemia (AML).

2.1. HOX Genes in CRC. Aberrant expression of HOX genes is seen in CRC [49, 50, 58, 59]. We previously reported that HOXA4, HOXA9, and HOXD10 are expressed in normal colonic SCs and dysregulation of HOX genes leads to aberrant SC differentiation, contributing to CRC development and growth. Furthermore, we showed that HOXA4 and HOXA9 genes promote self-renewal and proliferation of colonic SCs, contributing to CRC development [49, 50].

In this review, we also evaluate the role of HOX genes during CRC development using The Cancer Genome Atlas (TCGA) database. Tumor samples were collected from newly diagnosed patients (i) with colon or rectum adenocarcinoma (ii) undergoing surgical resection, and (iii) having received no prior treatment for their disease, including no chemotherapy and no radiotherapy. All cases were collected regardless of surgical stage or histologic grade. Cases were staged according to the American Joint Committee on Cancer (AJCC) staging system. Each frozen tumor specimen had a companion normal tissue specimen which could be blood/normal tissues, adjacent normal tissue taken from greater than 2 cm from the tumor, or previously extracted germline DNA from the blood [60]. Our analysis showed that HOXB9 was the most upregulated gene at all stages (Figure 4). HOXB6 and HOXB8 expression increased from stages I to IV but dramatically decreased at stage IVA. Interestingly, the expression of HOXB6 and HOXB8 was increased during stages I and II and decreased at stage III but again increased at stage IV (Figure 4(f)).

HOXD family gene expression increased at stage IVA compared to all other stages of CRC (Figure 4). Our analysis showed that there is no difference in HOX gene expression based on gender (Figure 5). When we compared TCGA datasets for HOX gene expression in CRC to overall survival,
Figure 4: Continued.
increased \textit{HOXB13} was found to be associated with decreased survival (data not shown). It was reported earlier that missense germline \textit{HOXB13} mutations, most commonly in G84E (\textit{HOXB13} p. Gly84Glu), are associated with early-onset prostate cancer and possibly associated with breast cancer and colorectal cancer [61–63]. Unlike \textit{HOXB13}, increased \textit{HOXB8} expression was associated with increased survival.

We observed similar trends in expression of other \textit{HOX} genes, whereby changes in the level of expression was correlated with improved survival and greater in tumor than tumor-free CRC cases (discussed below).

Next, we analyzed \textit{HOX} expression based on their family gene clusters. Among all \textit{HOX} families, the \textit{HOXB} family showed the highest expression in CRC. In the \textit{HOXB} family, \textit{HOXB9}, \textit{HOXB8}, \textit{HOXB6}, \textit{HOXB13}, \textit{HOXB}, and \textit{HOXB7} were all overexpressed in CRC (Figure 6(a)). The \textit{HOXA} family showed the next highest expression. In the \textit{HOXA} family, \textit{HOXA9} and \textit{HOXA10} showed higher expression than the remaining \textit{HOXA} family genes (Figure 6(b)). Among \textit{HOXD} family members, \textit{HOXD10}, \textit{HOXD11}, \textit{HOXD13}, and \textit{HOXD9} showed increased expression compared to the others (Figure 6(c)). The \textit{HOXC} family of genes showed the least expression compared to \textit{HOXA}, \textit{HOXB}, and \textit{HOXD} (Figure 6(d)).

We further assessed \textit{HOX} genes as a function of overall patient survival. Because we previously found that \textit{HOXA4} and \textit{HOXD10} are expressed in crypt SCs, we measured \textit{HOXA4} and \textit{HOXD10} levels in CRC cases \((n = 220)\) based on high versus low expression (cutoff at 25th percentile). \textit{HOXA4} and \textit{HOXD10} high-expressing cases \((n = 110)\) of CRC patients showed overall low survival rates. Increased \textit{HOXD10} expression was found to be significantly associated with poor overall survival in CRC (Figure 7(a)). \textit{HOXD10} high expressers showed only a 15% survival rate versus 55%
Figure 6: HOX family gene expression in CRC. (a) HOXB family gene expression, (b) HOXA family genes, (c) HOXD family genes, and (d) HOXC family genes were analyzed using TCGA RNAseq for $n = 273$ patient samples. $y$-axis denotes normalized FPKM values for HOX gene expression.

