Reflectance confocal microscopy for characterization of mammary ductal structures and development of neoplasia in genetically engineered mouse models of breast cancer

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Abstract. The earliest steps of breast cancer begin with aberrations in mammary ductal structure. Techniques that enable an investigator to image in situ and then analyze the same tissue using biochemical tools facilitates identification of genetic networks and signaling pathways active in the imagined structure. Cellular confocal microscopy (VivaCell-TiBa, Rochester, New York) is used to image mammary ductal structures and surrounding vasculature in situ in intact wild-type and genetically engineered mice that develop ERα-initiated ductal carcinoma in situ (DCIS) and ERα-driven invasive mammary cancer. In wild-type mice, normal mammary ductal structures that appear from puberty through lactation are visualized and serially sectioned optically, and a developmental atlas is created. Altering tissue preparation enabled visualization of the vasculature surrounding the ductal structures. In the genetically engineered mice, aberrant mammary ductal structures and cancers are imaged and compared to corresponding normal structures. Different preparation techniques are able to preserve tissue for routine histological analyses and RNA isolation. Comparative studies demonstrate that reflectance confocal imaging provides more cellular detail than carmine-alum-stained mammary gland whole mounts and equivalent detail with hematoxylin and eosin stained tissue sections. In summary, reflectance confocal microscopy is a tool that can be used to rapidly and accurately analyze mammary gland structure. © 2005 Society of Photo-Optical Instrumentation Engineers. [DOI: 10.1117/1.2065827]

Keywords: reflectance confocal microscopy; mouse model; mammary gland; breast cancer; development.

1 Introduction

Breast cancer begins with aberrant growth in the mammary epithelial structure of the mammary gland. Over the past two decades a series of genetically engineered mouse models have been developed to improve our understanding of this process.1 Traditionally, the mammary ductal structures of these mice are examined after excision from the animal. This is followed by either mounting of the fixed whole mammary gland on a glass slide after staining, or tissue sectioning after fixation/embedding with examination by conventional light microscopy.2,3 This study explored the utility of reflectance cellular confocal imaging as a method to examine the ductal epithelial structure of the mammary gland in situ in the mouse without fixation and staining.

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Reflectance confocal imaging is a technique that exploits different reflectance properties of subcellular structures to achieve virtual sectioning of intact tissue.4 Contrast agents such as acetic acid, toluidine blue, and hypertonic saline can be used to selectively increase the brightness of nuclear structures (acetic acid and toluidine blue) or cytoplasm5,6 (hypertonic saline). The technique has been used successfully to perform optical sectioning of normal and cancerous skin4,7-9 and for detection of malignancy in the oral cavity,10 liver,11,12 and parathyroid glands.13 Tissue phantoms have been used to demonstrate the feasibility of combining reflectance confocal imaging with targeted antibodies conjugated to gold nanoparticles.14

In this paper the effectiveness of the technique for evaluating normal and malignant mouse mammary gland structures in unfixed non-embedded tissue is examined. Both molecular medicine and developmental biology endeavor to correlate morphology with gene expression and activity. When tissue
can be accurately imaged without fixation and embedding, then this same tissue can be used for additional studies that aim to correlate biochemical and molecular events with specific structures. Normal wild-type mice and two different genetically modified mouse models were examined: conditional estrogen receptor α in mammary tissue (CERM) mice that exhibit abnormal ductal development with ductal carcinoma in situ (DCIS) and mammary adenocarcinoma estrogen receptor α conditional (MAERC) mice, transgenic mice that develop invasive mammary carcinomas. Different physiological time points were examined in wild-type mice to create a series of digital images that represent prepuberty, puberty, and lactation and verify that reflectance confocal microscopy can be used to define normal developmental structures in the mammary gland. Genetically engineered mouse (GEM) models were studied to test whether reflectance confocal microscopy could be used to identify abnormal mammary gland ductal development and mammary adenocarcinomas in unfixed nonembedded mammary tissue. Normal mammary gland development is characterized by a well-defined series of structural changes that are initiated during puberty and continue during pregnancy. Terminal end buds (TEBs) are the growing structures at the ends of mammary ducts that appear during puberty and are specifically susceptible to malignant transformation.\(^\text{16,17}\) As puberty proceeds, secondary and tertiary branches appear off the primary ducts.\(^\text{18}\) Vessels form around the developing duct epithelial structures.\(^\text{19}\) Mammary gland adenocarcinomas develop from ductal epithelium and invade into the surrounding mammary fat pad.\(^\text{20}\) To validate the technique direct comparisons were made with carmine-alum whole-mount images and hematoxylin and eosin (H&E)-stained sections.

