Feasibility study of autofluorescence mammary ductoscopy

Abstract. We report the technical feasibility of autofluorescence ductoscopy in the ex-vivo setting. The current imaging algorithm for visualizing tumor tissue against the normal tissue background, although developed and optimized for other organs, appears to provide discrimination between intraductal tumor and normal ductal tissue. Point fluoroscopy is also performed. Although the optical “geometry” for this is different, the findings are consistent with the imaging observations. © 2009 Society of Photo-Optical Instrumentation Engineers. [DOI: 10.1117/1.3210773]

Keywords: ductoscopy; cancer; autofluorescence; imaging; spectroscopy.

1 Introduction

Mammary ductoscopy (MD) uses a submillimeter endoscope inserted into breast ducts for direct visualization and to yield high-resolution white-light images of the ductal epithelium. Clinically, it has been most commonly used in the management of pathological nipple discharge (PND), as it allows removal of intraductal papilloma therapeutically and guidance of surgical excision intraoperatively. MD has also been used as a diagnostic tool for ductal carcinoma, which is the most common form of cancer in the breast. Here, we sought to enhance the diagnostic accuracy of MD by the addition of autofluorescence imaging, and diffuse reflectance and fluorescence point spectroscopy. In this exploratory study, we added these capabilities into a commercial ductoscope and used the
Besides assessing the technical feasibility of autofluorescence to examine ten fresh mastectomy specimens from patients with known ductal carcinoma.

 system to examine ten fresh mastectomy specimens from patients with known ductal carcinoma.

 Besides assessing the technical feasibility of autofluorescence to produce acceptable image quality in the ducts, we also assessed whether there are distinct changes in the tissue autofluorescence images between malignant and benign tissues that potentially can facilitate visualization of lesions that are not seen under conventional white-light ductoscopy. We used blue-light excitation and detected the green fluorescence emission, as has been reported in other hollow organs such as the gastrointestinal tract, bronchus, and urinary bladder. Collagen and elastin are believed to be the main fluorophors responsible for the autofluorescence in the green range under blue excitation. The question remains as to what is the true source of the autofluorescent contrast between malignant and normal/benign tissues that makes such lesions visible under fluorescence examination, but not visible under conventional white-light examination, modification of the intrinsic autofluorescent properties of the tissue, or alterations of tissue absorption and/or scattering, for example, due to the cancer angiogenesis, or both? We recognize, of course, that frank tumor as examined here does not necessarily have the same optical characteristics as premalignant lesions. For simplicity, we used an existing autofluorescence imaging system that had been developed and optimized for lung and GI endoscopy. A priori, this is not necessarily optimal for ductoscopy, so we included the point fluorescence and reflectance spectroscopies to gain further data that may inform the interpretation of the imaging results and, potentially, to provide additional information that may be used to optimize the imaging parameters for this specific application.

2 Materials and Methods

Ten consented patients with a preoperative diagnosis of palpable invasive ductal carcinoma who required a mastectomy were recruited into the study between May 2005 and July 2008. This ex-vivo pilot study was approved by the Research Ethics Board at University Health Network, Toronto. All mastectomy specimens were examined within 1 to 1.5 h after resection. The mastectomy specimen was placed onto a dome-shaped pad to spread the milk ducts for easier passage of the rigid fiber ductoscope (model MS-611, Fibertech, Japan). Two different ductoscopes were used. The first three cases were carried out with a 1.1-mm external diameter instrument. However, this was found to limit access, so that the remaining seven cases were done using a 0.7-mm ductoscope. Both devices had a working length of 70 mm, field of view of 70 ± 5 deg, and depth of view of 1 to 10 mm.