Figure 7: Overall survival analysis for HOXA4 and HOXD10 in colorectal cancer. Kaplan-Meier survival analysis of the 220 colorectal cancer patients using TCGA dataset. (a) HOXD10 and (b) HOXA4 survival analysis was performed for CRC patients with a cutoff value of 25th percentile. Credits: http://www.oncolnc.org.
survival rate of HOXD10 low expressers (Figure 7(a)). HOXA4 high expressers showed about a 30% survival rate as compared to a 50% survival rate of HOXA4 low expressers (Figure 7(b)). We also analyzed the association of HOXA9 with the SC marker ALDH1A1 in CRC patients using TCGA database. A significant positive correlation was observed between HOXA9 and ALDH1A1 in CRC ($r = 0.12, P = 0.048$) (Figure 8(a)). Retinoid receptors, RXRB, showed negative significant correlation with ALDH1A1 ($r = -0.13, P = 0.026$) (Figure 8(b)). Another stem cell marker, ALCAM (also known as CD166), was correlated with HOX gene expression in CRC. Expression of HOXA4 negatively correlated with ALCAM in CRC patients ($r = -0.14, P = 0.024$) (Figure 8(c)). HOXA9 was positively correlated with ALCAM ($r = 0.18, P = 0.0027$) (Figure 8(d)). HOXD10 showed significant negative correlation with ALCAM ($r = -0.18, P = 0.003$) (Figure 8(e)) whereas HOXB8 showed a significant positive correlation with ALCAM ($r = 0.17, P = 0.006$) (Figure 8(f)).

Other published reports on the involvement of HOX genes in CRCs were reviewed [49]. The expression of HOXD8 is downregulated in clinical CRCs compared to normal colon tissues, and the stable expression of HOXD8 in CRC cells significantly reduced cell proliferation, anchorage-independent growth, and invasion. Apoptotic inhibitor genes such as STK38 and MYC were found to be negatively associated with HOXD8 in analyses using The Cancer Genome Atlas (TCGA). Mansour and Senga demonstrated that HOXD8−/− mice pro-B cells resulted in decreased FLT3-ITD-dependent cell proliferation, reduced colony formation, and increased apoptosis, suggesting that HOXB2 and HOXB3 are regulators of FLT3-ITD-driven AML [77]. Several studies also showed that HOX genes promote AML development by forming chimeric fusions with other genes. Fusion of the nuclear protein NUP98 with HOXA9 via chromosome translocation t(7;11) (p15s;p15) causes development of AML [78]. Mice overexpressing Hoxa9 and Meis1a induced growth factor-dependent AML in less than 3 months. However, the overexpression of Hoxa9, Meis1a, or Pbxb1b alone, or in combination with Hoxa9 and Pbxb1b, failed to transform these cells acutely within 6 months posttransfection [79]. NUP98-HOXA9 fusion genes induced long-term proliferation and blocked differentiation of human CD34+ HSCs [80]. Recent data showed that mixed lineage leukemia (MLL) is crucial for NUP98-HOXA9 leukemia initiation [81]. We analyzed the TCGA dataset and did overall survival analysis for HOXA9 in AML patients ($n = 74$) and found that HOXA9 high expressers had a 20% survival rate compared to HOXA9 low expressers which had a 50% survival rate (Figure 9).

2.2. Cancer Stem Cells. Cancer stem cells (CSCs) are multipotent and have the ability to undergo both self-renewal and differentiation. We and others have shown that CSCs are the root cause of cancer development [46, 47]. These CSCs are resistant to chemotherapy and radiation. Previously, we identified HOXA4, HOXA9, and HOXD10 signatures for normal colonic SCs and that these HOX genes are upregulated during CRC development. Indeed, HOXA4 and HOXA9 were found to have roles in self-renewal and proliferation of colonic SCs that contribute to CRC development [49, 50]. Moreover, HOXA9 is known to have a pivotal role in HSC self-renewal and that the upregulation of HOXA9 leads to AML [82]. Another report showed that mir-375 inhibited the proliferation of CSCs and tamoxifen resistance by targeting HOXB3 in human ER-positive breast cancers [83].

2.1. CDX1/CDX2 Genes in CRC. Another set of Hox genes, the Cdx genes (also classified as ParaHox genes or caudal-related homeobox genes), is expressed in a wide variety of organisms [69]. Three Cdx genes, Cdx1, Cdx2, and Cdx4, exist in mouse and humans (CDX1, CDX2 and CDX4) and regulate anterior-posterior patterning [70, 71]. The CDX genes are not located in a homeobox cluster, CDX1 is located on human chromosome 5q31–33, CDX2 gene is on chromosome 13q12, and CDX3 is on Xq13.2. In mice, Cdx1 and Cdx2 are important for gastrointestinal tract development. CDX1 and CDX2 are also actively expressed in adult intestinal epithelium and are involved in the regulation of enterocyte proliferation and differentiation as well as WNT-mediated beta-catenin signaling [70, 72, 73]. Moreover, reduced expression of CDX2 appears to contribute to the development of intestinal neoplasia and is a prognostic biomarker for stage II and stage III colon cancer by identifying high-risk patients who might benefit from adjuvant chemotherapy [74–76].

