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CHARACTERIZATION OF DENIM FIBERS USING VISIBLE MICROSPECTROPHOTOMETRY

presented by

DANIELLE NICHOLE ALBERT

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of the requirements for the

MASTER OF SCIENCE degree in FORENSIC SCIENCE

Major Professor's Signature

4/3/01

Date

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CHARACTERIZATION OF DENIM FIBERS USING VISIBLE MICROSPECTROPHOTOMETRY

By

Danielle Nichole Albert

A THESIS

Submitted to
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ABSTRACT

CHARACTERIZATION OF DENIM FIBERS USING VISIBLE MICROSPECTROPHOTOMETRY

By

Danielle Nichole Albert

Denim fiber evidence is often encountered at crime scenes due to the shedding and transfer properties of fibers and popularity of jeans. Forensic scientists are continually looking for new ways to characterize fiber evidence and increase its evidentiary value in a court of law. The purpose of this research was to examine different denims using visible microspectrophotometry and to determine whether or not denim could be characterized by dye color. Twenty-six samples of new pairs of jeans were used for analysis in the main study. Three pairs of new jeans and ten pairs of worn jeans were analyzed for the wash and worn studies, respectively. Spectra were compiled for each of these studies.

The results indicated that denim could not be characterized by dye color using visible microspectrophotometry. While jeans visually look different, the actual dye (indigo) is quite similar or identical among jeans.

ACKNOWLEDGMENTS

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INTRODUCTION

Forensic science continues to be an evolving field and new techniques are being examined to better characterize different types of evidence. Fiber evidence is often encountered at crime scenes due the shedding and transfer properties of fibers or, more generally, the ability of fibers to transfer from fabric to another surface. Denim fibers are commonly seen due to the popularity of jeans and other clothing containing denim. Denim can be typically defined as a "warp-faced cotton fabric, made from indigo dyed warp and undyed weft yarns" (Bajaj and Agarwal, 1999). Warp refers to the set of yarn that runs lengthwise and parallel to the narrow edge of woven fabric. Warp is interwoven with weft, or filling, which is the yarn running perpendicular to warp (Celanese Acetate LLC, 2001). Visual inspection of many different types and/or brands of jeans indicate slightly different colors. The observed color variation can be attributed to different dyes, bleaches, or other modification techniques. The purpose of this research will be to examine different denims using a visible microspectrophotometer and attempt to characterize denims by their dyes. Visible microspectrophotometry has been chosen to satisfy both the need to further characterize denim fibers and also the need to examine evidence efficiently. Visible microspectrophotometry requires less prep work than other instrumental methods and analysis is done in seconds. The significance of this research is that better characterization of denim fibers can increase the value of this type of fiber evidence. There are several classifications of fibers, most involving the polymer structure; however, dyes are able to further differentiate

fibers and increase the degree of certainty that two fibers are associated with each other.

Microspectrophotometry

Microspectrophotometry is a specialized form of spectroscopy and, therefore, is based on the same principles. Spectroscopy uses electromagnetic radiation to provide information on the atomic or molecular composition of substances. Visible microspectrophotometry achieves this goal by measuring absorption or transmittance of wavelengths found in the visible light region in microscopic amounts of materials. Specifically, visible light interacts with the outer shell electrons in materials by exciting them to a higher energy level. Bonds and atoms present in a substance determine the wavelengths absorbed and how much energy the electrons will attain at the new level. Thus, differentiation between substances is achieved due to the differences in atomic and molecular composition. The wavelengths of light reflected or transmitted give items their color and often our eye cannot differentiate between similar shades. The absorbance spectra obtained from light and molecule interactions result in a higher sensitivity, which can aid in differentiating colored objects. Microspectrophotometry is usually coupled with computer software that graphs the absorbance or transmittance spectrum of the item being scanned.

Textiles and Dyes

The typical textile dyes used in denim manufacturing are vat blue dyes, natural or synthetic. Vat dyes are a "class of water-insoluble dyes which are applied to the fiber in a reduced, soluble form (leuco compound) and then

reoxidized to the original form" (Hoechst, 1990). Vat dyes are known to be resistant to washing and sunlight, making them economically and fashionably desirable to be used on cotton fibers by denim manufacturers. However, indigo does not strongly bind to cotton fibers and will slowly be removed after continuous repeated wash and wear over a long period of time (Wikipedia, 2004).

Vat dyes are applied to fibers using a dye bath. As stated earlier, these dyes are applied in a soluble form and then reoxidized to their original form. This reoxidation process can cause uneven dye distribution problems as the indigo dye molecules are "developed" to precipitate on both inside and outside of the woven cotton fibers, not necessarily evenly adhering to the surface of the fibers. Also, any jeans that have undergone any type of washing effects may experience "back staining", which is color removal and redeposition of the dye onto the surface. The varying composition of cotton fibers and their lack of strong binding to the dye can also lead to uneven dye distribution problems, which may result in variation seen within one fiber or among many fibers (Bajaj and Agarwal, 1999 and University of Colorado, Boulder, Dept of Chem and Biochem, 2003).

Indigo is the specific vat dye most widely used in denim production. Denim first became widespread in the 18th century when slave laborers and plantation workers needed clothes of good durability. From this time up to around 1900, natural indigo was used to dye the cotton fibers. Natural indigo is obtained from plants in the genus *Indigofera* in the tropics and from the plants woat and dyer's knotweed in temperate climates. As synthetic indigo was being developed and improved, both it and natural indigo were used for producing

denims. Today, synthetic indigo is almost exclusively used due to inexpensive dye production and more uniform concentration. Hence, it is possible that one cannot use instrumentation to differentiate between denim dyes. It is also possible that differentiation may be hindered due to the one dye component application in denim. Other dyes in fabrics are usually applied in mixtures of more than one component, making differentiation easier because of differences in dye chemical structures (Jeans My Age, 2004, Robertson and Grieve, 1999, and Wikipedia, 2004).

Denim manufacturers generally refused requests for dye composition used in various brands of jeans. However, research indicated that all major denim manufacturers currently use synthetic indigo dye. Buffalo Color Corporation, a dye distributor, makes product information public. One such dye, synthetic Indigo NACCO is produced and analyzed as Indigo and is considered Vat Blue 1, number 73000 in the Color Index. Its molecular formula is $C_{16}H_{10}N_2O_2$ (Figure 1) and it has a molecular weight of 262.26. Its chemical name is 3H-Indol-3-one, 2-(1,3 dihydro-3-oxo-2H-indol-2-ylidene)-1,2, dihydro and its physical appearance is thin and dark blue. It may come in an aqueous paste, as the original water-insoluble dyes can be brought into solution through reduction in alkaline liquor (Derrett-Smith and Grey, 1967).