As shown in Fig. 1, the ductoscope was coupled via a standard eyepiece to a fluorescence endoscopic imaging system (OncoLIFE®, Xillix Technologies Corporation, British Columbia, Canada, now Pinpoint®, Novadaq Technologies Corporation, Ontario, Canada). The principle of operation (Fig. 1) and technical details have been reported elsewhere. Briefly, standard white-light and autofluorescence images are recorded at 30 frames per second using 6.3-mW broadband light and 5.3-mW blue band (390 to 450 nm), respectively. The operator can switch between the two modes of imaging rapidly. In fluorescence imaging mode, the endogenous fluorescence (collected within 490 to 580 nm) is normalized by the red reflectance (690 to 750 nm) to minimize effects due to varying tissue distance and angle or shadowing. In general for other organs, premalignant tissues have a reduced green autofluorescence relative to normal tissues when excited by blue light, such that normal tissue appears as cyan, while abnormal tissue is shown as a range of red color in each pixel, depending on the red-to-green ratio. The central 16 × 12 pixels are averaged over four frames and continuously displayed on the fluorescence image as a numerical color value (NCV). The higher the NCV, the lower the fluorescence intensity, which has been associated with neoplasia: hence high NCVs helped to confirm the abnormality seen on the fluorescence image, as shown in Figs. 3(b) and 3(d). The deviation of the NCVs found across the investigated area

Fig. 1 Experimental setup for autofluorescence and white-light imaging, and for diffuse reflectance and fluorescence point spectroscopies. (a) Close-up of the distal tip of the ductoscope. (b) Schematic of the imaging/spectroscopy elements: A is an endoscopic light source comprising a 200-mW high-pressure mercury arc lamp (VIP R 150/P24 gN2, Osram, Germany); B shows the image capture and processing unit, comprising a standard three-color CCD camera for white-light imaging and an intensified CCD camera for autofluorescence imaging; C show the ductoscope (Fibertec, Japan), including collimating lenses (f/2.7: Edmund Optics, Barrington, New Jersey), automated filter wheel (AB-300, Spectral Products, Putnam, Connecticut), and spectrometer (MSL-CS1-USB-VK®, Mespeclab Incorporation, Canada); G is tissue (duct wall); H is the biopsy probe; I shows the light delivery fibers; J is the imaging guide (with 0.35-mm-diam coupled lenses); and K is the biopsy channel (0.3 mm diam in the 0.7-mm scope).
(within a single spot of observation) was ±15% for normal tissue and ±25% for cancerous tissue.

The point spectroscopy system comprised a small-diameter silica fiber coupled to a fiber optic spectrometer through an automated filter wheel. The light delivered by the fiber scope was used for illumination/excitation. The collecting fiber was placed through the biopsy channel and positioned in the center of the imaging field of view, gently touching the tissue surface. Two different filters were used: a color correction filter (C-filter, Edmund Optics, Barrington, New Jersey), that balanced the blue and red components of the diffuse reflectance spectrum to be within the detector dynamic range, and a customized filter (YF2: Barr Associates, Westford, Massachusetts) that enabled the green fluorescence to be collected with high efficiency (transmission 90% at 455 to 575 nm), together with a fraction of the diffuse blue and red reflectance (steep cut-off from 90 to 1% transmission between 455 and 445 nm and from 90 to 5% between 575 and 590 nm). The combination of YF2 with the existing OncoLIFE® excitation light source filter almost completely blocks (OD=6) the excitation light within the green band, so that only the autofluo-

Fig. 2 Principle of the autofluorescence imaging system. An autofluorescence image is formed from two separate images: in each pixel the green fluorescence signal \( F \) (490 to 580 nm) collected by the ICCD camera is normalized by the red reflectance signal \( R \) (690 to 750 nm) collected by the standard three-color CCD camera. The numerical color values (NCVs) are displayed on a false-color image, which generally shows high levels of NCV as reddish and low levels as blue-green.

Fig. 3 Case 2 (valid): normal region [(a) white light and (b) autofluorescence] compared to tumor region [(c) white light and (d) autofluorescence]. The forward-looking field of view is approximately 1 mm. The NCV locations and corresponding values are seen in (b) and (d).
rescence is collected [G-band in Fig. 4(b)], while also providing acquisition of some portions of blue and red reflectance from the excitation light [B- and R-bands accordingly on Fig. 4(b)], whose intensities are comparable with the that of the autofluorescence. This permits simultaneous acquisition of all three parameters (blue reflectance, green autofluorescence, and red reflectance) in a single spectrum within the detector dynamic range [Fig. 4(b)]. The spectra were collected using customized software driving the filter wheel and the OncoLIFE® light source to switch at 2.5 Hz between the diffuse reflectance and fluorescence modes, and integrating 10 to 15 spectra in each mode at each observation spot. The integrated fluorescence signal had a standard deviation at a given site of typically ±8% for normal tissue and 15% for cancerous lesions.