2.1.2. HOX Genes in AML. Studies of AML patients show that many cases (~35%) have mutations in type III receptor tyrosine kinase FLT3 and that HOXB2 and HOXB3 are increased in AML patients with FLT3-ITD (internal tandem duplication) mutation. The overexpression of Hoxb2 and Hoxb3 in mouse pro-B cells resulted in decreased FLT3-ITD-dependent cell proliferation, reduced colony formation, and increased apoptosis, suggesting that HOXB2 and HOXB3 are regulators of FLT3-ITD-driven AML [77]. Several studies also showed that HOX genes promote AML development by forming chimeric fusions with other genes. Fusion of the nuclear protein NUP98 with HOXA9 via chromosome translocation t(7;11) (p15s;p15) causes development of AML [78]. Mice overexpressing Hoxa9 and Meis1a induced growth factor-dependent AML in less than 3 months. However, the overexpression of Hoxa9, Meis1a, or Pbxb1b alone, or in combination with Hoxa9 and Pbxb1b, failed to transform these cells acutely within 6 months posttransfection [79]. NUP98-HOXA9 fusion genes induced long-term proliferation and blocked differentiation of human CD34+ HSCs [80]. Recent data showed that mixed lineage leukemia (MLL) is crucial for NUP98-HOXA9 leukemia initiation [81]. We analyzed the TCGA dataset and did overall survival analysis for HOXA9 in AML patients ($n = 74$) and found that HOXA9 high expressers had a 20% survival rate compared to HOXA9 low expressers which had a 50% survival rate (Figure 9).
Figure 8: Correlation analysis of HOX genes and retinoid receptors with stem cell markers in colorectal cancer. (a) The expression of HOXA9 and ALDH1A1 (SC marker) in colorectal cancer (CRC) patients is correlated by Pearson correlation. A positive significant correlation was observed between HOXA9 and ALDH1A1 \((r = 0.12, P = 0.048)\). (b) The expression of retinoid receptor RXRB and ALDH1A1 in CRC patients is correlated by Pearson correlation. A negative significant correlation was observed between RXRB and ALDH1A1 \((r = -0.13, P = 0.026)\). (c) The expression of HOXA4 and ALCAM (CD166, SC marker) in CRC patients correlated by Pearson correlation. A negative significant correlation was observed between HOXA4 and ALCAM \((r = -0.14, P = 0.024)\). (d) The expression of HOXA9 and ALCAM in CRC patients correlated by Pearson correlation. A positive significant correlation was observed between HOXA9 and ALCAM \((r = 0.18, P = 0.0027)\). (e) The expression of HOXD10 and ALCAM in CRC patients correlated by Pearson correlation. A negative significant correlation was observed between HOXD10 and ALCAM \((r = -0.18, P = 0.003)\). (f) The expression of HOXB8 and ALCAM in CRC patients correlated by Pearson correlation. A positive significant correlation was observed between HOXB8 and ALCAM \((r = -0.17, P = 0.006)\).

Figure 9: Overall survival analysis for HOXA9 in acute myeloid leukemia. Kaplan-Meier survival analysis of HOXA9 in acute myeloid leukemia (AML) using TCGA dataset. Survival analysis was performed for AML patients \((total n = 74)\) with a cutoff value of 25th percentile. Credits: http://www.oncolnc.org.

3. Mechanisms Involved in HOX Gene Dysregulation in Cancer

3.1. Aberrant Self-Renewal and Proliferation. We have shown that HOXA4 and HOXA9 are upregulated in CRC SCs \([49, 50]\) and that siRNA knockdown of HOXA4 and HOXA9 reduces proliferation and sphere-formation ability of CRC SCs. HOXA4 and HOXA9 knockdown also changed the expression of SC markers, such as ALDH1, ALCAM, (CD166) and LGR5. Treatment of CRC cells with the differentiating agent all-trans-retinoic acid (ATRA) decreased HOXA4, HOXA9, and HOXD10 expression in parallel with decreases in SC levels. Overall, our study demonstrated a role for HOX genes in self-renewal and proliferation of CRC SCs. Thus, strategies designed to modulate HOX expression may provide a means to target malignant SCs and to develop more effective therapies for CRC \([50]\).

Notably, the self-renewal ability of HOXB4 is dependent upon a proline-rich sequence near the N terminus, which is also unique and highly conserved among the other HOX proteins. Deletion of this domain significantly enhanced the oncogenicity of Hoxb4, promoting features of acute leukemia...
in mice. Insertion of this domain into Hoxa9 impaired oncogenic potential for leukemia. Overall, this study showed that such proline-rich stretches in HOX genes attenuate the potential of SCs to acquire oncogenic properties [85].