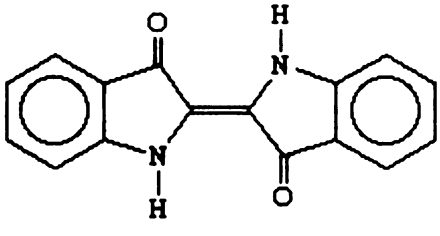


Figure 1- Synthetic Indigo

As noted in the introduction, denim consists of cotton fibers. The composition of fibers can have an impact on the method of analysis used. It is

known that natural fibers, including cotton, are composed of a variety of chemical constituents that are not distributed homogeneously throughout the fiber, unlike synthetic polymers (Robertson and Grieve, 1999). As a result, intra-sample variation is much more prevalent and the composition of a fiber has an impact on the visible spectrum. The chemical intra-sample variation, along with the dye distribution intra-sample variation may cause problems with differentiating fiber dyes using visible microspectrophotometry. Too much variation within a sample can make it difficult to distinguish differences between samples.

Literature Review

Fiber analysis has been a popular area of research within forensic science for many years. The initial method of analysis was simple microscopy using a comparison microscope. Analysis was expanded to include polarized light microscopy (PLM), Fourier transform infrared (FTIR) spectroscopy, pyrolysis gas chromatography (Py-GC), and uv-visible microspectrophotometry. Microscopic comparison allows examiners to evaluate differences in fiber diameter, length, shape (cross-sectional), surface features, color, and fluorescence (Robertson and Grieve, 1999). PLM and instrumental analysis examine the compositional structure of fibers, which are polymers. PLM takes advantage of the different effects seen with different polymers due to optical properties when polarized light is applied. Microspectrophotometry can be used to differentiate fiber color based on dyes and/or pigments.

Differentiating dyes based on color has been researched with a variety of methods. Thin layer chromatography (TLC) was applied to fiber dye

differentiation in 1981 (Resua et al., 1981). Resua et al. looked at dye extraction and classification from fibers using the separation solvent system of TLC. Other researchers later expanded on his work. High performance liquid chromatography (HPLC) has also been used to analyze dyes. TLC and HPLC are able to characterize dyes by separating out their various components. It has been found that dyes can contain different components or similar components in different amounts yielding a high differentiation of fiber dyes using HPLC (Joyce et al., 1982). Other methods for dye examination include FTIR (Ma et al., 2001) and Raman spectroscopy (Keen et al., 1998). The use of visible microspectrophotometry has been briefly examined and will be discussed in further detail below.

Grieve et al. examined various fiber dyes in 1990 using visible microspectrophotometry and TLC. Concerning blue dyes, they found that only 0.24% of possible pairings showed the same absorption spectrum. If two different dye samples gave the same spectrum, they were considered a pair. These pairs were sulfur or leucosulfur dyes; thus, none of the vat dyes (dyes used in denim) exhibited this effect. As a result, it is reasonable to conclude that visible microspectrophotometry has the potential to discriminate among denim dyes. Grieve et al. also examined reproducibility among single blue dyed fiber samples and found one instance of peak reversal and eight instances (10% total samples) of maximum absorption shifts greater than 17 nm. Of these nine instances, four were vat dyes. While this indicates a possible reproducibility problem, it does not decrease the discriminating power of visible

microspectrophotometry. These instances occur at a low percentage and with multiple scans taken, the averages could possibly even out. Multiple scanning of a single fiber is often a requirement anyway to account for uneven dye distribution and saturation.

The authors' examination of fiber dyes using TLC yielded the following conclusions: there is often variation in the amount of discrimination possible among dyes, some dyes are difficult to differentiate, and the technique is limited by the difficulty of extraction. They also noted that samples are partially used or altered with the TLC method. In contrast, visible microspectrophotometry allows adequate discrimination consistently, involves no extraction, only a light washing to remove outside contaminants, and does not use up or alter the sample. Finally, the authors refer to reproducibility issues and suggest multiple scans per fiber. Overall, the study suggests that visible microspectrophotometry is adequate at differentiating among the dyes used in their research.

MATERIALS AND METHODS

Collection

The denim samples used throughout the research were obtained from various retail stores. The fibers used in the main study were collected from five different areas per pair of jeans. Oral consent was sought from store employees in order to apply tape to the jeans. Scotch tape was cut into small pieces and used to tapelift the jeans. Each pair of jeans was considered a primary sample, while the tapelifts from the five different areas were considered secondary samples. A total of 50 pairs of jeans were sampled and labeled 1-50. The secondary samples were tapelifted from the front top area, back top area, front middle right leg, back middle left leg, and bottom right front leg. These were labeled as a, b, c, d, and e respectively. The tapelifts were put on transparencies to protect the fibers. There was one primary sample per transparency sheet. At the time of collection, a description of the denim, as well as sample number, store, brand, type, and materials/color were recorded in a lab notebook. This information was useful for identification and comparison. It should be noted that all 50 pairs of jeans were not analyzed. Upon analysis, the similarities seen in the spectra became evident and after samples 1- 22 were completed, the only other samples analyzed were samples 25, 39, 44, and 48. These four were added so at least one pair of jeans from each brand collected was analyzed.