The procedure for each mastectomy specimen was first to perform white-light ductoscopy. Once a region of tumor was identified, the white-light image video was collected for 10 to 15 s, and then the imaging system was switched to fluorescence mode for another 15 to 20 s. Following this, point spectroscopy was performed for both diffuse reflectance and fluorescence, respectively. In white-light mode, the intraductal carcinoma appeared reddish compared to the surrounding ductal tissue, which can be seen in the lumen of the normal duct. In fluorescence mode, the same intraductal carcinoma appeared reddish compared to the surrounding ductal tissue, which was blue-green (cyan) in color. It was noted that debris seen in the lumen of the normal duct [Fig. 3(a)], which can be misinterpreted as cancer, appropriately appeared blue-green in fluorescence mode, demonstrating the ability of fluorescence ductoscopy to differentiate cancer from noncancer tissue in this case.

Figure 4 shows an example of the reflectance and autofluorescence spectra. The point spectroscopy and imaging gave qualitatively similar results. However, the tumor-to-normal tissue contrast is better represented in the imaging mode (NCV=1:10 versus 1:5). This is, in part, due to the imaging ductoscope and seven with 0.7-mm ductoscope, the latter providing high-quality videos and spectra data. A detailed analysis and discussion of the clinical findings will be presented in a subsequent paper.

Ductoscopy can access ducts about 6 to 10 cm from the nipple openings. Smaller ducts can also be cannulated when distended with saline. It cannot reach ducts that are less than about 0.7 mm when distended, even though the natural diameter before distension can be very small. We typically see fourth and fifth duct bifurcations. This being said, most ductal carcinomas and papillomas that produce nipple discharge are likely to be within reach of ductoscopy. Peripheral lesions are unlikely to have nipple discharge. Our judgement is that >95% of breast cancers and papilloma with nipple discharge can be seen.

Figure 3 shows examples of ductoscopic images, in both white-light and autofluorescence modes, from a 53-year-old woman who underwent a modified radical mastectomy for a 3.5-cm invasive ductal carcinoma (AJCC T2N1M0). A corresponding video clip is also available.

As shown in Fig. 3 and Video 1, the images had adequate brightness and resolution in both imaging modes. Figures 3(a), and 3(b) show images taken from a normal duct from the same patient in white-light and fluorescence modes, respectively. In white-light mode, the intraductal carcinoma appeared as irregular protrusions into the ductal lumen, with color similar to the surrounding ductal tissue [Fig. 3(a)]. In fluorescence mode [Fig. 3(c)], the same intraductal carcinoma appeared reddish compared to the surrounding ductal tissue, which was blue-green (cyan) in color. It was noted that debris seen in the lumen of the normal duct [Fig. 3(a)], which can be misinterpreted as cancer, appropriately appeared blue-green in fluorescence mode, demonstrating the ability of fluorescence ductoscopy to differentiate cancer from noncancer tissue in this case.

Figure 4 shows an example of the reflectance and autofluorescence spectra. The point spectroscopy and imaging gave qualitatively similar results. However, the tumor-to-normal tissue contrast is better represented in the imaging mode (NCV=1:10 versus 1:5). This is, in part, due to the imaging ductoscope and seven with 0.7-mm ductoscope, the latter providing high-quality videos and spectra data. A detailed analysis and discussion of the clinical findings will be presented in a subsequent paper.

Ductoscopy can access ducts about 6 to 10 cm from the nipple openings. Smaller ducts can also be cannulated when distended with saline. It cannot reach ducts that are less than about 0.7 mm when distended, even though the natural diameter before distension can be very small. We typically see fourth and fifth duct bifurcations. This being said, most ductal carcinomas and papillomas that produce nipple discharge are likely to be within reach of ductoscopy. Peripheral lesions are unlikely to have nipple discharge. Our judgement is that >95% of breast cancers and papilloma with nipple discharge can be seen.