In summary, in the mouse mammary gland reflectance confocal imaging can be used to identify, optically section, and map terminal end buds; normal and abnormal ductal and alveolar structures; the network of vasculature structures that surround the ducts; and mammary adenocarcinomas.

2 Materials and Methods

2.1 Mouse Models

Mammary glands from wild-type C57Bl/6 female mice were examined at different developmental and physiological time points: nonpregnant 2-, 5-, 6-, and 8-week-old mice and lactating 4-month-old mice by reflectance confocal microscopy. Abnormal mammary gland development and adenocarcinomas were imaged in mammary glands from 4-month-old CERM C57Bl/6 female mice\(^\text{15}\) (MMTV-tTA/tet-op-ERα, transgenic mouse model of ERα dependent abnormal mammary duct development) and 14-month-old MAERC C57Bl/6 female mice\(^\text{20}\) (MMTV-tTA/tet-op-ERα/tet-op-TAg, transgenic mouse model of ERα-driven mammary adenocarcinoma development). All animal procedures were approved by the Georgetown Animal Use and Care Committee.

2.2 Reflectance Confocal Microscopy

Reflectance confocal microscopy was performed using an instrument from VivaCell-TiBa (Rochester, New York, USA). A dilute (5%) acetic acid solution was used as a contrast agent to enhance visualization of the nuclei within cells by promoting condensation of nuclear material. RNalater (Qiagen, Valencia, California, USA) was used as a contrast agent for vascular structures by initiating blood coagulation. Prior to reflectance confocal imaging, mice were euthanized, followed by a midline incision to expose the mammary glands. For imaging, the entire mouse was placed on the reflectance confocal microscope with the lens underlying the mammary gland. Z-stack imaging (VivaStack) on the VivaCell-TiBa consists of 16 optical sections through the tissue at a user...
defined depth. Each image is $500 \times 500 \mu m$. In the studies presented here, Z-stack imaging was performed in $3.5-\mu m$ increments and viewed as sequential individual images. VivaBlock was used to map large areas of interest. VivaBlock is a composite of horizontally tiled images, each $500 \times 500 \mu m$. The size of the macroscopic map is user defined and can range from 2 to 20 mm$^2$. In the studies presented here, 6-mm$^2$ squares were used for mapping.

2.3 Imaging of Carmine-Alum Whole Mounts and H&E Stained Sections

After reflectance confocal imaging, the mammary glands were removed, fixed, and stained with carmine-alum for whole-mount examination, or formalin-fixed, embedded, and 5-\mu m sections prepared for H&E staining, as described previously. Whole mounts and H&E-stained sections were imaged on an Eclipse E800M microscope (Nikon Instruments Inc., Melville, New York, USA).

3 Results
3.1 Imaging Ductal and Alveolar Mammary Gland Development

Reflectance confocal microscopy was used to follow normal stages of mammary gland development from puberty through lactation (Fig. 1). At 2 weeks of age there is no more than minimal ductal development and only the fat pad and central lymph node were visualized [Fig. 1(a)]. By 5 weeks of age, TEBs, the growing ends of the ducts, were seen progressing through the fat pad [Fig. 1(b), white arrow]. By 6 weeks of age, the ducts reached the edge of the fat pad [Fig. 1(c), double lined arrow] and secondary branches have appeared (thin white arrows). Rounded grapelike alveolar develop-
Fig. 5 Imaging of a mammary adenocarcinoma using reflectance confocal microscopy. (a) The nuclei of mammary adenocarcinoma cells in the mammary gland of a 14-month-old genetically engineered female MAERC mouse are more reflectant than the nuclei of the surrounding cells in the fat pad. Extension into the fat pad at the edges of the tumor can be seen (double lined arrow). Relatively normal appearing primary (wide white arrow), secondary (thin white arrows), and tertiary (*) ducts can be seen in the adjacent area. (b) Higher power image of the mammary adenocarcinoma tissue demonstrating the relatively dense organization of the highly reflecting nuclei of the malignant mammary epithelial cells. Contrast agent: 5% acetic acid.

3.2 Optical Sectioning of a TEB

TEBs were identified on reflectance confocal microscopy by their characteristic globular appearance at ductal ends [Fig. 5(a)]. Z-stack imaging with optical sectioning through the internal structure of a TEB revealed internal lumen formation [Fig. 5(b), white arrows].

3.3 Visualization of Primary, Secondary, and Tertiary Branching in the Mammary Gland

At 5 weeks of age, relatively widely separated secondary branches point off a primary duct [Fig. 3(a), primary duct indicated by thick arrow, secondary ducts indicated by thin arrows]. At 6 weeks of age the number of secondary ducts was significantly increased [Fig. 3(b), primary duct indicated by thick arrow, representative secondary ducts indicated by thin arrows]. By 8 weeks of age, small tertiary ducts were found branching off an extended secondary duct [Fig. 3(c), primary duct, thick arrow; secondary ducts, thin arrows; tertiary ducts, *].