4. HOX Genes and Related Therapeutics

4.1. HOTAIR Long Noncoding RNA (lncRNA). HOTAIR is a 2.2 kilobase trans-acting lncRNA residing in the HOXC loci that function to repress transcription of 40 kilobases of the HOXD locus. HOTAIR has been shown to interact with polycomb repressive complex 2 (PRC2). Its interaction with PRC2 is required for PRC2 occupancy and histone H2 lysine-27 trimethylation of the HOXD locus [86]. HOTAIR has been proposed as a biomarker in cervical cancer [87], nasopharyngeal carcinoma [88], and gallbladder cancer [89]. Indeed, meta-analysis involving 748 patients from 8 studies showed HOTAIR is a molecular marker for lymph node metastasis. The results indicated a significant difference in the incidence of lymph node metastasis between high and low HOTAIR expression groups [90]. HOTAIR lncRNA plays a crucial role in epithelial-mesenchymal transitions and is required for the maintenance of colon and breast cancer stem cell stemness [91]. Overall, HOTAIR lncRNA has potential as a therapeutic strategy in several cancer types. A recent study showed that expression of HOTAIR increased in CRC cells and cell lines and HOTAIR knockdown promoted apoptosis and inhibited proliferation, migration, and invasion in vitro and in vivo. Furthermore, HOTAIR modulated CRC progression by competitively binding miR-197 [92].

4.2. PBX/HOX Dimer. One of the mechanisms that regulates HOX transcriptional expression is through binding with PBX proteins. Both HOX and PBX proteins are known to play critical roles in carcinogenesis, which makes it an attractive therapeutic target for cancers. One study showed that PBX3 is a potential pathologic cofactor of HOXA9 involved in cytogenetically abnormal acute myeloid leukemia (CA-AML), particularly MLL-rearranged AML. The depletion of PBX3 expression by shRNA significantly inhibited MLL-fusion-mediated cell transformation, whereas coexpression of PBX3 with HOXA9 promoted cell transformation in vitro and leukemogenesis in vivo. A small peptide, known as HXR9, that disrupts the interaction between HOX and PBX proteins was found to be effective in killing leukemic cells that were overexpressing HOX/PBX3 genes, which suggests a potential therapeutic strategy for CA-AML patients [93]. HXR9 has anticancer effects in other tumor types, such as breast [94], mesothelioma [95], ovarian [96], meningioma [97], prostate [98], and non-small cell lung [99]. Additionally, the disruption of HOXB7/PBX2 proteins by HXR9 is a potential therapeutic target in malignant melanoma [100]. A recent study also showed that the expression of HOX5, HOXB2, HOXB4, HOXB9, and HOXC9 (but not HOXA9) in primary AML cases is significantly correlated with survival. HXR9 treatment is cytotoxic to AML-derived cell lines and primary AML cells from patients. And it was shown that cell death is independent of apoptosis. Rather, it involves necroptosis (a regulated form of necrosis) [101]. This study suggests that HXR9 treatment for cancers should be seriously explored in future studies. In addition to the upregulation of HOXA4, HOXA9, and HOXD10 in CRC [49, 50, 58], the PBX genes are also overexpressed in CRC, which correlates with invasive potential in vitro and lymph node invasion, distant metastasis, advanced TNM stage, and poor overall survival of patients [102]. These reports suggest that HXR9 treatment in CRCs might be therapeutically useful to target HOX/PBX proteins in CRCs.

5. Conclusion

The above findings suggest that (i) HOX genes play diverse roles in normal SC functions and properties, from self-renewal to multilineage differentiation, and (ii) the dysregulation of HOX genes contributes to cancer development through aberrant self-renewal and differentiation of SCs. Thus, understanding the molecular mechanisms for how HOX genes control SC self-renewal and differentiation will ultimately help us understand how SC populations are maintained in normal, disease-free states and how the dysregulation of HOX genes leads to abnormal SC self-renewal and differentiation that drive cancer development. Ultimately, understanding the mechanisms by which HOX genes are regulated in SC might help to find ways to manipulate SC fate resulting in the development of novel, more effective SC-targeted treatments for cancer.

Disclosure

This work was done at the Center for Translational Cancer Research, Helen F. Graham Cancer Center and Research Institute, Newark, Delaware, and University of Delaware, Newark, Delaware.

Conflicts of Interest

The authors do not present any conflicts of interest.

Acknowledgments

The authors thank Dr. Nicholas Petrelli for his ongoing support.

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The role of HOXB2 and HOXB3 in acute myeloid leukemia,