Table 1: Main Study

SAMPLE #	STORE	BRAND	TYPE	MATERIALS/COLOR
1	Mervyns	Levis	501-W	100% Cotton/Vint. Wash
2	Mervyns	Levis	515-W	78% Cotton/22%Lycra
3	Mervyns	Levis	515-W	100% Cotton
4	Mervyns	Lei	Stretch, 85781821D02, 695556	88% Cotton/11% Polyester/1% Spandex/SB Drk Stn
5	Mervyns	Lei	Denim, 23921181D02, 695956	100% Cotton/SB Drk Stn
6	Mervyns	Mudd	Hiphugger, 4W1698-style, 64938CW-cut	100% Cotton/Sand Blast
7	Mervyns	Mudd	Hiphugger, 4EG276-style, 63591CW-cut	100% Cotton/Sand Blast Coffee
8	Mervyns	Levis	501-M	100% Cotton
9	Mervyns	Levis	501-M	100% Cotton
10	Mervyns	High Sierra	90798-style, 008335-cut	100% Cotton
11	Mervyns	High Sierra	Loose, RN48557, VN 372102	100% Cotton/Stonewash
12	Mervyns	Lee	Relaxed, 205-5591	100% Cotton/Classic Stn
13	Mervyns	Lee	Regular 200-8989	100% Cotton/Pepper Prewash
14	Old Navy	Old Navy	Curvy Ultra Low Rise, VDN#300876B23, 136771-00-1	100% Cotton
15	Old Navy	Old Navy	Low Waist Flare, 157536-00-1	100% Cotton
16	Old Navy	Old Navy	Ultra Low Waist Boot Cut Stretch, 184142-00-1	99% Cotton/1%Lycra
17	Old Navy	Old Navy	Relaxed, 171121-01-1	80% Cotton/18% Polyester/2% Lycra
18	Old Navy	Old Navy	Painters Jeans, 154696-02-1	100% Cotton
19	Old Navy	Old Navy	Number 7 Jeans, 401000-21-1	100% Cotton
20	Express	Express	Low Rise Flare, st1366, co31	100% Cotton
21	Express	Express	Precision Fit Low Rise Flare, st1393, co29	100% Cotton
22	Express	Express	Low Rise Flare, st2770, co21	100% Cotton
25	Structure	Express	Precision Fit Carpenter, st1751, co24	100% Cotton/Sand Blast
39	Gap	Gap-M	Carpenter, 174245-00-1	100% Cotton/Antiqued
44	Marshall Fields	Union Bay	Loose Fit Bootleg, Y162726	100% Cotton/Md White Hot Whisker
48	Marshall Fields	Polo Jean Co.	Woodrow Baggy Fit, st7416YA12885, cut26211	100% Cotton

For the worn study, samples were obtained from various pairs of jeans known to have been worn and washed at least ten times. The jeans were collected from various people, surveyed on the length of time the jeans were in

possession and the approximate times worn and washed. The samples were collected in the same way as the main study, however, for uniform colored jeans, only one sample was taken and for jeans with fading, two samples were collected (faded and unfaded areas). Deviation from the five-sample collection was due to analysis results from the main study indicating that a specific area of jean did not affect the spectrum obtained.

Table 2: Worn Study

SAMPLE #	BRAND	TYPE	MATERIALS/COLOR
1	Ralph Lauren	NA	100% Cotton
2	Gap	Flare	100% Cotton
3	Express	Extreme Flare	96% Cotton/4% Lycra
4	Mudd	Flare	100% Cotton
5	Express	Low Rise Flare	100% Cotton
6	Express	Hipster Flare	100% Cotton
7	Levis	550 Relaxed Fit, Tapered Leg	100% Cotton
8	Old Navy	Bootcut	100% Cotton
9	Levis	505 Lowrise, Straight Leg	100% Cotton
10	Levis	517 Lowrise, Bootcut	100% Cotton
11	Arizona	Relaxed	100% Cotton
12	Lee	Relaxed	100% Cotton
13	Lee	Dungarees	74% Cotton/26% Polyester
14	Levis	569 Loose Straight Fit	100% Cotton
15	Sonoma	Carpenter	100% Cotton
16	Levis	Silvertab	100% Cotton
17	Levis	Silvertab Baggy Fit	100% Cotton
18	Northpeak	NA	100% Cotton
19	Utility	NA	100% Cotton
20	Lee	NA	100% Cotton

Three pairs of newly bought uniform color jeans were used for the wash study. All washes were done using Tide detergent containing bleach. All washes were done using the same cycle (6 minute normal) and temperature (warm). Following each wash, the jeans were dried on the "more dry" setting and then rubbed in dirt to emulate significant wash/wear. The first pair of jeans was tapelifted after every wash with a total of twenty washes. A pre-wash sample was taken also. The final two pairs of jeans were tapelifted after washes one, five, ten, fifteen, and twenty. The difference in tapelifting method was due to prior examination of the first pair of jeans and the resulting findings. It was deemed unnecessary to tapelift after each wash, as there were no observable differences between fibers from each lift on the first pair of jeans.

Table 3: Wash Study

SAMPLE #	STORE	BRAND	TYPE	MATERIALS/COLOR
1	Express	Express	st1366, co31	100% Cotton
2	Old Navy	Old Navy	Ultra Low Rise Flare, 200669-00-1	98% Cotton/2% Lycra
3	Mervyns	Levis	550 Relaxed	100% Cotton

Slide Preparation

In all three studies slides were prepared using the same procedure. Fibers were removed from the tape using tweezers and a scalpel and put on glass slides. Permount was used to affix the fibers in place and coverslips were put over them. The tweezers and scalpel were rinsed in xylene between samples to prevent cross-fiber contamination. The slides were labeled accordingly and placed in a labeled slide box.

Fiber Analysis

The analysis of fiber color or dye was done using visible microspectrophotometry. For this study, an SEE 1100 Microspectrophotometer and Grams 32 software were used. Before each day's use, the SEE 1100 microspectrophotometer was calibrated using the National Institute of Science and Technology (NIST) filters. Absorbance was the method of measurement used for examination of the fibers. Calibration of the instrument was performed each day according to the following procedure. The instrument is first turned on and the light source is set to transmission. The computer is also turned on; the Grams 32 and SEE Image software are automatically loaded. Next, the reference filter is put on the stage and into focus, using the 20X objective. The microscope is adjusted for Kohler illumination by moving the field stop all the way to the right and using the condenser knob to illuminate an octagon with a blue halo. The field stop is then moved to the working position, two spots to the left. Next, the parameters need to be approved. The "autogain" button is pressed on the Grams 32 software and the parameters are noted. The "maximum y counts" may need to be adjusted so it falls between 3500 and 4000.

To begin the rest of the calibration, a dark scan is first performed. This is done by closing the transmission shutter, selecting "dark scan", and naming the file according to protocol under the calibration folder. A reference scan is next done by opening the transmission shutter, selecting "reference scan", and naming the file according to protocol. The dark scan and reference scan files are then closed. The holmium oxide filter is placed onto the field stop to calibrate the

wavelengths from 280nm to 640nm. One selects "sample scan", "% transmission", and names the file according to protocol. Following the scan, the "NIST" button is pressed to check the values of the scan against the National Institute of Science and Technology (NIST) certificate values. The spectrum is printed for records. The same procedure is repeated with didymium filter, which calibrates wavelengths from 440nm to 880nm. Finally, the instrument is calibrated with three neutral density filters, which are utilized to measure the optical accuracy. They are expected to give a flat line or no optical response between wavelengths of 250nm to 1000nm. The three filters have optical densities of 0.1, 0.5, and 1.0. The same procedure as used for holmium oxide and didymium is followed except "absorbance" is selected instead of "% transmission". Following satisfactory comparison to NIST standard spectra, the instrument is ready for use with samples.