3 Results and Discussion

In total we examined ten mastectomy specimens with histologically confirmed malignant tumor: three with the 1.1-mm ductoscope and seven with 0.7-mm ductoscope, the latter providing high-quality videos and spectra data. A detailed analysis and discussion of the clinical findings will be presented in a subsequent paper.

Ductoscopy can access ducts about 6 to 10 cm from the nipple openings. Smaller ducts can also be cannulated when distended with saline. It cannot reach ducts that are less than about 0.7 mm when distended, even though the natural diameter before distension can be very small. We typically see fourth and fifth duct bifurcations. This being said, most ductal carcinomas and papillomas that produce nipple discharge are likely to be within reach of ductoscopy. Peripheral lesions are unlikely to have nipple discharge. Our judgement is that >95% of breast cancers and papilloma with nipple discharge can be seen.

Figure 3 shows examples of ductoscopic images, in both white-light and autofluorescence modes, from a 53-year-old woman who underwent a modified radical mastectomy for a 3.5-cm invasive ductal carcinoma (AJCC T2N1M0). A corresponding video clip is also available.

As shown in Fig. 3 and Video 1, the images had adequate brightness and resolution in both imaging modes. Figures 3(a) and 3(b) show images taken from a normal duct from the same patient in white-light and fluorescence modes, respectively. In white-light mode, the intraductal carcinoma appeared as irregular protrusions into the ductal lumen, with color similar to the surrounding ductal tissue [Fig. 3(a)]. In fluorescence mode [Fig. 3(c)], the same intraductal carcinoma appeared reddish compared to the surrounding ductal tissue, which was blue-green (cyan) in color. It was noted that debris seen in the lumen of the normal duct [Fig. 3(a)], which can be misinterpreted as cancer, appropriately appeared blue-green in fluorescence mode, demonstrating the ability of fluorescence ductoscopy to differentiate cancer from noncancer tissue in this case.

Figure 4 shows an example of the reflectance and autofluorescence spectra. The point spectroscopy and imaging gave qualitatively similar results. However, the tumor-to-normal tissue contrast is better represented in the imaging mode (NCV=1:10 versus 1:5). This is, in part, due to the imaging
and spectroscopy bands not being identical, but also probably indicates that there is a difference in the effective width of the excitation light and higher reabsorption of the autofluorescence mode in a region of normal duct, which appears blue-green (cyan) in color. In the subsequent white-light mode, the normal duct appears reddish and smooth. Debris seen in the lumen of the normal duct appears blue-green in autofluorescence mode. In the second half of the video clip, ductal carcinoma appears red with a high NCV value in autofluorescence mode, while the corresponding tumor in white-light mode appears reddish in color similar to that of normal ductal epithelium except for the irregular surface. (QuickTime, 4.7 MB) [URL: http://dx.doi.org/10.1117/1.3210773.1]

4 Conclusions
We demonstrate the technical feasibility of autofluorescence ductoscopy, even in the more challenging ex-vivo setting. The current imaging algorithm for visualizing tumor tissue against the normal tissue background, although developed and optimized for other organs, appears to provide discrimination between intraductal tumor and normal ductal tissue. The point spectrosopies appear to be consistent with the imaging findings, and to demonstrate any other particular spectral bands that should be employed, at least over the wavelength ranges used and for frank malignancy. The next step will be to carry out similar studies in vivo and in patients who do not have known malignancy, e.g., women presenting with abnormal nipple discharge. More detailed analysis of the clinical findings and implications of the present study will be reported separately.

Acknowledgments
This study was supported by the Ontario Research and Development Challenge Fund, the Princess Margaret Hospital Foundation, and Xillix Technologies Corporation, Canada. The authors thank B. Shnapir of Barr Associates and S. Miike of Fibertech, Japan, for their cooperation.

References
7. A. Douplik, S. Zanati, N. Marcon, M. Ciocci, C. Wilson, J. Boehm, S. Rychel, and J. Fengler, “Combined autofluorescence and white-light endoscopy for improved detection of dysplastic colonic le-