3.4 Demonstration of Vasculature Structure in the Mammary Gland

Vascular structures were not effectively imaged when acetic acid was used as the contrast agent. However, the use of RNA L later as a contrast agent selectively enhanced visualization of the vascular network (Fig. 4, arrows indicate representative vessels). After imaging, the tissue was kept in RNA L over night at 4 °C and removed and frozen at −70°C the next morning, and high-quality RNA was extracted several weeks later (data not shown).

3.5 Mapping Adenocarcinomas and Ducts within the Mammary Fat Pad

The mapping function of the reflectance confocal microscope was used to localize an adenocarcinoma (double arrow) and surrounding ductal structures in the fat pad of a genetically engineered MAERC mouse [Fig. 5(a)]. The adenocarcinoma appeared as a dense collection of reflective cell nuclei [Fig. 5(b)]. Normal-appearing mammary gland ductal structures with primary (thick arrow), secondary (thin arrow) and tertiary branches (*) were found adjacent to the adenocarcinoma.

3.6 Comparison of Reflectance Confocal Microscopy with Light Microscopy of Carmine-Alum Stained Mammary Gland Whole Mounts

Equivalent images were taken with reflectance confocal microscopy of unfixed nonmounted mammary glands in situ and with conventional light microscopy of carmine-alum stained whole mounts (Fig. 6). Comparable images of secondary branches at the terminus of mammary gland ducts [Figs. 6(a) and 6(b), open arrows] and cross sections of ducts [Figs. 6(c) and 6(d), solid arrows] were found on reflectance confocal microscopy and conventional microscopy of a carmine-alum-stained whole mount. Reflectance confocal imaging was more time-efficient than conventional microscopy of carmine-alum-stained whole mounts because imaging was performed immediately on unfixed and unmounted in situ specimens at the time of necropsy. In contrast, carmine-alum-stained whole mounts imaging by light microscopy was performed only days after the mammary glands were removed from the mouse and required hours of preparation time.
3.7 Comparison of Reflectance Confocal Imaging with Light Microscopy of H&E Stained Sections

Analogous images of ductal structures were found using reflectance confocal imaging and conventional light microscopy of H&E stained sections (Fig. 7). Ductal end structures were compared in mature 4-month-old wild-type and genetically engineered CERM mice. One of the characteristic pathological findings in the 4-month-old CERM mice was the abnormal lateral budding that extended along the duct away from the terminal end [Figs. 7(d)–7(f) arrows]. In CERM mice, abnormal persistent estrogen-mediated growth signals result in numerous abortive branches termed lateral budding. Normal development of ductal branching during puberty is also initiated by budding (Fig. 3) but resolves into a normal branching pattern by 4 months of age [Figs. 7(a)–7(c)].

4 Discussion and Summary

Reflectance confocal microscopy can be used to analyze changes in mammary gland morphology through both normal development and cancer progression. TEBs were specifically identified as well as the extent of ductal penetration through the fat pad during puberty. The milk-producing alveolar structures that develop at the end of pregnancy were clearly distinguishable from the purely ductal structures found in the nonpregnant gland. Development of mammary cancers from the ducts were visually identifiable. Imaging quality of unfixed, nonembedded tissue in situ performed at the time of necropsy using reflectance confocal microscopy was comparable to that achieved by light microscopy after tissue fixation and embedding. The most immediate advantage of reflectance confocal microscopy was that it can be performed on nonfixed, nonembedded in situ specimens promptly at the time of necropsy. Other benefits were the rapid acquisition of images for analysis coincident with necropsy, the ability to use the imaged and morphologically characterized tissue in follow-up experiments, and the capacity to readily sample and optically section an unrestricted number of areas within the tissue. This last attribute enables an investigator to rapidly and economically survey an entire tissue without laborious processing and serial sectioning of fixed embedded specimens, which may preclude use of the same tissue for other types of experiments. Serial Z-stack images can be used for 3-D reconstructions of TEBs and cancers, enabling an investigator to follow the invasion of these structures into surrounding tissue. Acquisition of real-time images of pathology at the time of necropsy enables an investigator to immediately initiate follow-up diagnostic and mechanistic studies, rather than having to wait for the more laborious conventional processing and staining of tissue samples. Confocal reflectance imaging will clearly be a useful tool in future studies for the analysis of mammary gland structure and mammary cancer development.

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