To begin analysis, a slide was put onto the stage and into focus. The aperture was then moved off of any sample fiber and a dark scan and a reference scan were run. Following these scans, five fibers were each scanned five times. The spectra peaks were marked, either by the computer software or manually. The final graphs include five overlayed spectra, one spectrum representing each secondary sample (taken out of the 25 spectra run). The reasoning for this is discussed in results and conclusions.

The worn and washed study samples were analyzed using the same procedure, but the final graph overlays differ somewhat since not as many secondary samples were obtained.

RESULTS AND DISCUSSION

The results indicate that the differences in visual appearance of denim fabrics on a whole are not due to different dyes. Visible microspectrophotometry was unable to differentiate between multiple brands and types of jeans. The results also indicate that washing, even with detergent containing bleach, and wearing of jeans according to this study's protocol do not affect the measured color properties.

The figures in the appendix illustrate the similarities of the scans. The five scans of a single fiber were found to be similar so one representative scan from each fiber was sufficient. Upon comparing the five fibers from a secondary sample, one again noticed the similarity, narrowing down the required scans to one from each secondary sample. Therefore, the final graphs of samples from the main study contain five scans, one fiber per secondary sample to represent the primary sample. The graphs from the wash study also show five scans, illustrating the spectra seen from one sample after washes 1, 5, 15, and 20. The graphs from the worn study show five to six scans depending on if the samples contain uniform color or faded areas. Those with faded areas are illustrated by six representative spectra- three scans of fibers from faded areas and three scans of fibers from non-faded areas.

Although no major differences were detected and differentiation could not be achieved, there were some slight differences that bear explanation. Throughout the research it was discovered that the natural twists and concentration of dye in the fibers affected the resulting spectra slightly. A higher

concentration of dye can saturate the spectrophotometer detector. Twists in the fibers have the same effect. When the microspectrophotometer attempts to analyze the fiber, it requires transparency for proper absorption readings. Broader, rougher peaks result from scans of opaque parts of fibers (Figure 2). Normal scans of denim fibers result in a spectrum with a main peak at approximately 650-660 nm and a sharp decreasing slope from the peak. Normal spectra also have a shoulder around 540 nm that gradually leads into the peak, with no decreasing slope. Scans of twists and high dye concentrations show a flatter plateau beginning at the shoulder and extending to the main peak area, ending again with a sharp decreasing slope. These differences are thought to be inconsequential because the dye still absorbed light in the same area, but some resolution has been lost due to excessive absorption. This loss of resolution seen in high dye concentrated fibers contributes to the difficulty of using microspectrophotometry for differentiation among denims. Even if denims could be differentiated, there would still be potential problems with darker (more concentrated) denims—note that darker denims are not darker because of a difference in dye chemical composition, which would affect where the absorbance occurred, but rather they are darker due to a higher concentration of dye.

Other slight differences among spectra were seen with peak heights. The y-axis measures the amount of absorbance or intensity. Again, dye concentration affects this aspect of the spectra. A more concentrated fiber or segment of fiber results in a higher absorbance (intensity) until it saturates the

detector. Differences of intensity were seen among fibers and within fibers (Figure 3). This variation can be traced to the dyeing process. Often, fibers will not have even distribution of dye throughout them. This variation is inconsequential because there is no way of using it to distinguish between denims due to the presence of intra-sample variation. It should be assumed that fibers do not necessarily have the same intensity within and among themselves even if they were obtained from the same garment. Since the most significant aspect of distinguishing fibers by true color is where the absorbance occurs, intensity can be assumed to have a trivial effect in this study.

The position of absorbance, measured on the x-axis, indicates the exact color of dye. This study has shown that all denims use the same color of dye, and are most likely manufactured using the exact same dye, indigo. While the slight variations seen between spectra might seem advantageous in differentiating between the similar spectra, this is not the case. These variations were not just seen between samples, but were also seen within samples (Figure 4). One cannot use variation to distinguish fibers when the intra-sample variation is as just as great as the inter-sample variation. There might be future exceptions on a case-by-case basis if a large quantity of known and unknown fibers are examined and the intra-sample variation is found to be less than the inter-sample variation.

CONCLUSION

The results and discussion indicate the difficulty in using visible microspectrophotometry to differentiate denims. As noted in the literature review, researchers have found this to be the case due to the natural cotton polymer, uneven dye application, and one-component dye used. This research supports the claims that visible microspectrophotometry has limited usefulness for distinguishing fibers from denim in forensic casework. This research also supports a study done in 1988 that indicated "the evidentiary value of blue denim fibers is necessarily very low" (Grieve et al., 1988). That previous study examined 30 samples originating from16 different brands of jeans and concluded that all samples produced similar spectra within a certain range. The research for this paper was controlled carefully by using only cotton fibers, calibrating the instrument daily, and avoiding any contamination that might have affected the absorption spectra. The general similarity of the spectra between samples in addition to the similar intra and inter-sample variation is responsible for the inability to effectively characterize denims based on their dyes.

Future Work

Although this study indicated a lack of differentiation among new, washed, and worn jeans, there are some suggestions for future research. None of the jeans used in this study were considered "decorated". As styles become more outrageous, it is likely one will see denims with added components. One such component, already seen in stores, is glitter. Glitter powder is available from companies like Americos Industries Inc. for application to textiles. Denim

containing glitter may be differentiated from other denims using microspectrophotometry to analyze the glitter particles in addition to the fiber dye.

Another avenue for future research is differentiating among denims with multiple fiber types and varying amounts of different fibers. Although, some of the jeans in this study contained polyester, spandex, and Lycra in addition to cotton, I only concentrated on analysis of cotton fibers to maintain consistency and control for differing polymer composition when running microspectrophotometry analysis. It might be possible to differentiate denims using dye and polymer composition using visible microspectrophotometry. However, this would likely require a large sample set, consisting of more than a few fibers. Often, collection from crime scenes or victims may yield only one or two fibers, limiting the practical application of results from such research.

Finally, it is probable that ultraviolet microspectrophotometry may have a better chance of differentiating between denims encountered in casework. The reasoning for this is that jeans are washed with detergents that typically contain optical brighteners. These chemicals are fluorescent agents added to detergents to make clothes look cleaner. They work by converting ultraviolet light to visible light. As a result, they will absorb ultraviolet light differently than the dyes in the denim and differentiation of denims is possible due to the following variable factors among pairs of worn jeans: number of times washed, detergent used, and type of optical brighteners in detergent. While visible microspectrophotometry cannot characterize denims well, it is likely that ultraviolet microspectrophotometry can be useful for this purpose.

APPENDIX

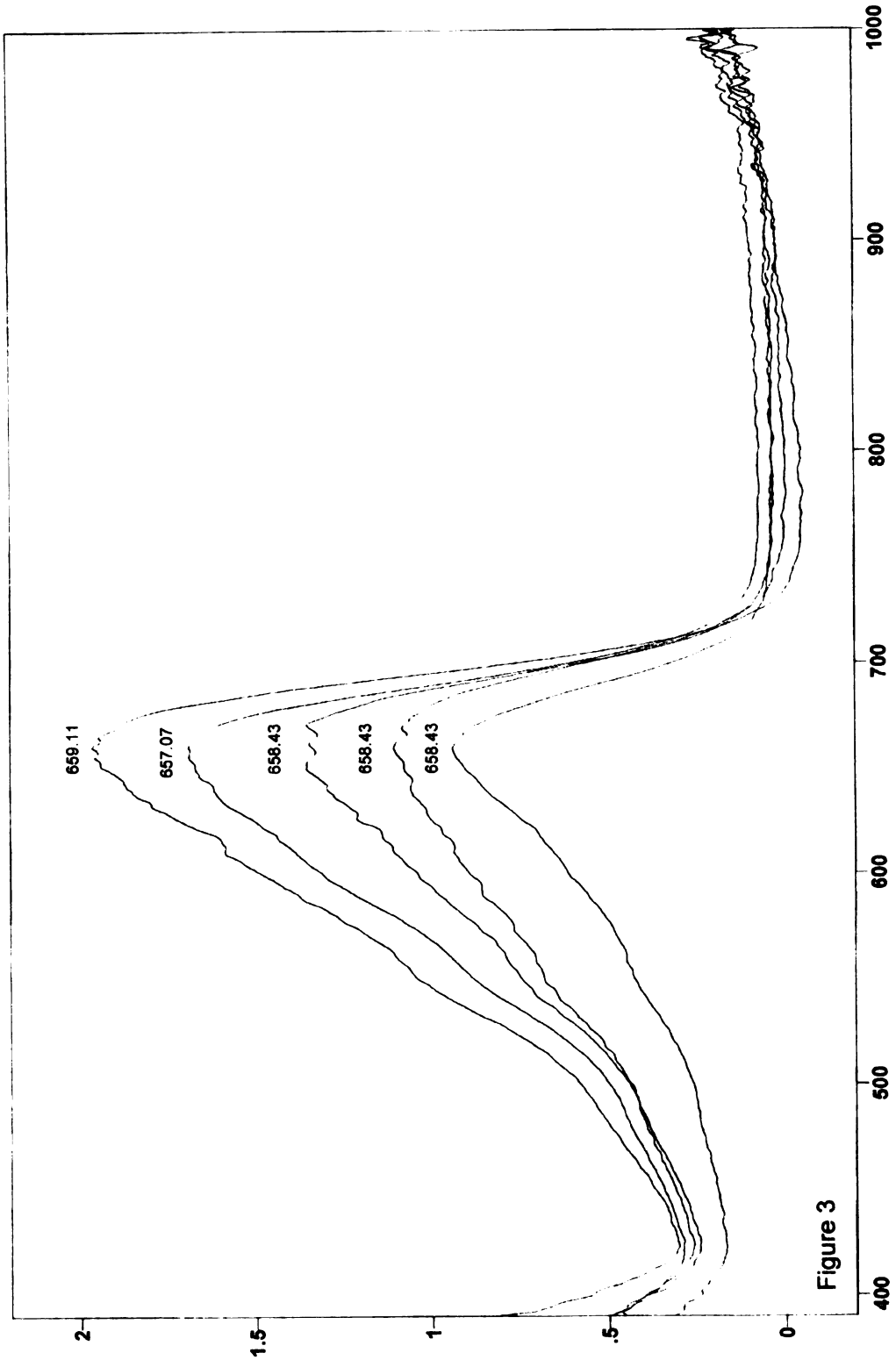
Visible Microspectrophotometry Spectra-

Nanometers X-axis and Absorbance Y-axis

Figure 2- Sample 20 Main Study

Figure 2

Figure 3- Sample 44 Main Study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657.07
658.43
658.43
658.43
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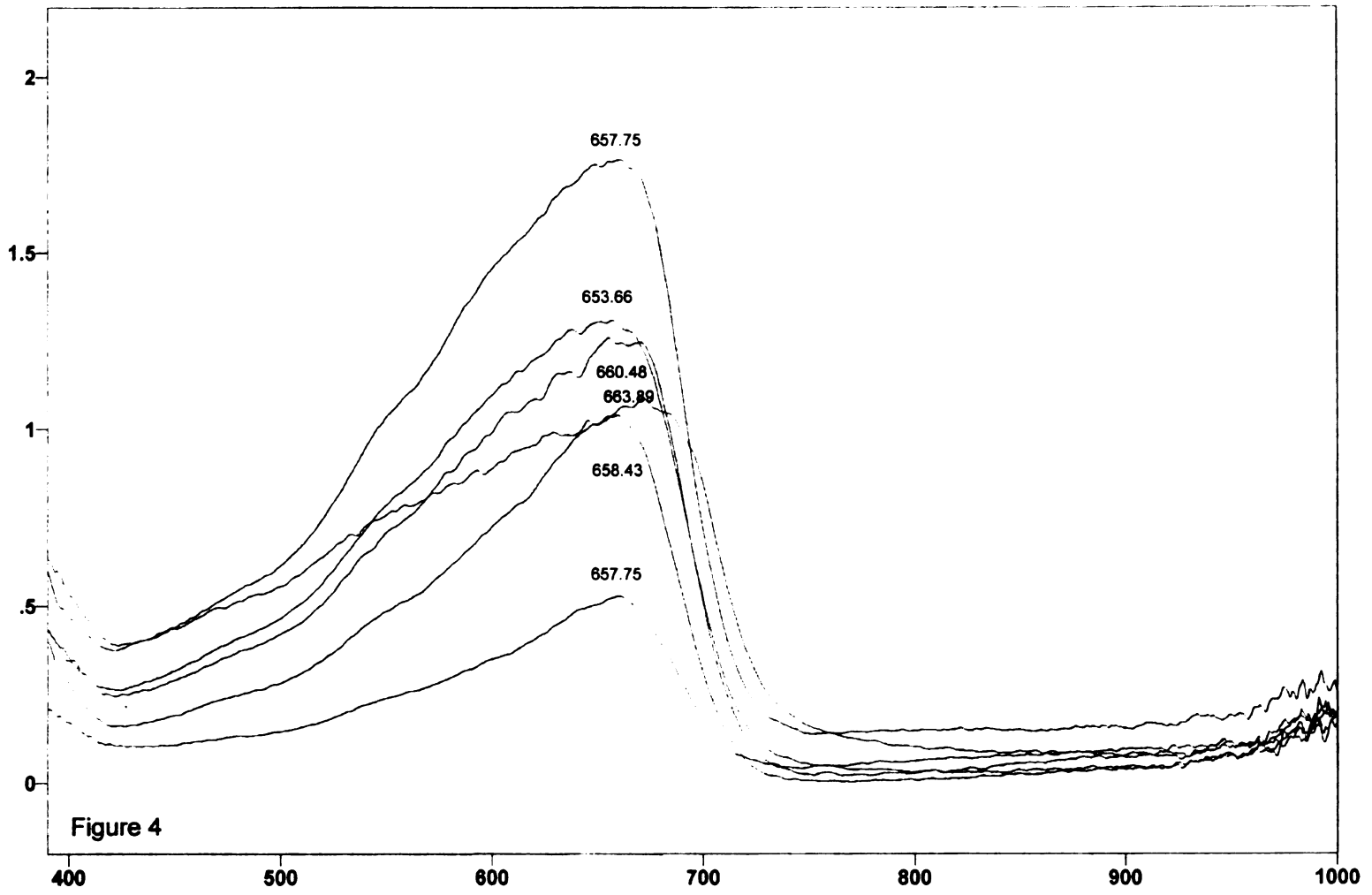
400
500
600
700
800
900
1000

Figure 3

Figure 4- Sample 3 Wash Study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0
657.75
653.66
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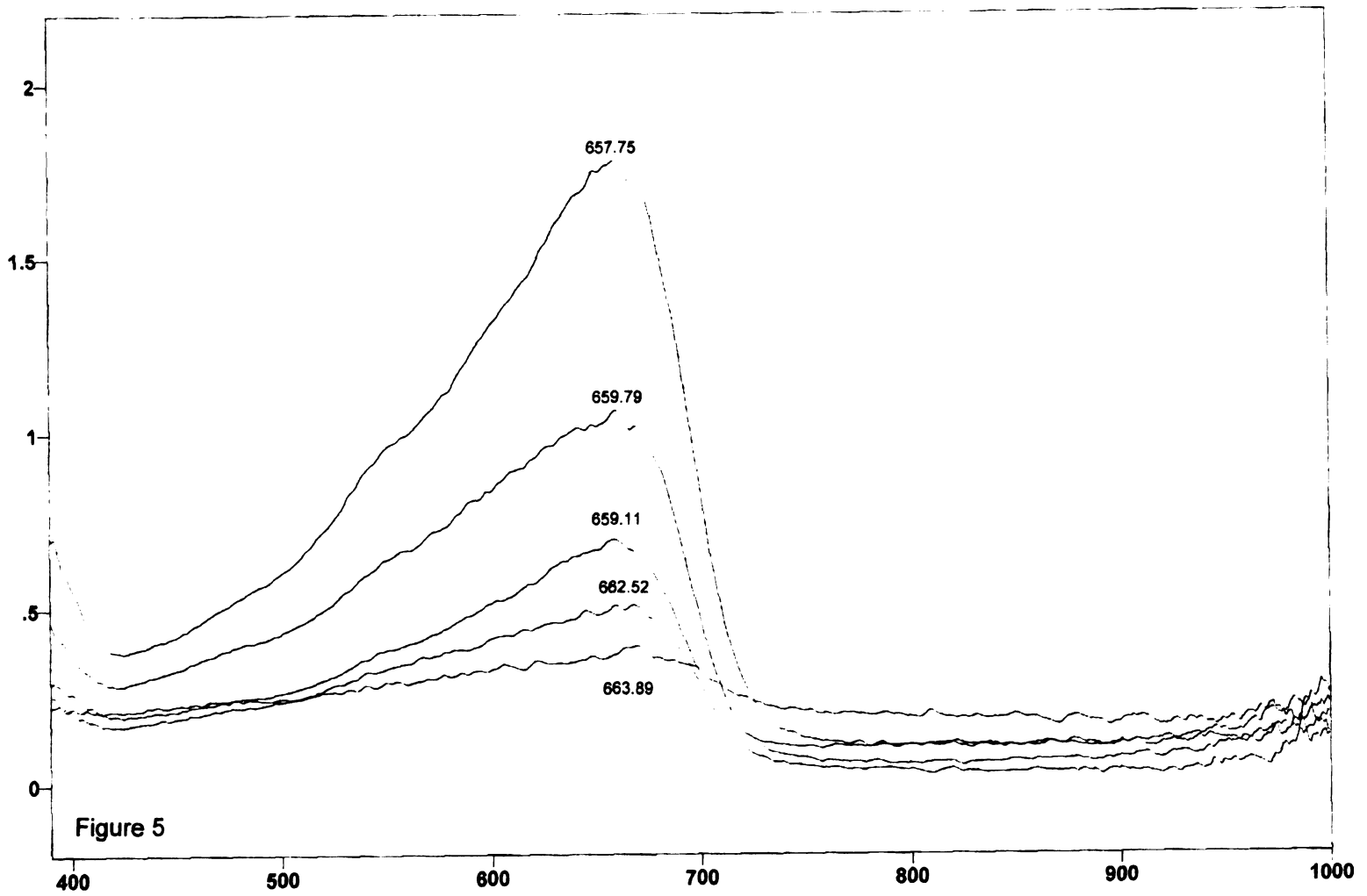
658.43
657.75
400
500
600
700
800
900
1000

Figure 4

Figure 5- Sample 1 Main Study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1
.5
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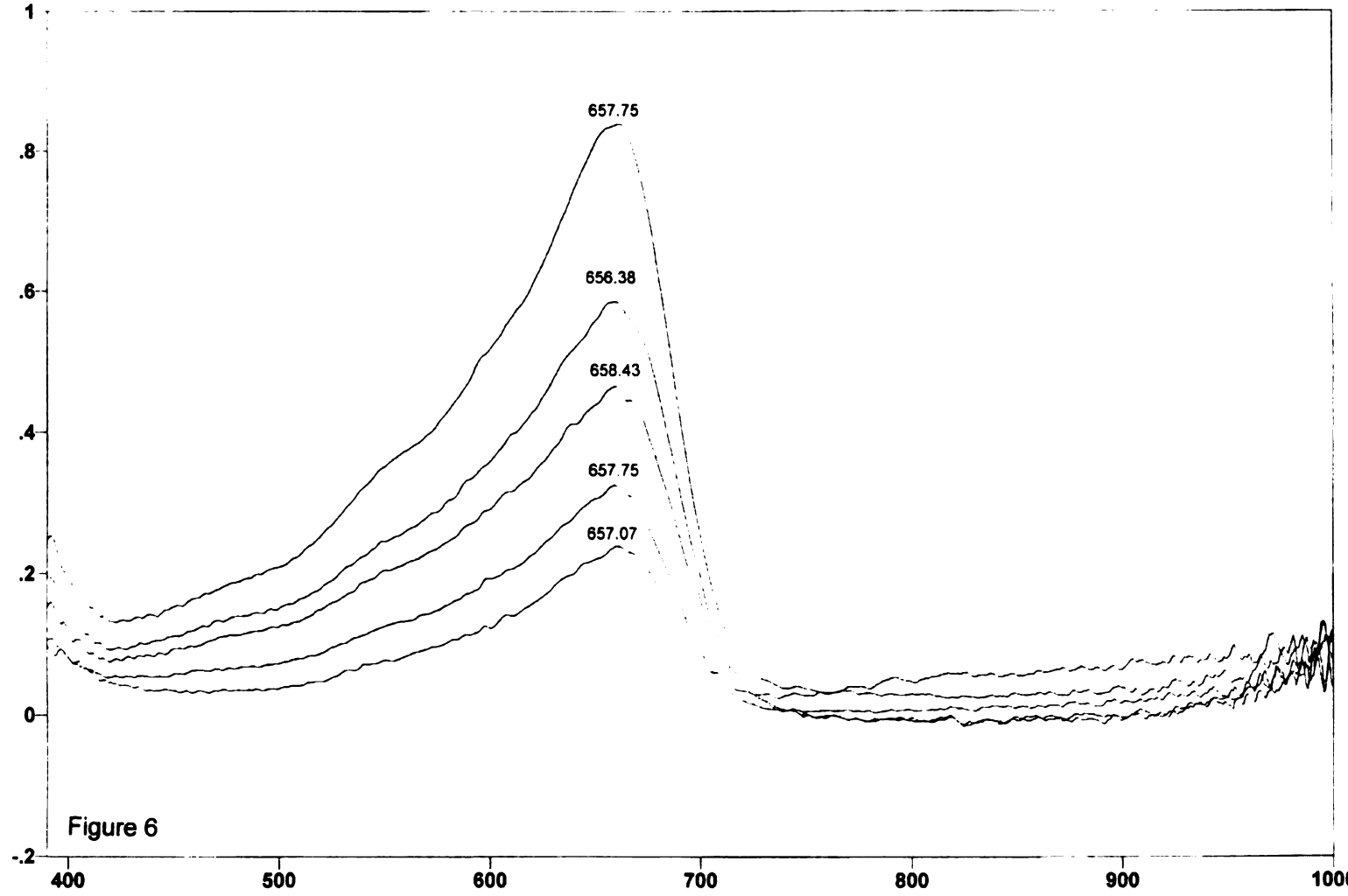
659.79
659.11
662.52
663.89
400
500
600
700
800
900
1000

Figure 5

Figure 6- Sample 2 Main Study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400
500
600
700
800
900
1000

Figure 6

Figure 7- Sample 3 Main Study

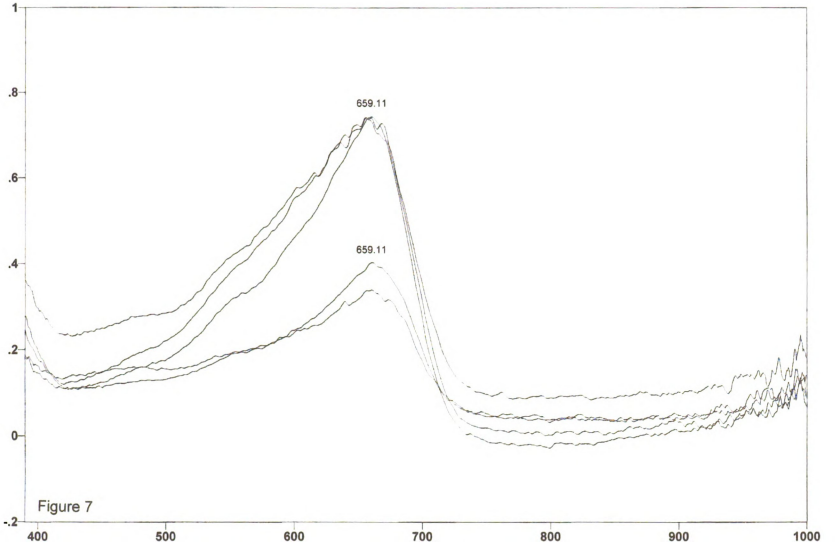

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Figure 8- Sample 4 Main Study

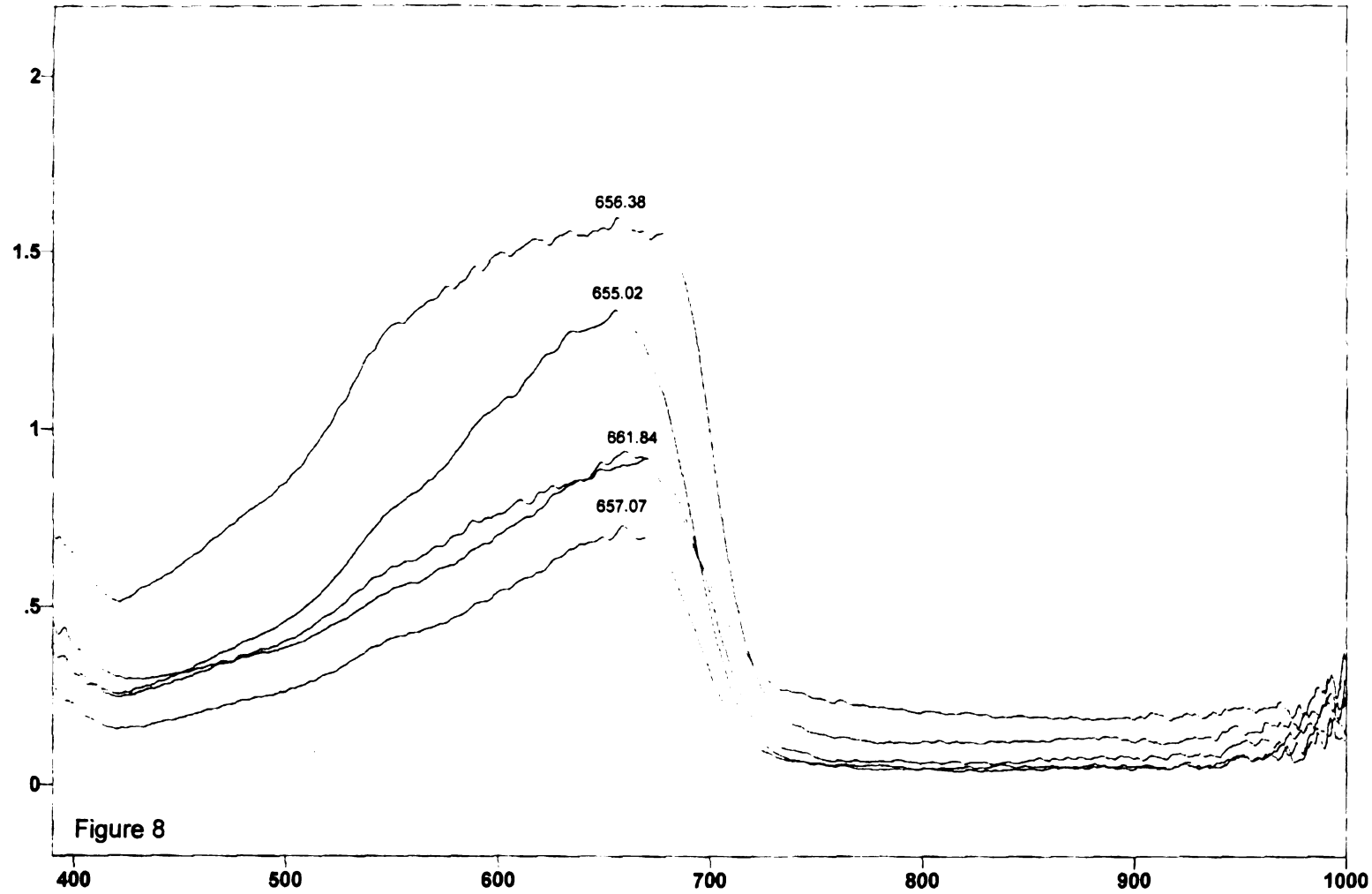

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Figure 9- Sample 5 Main Study

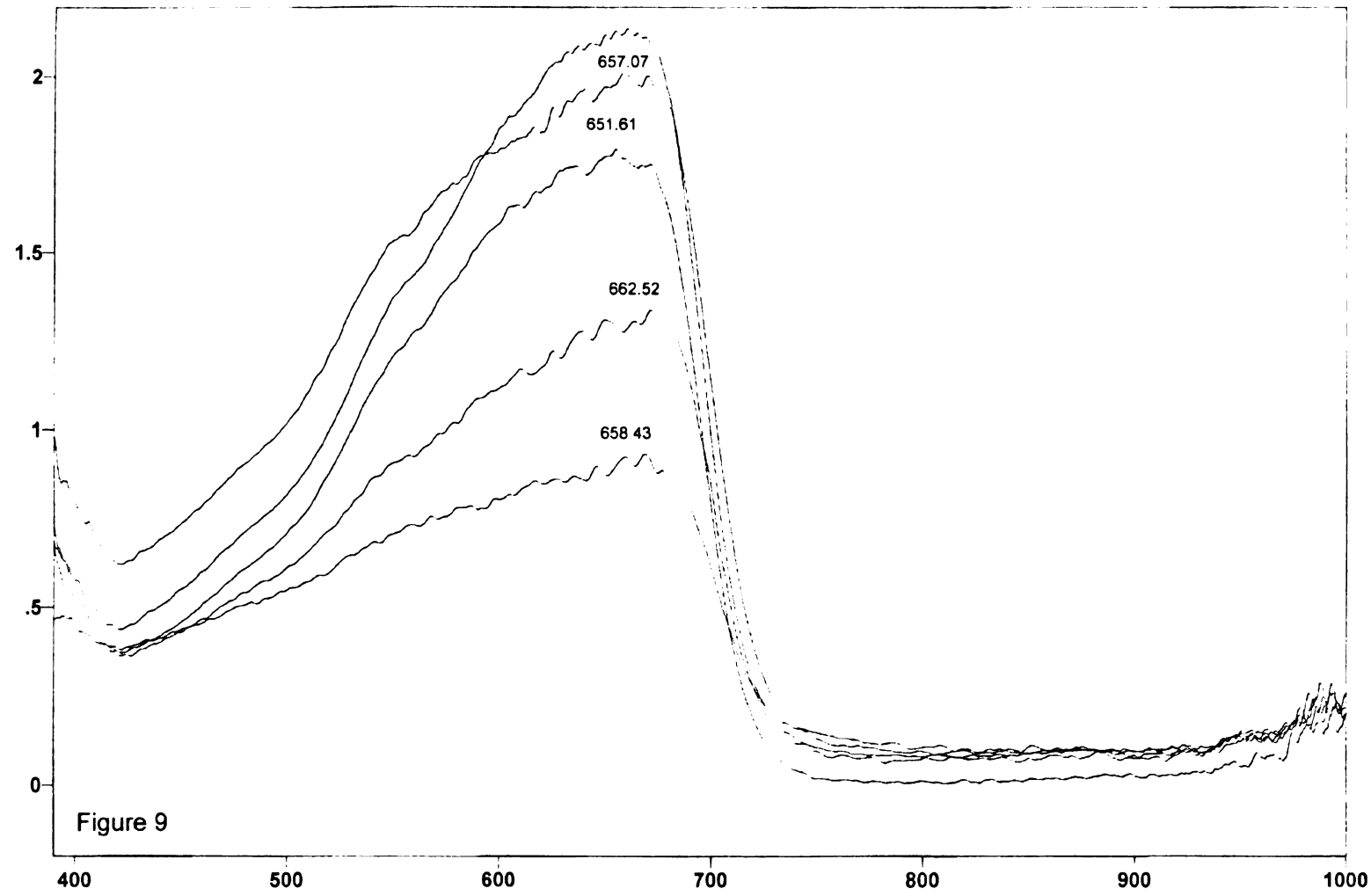

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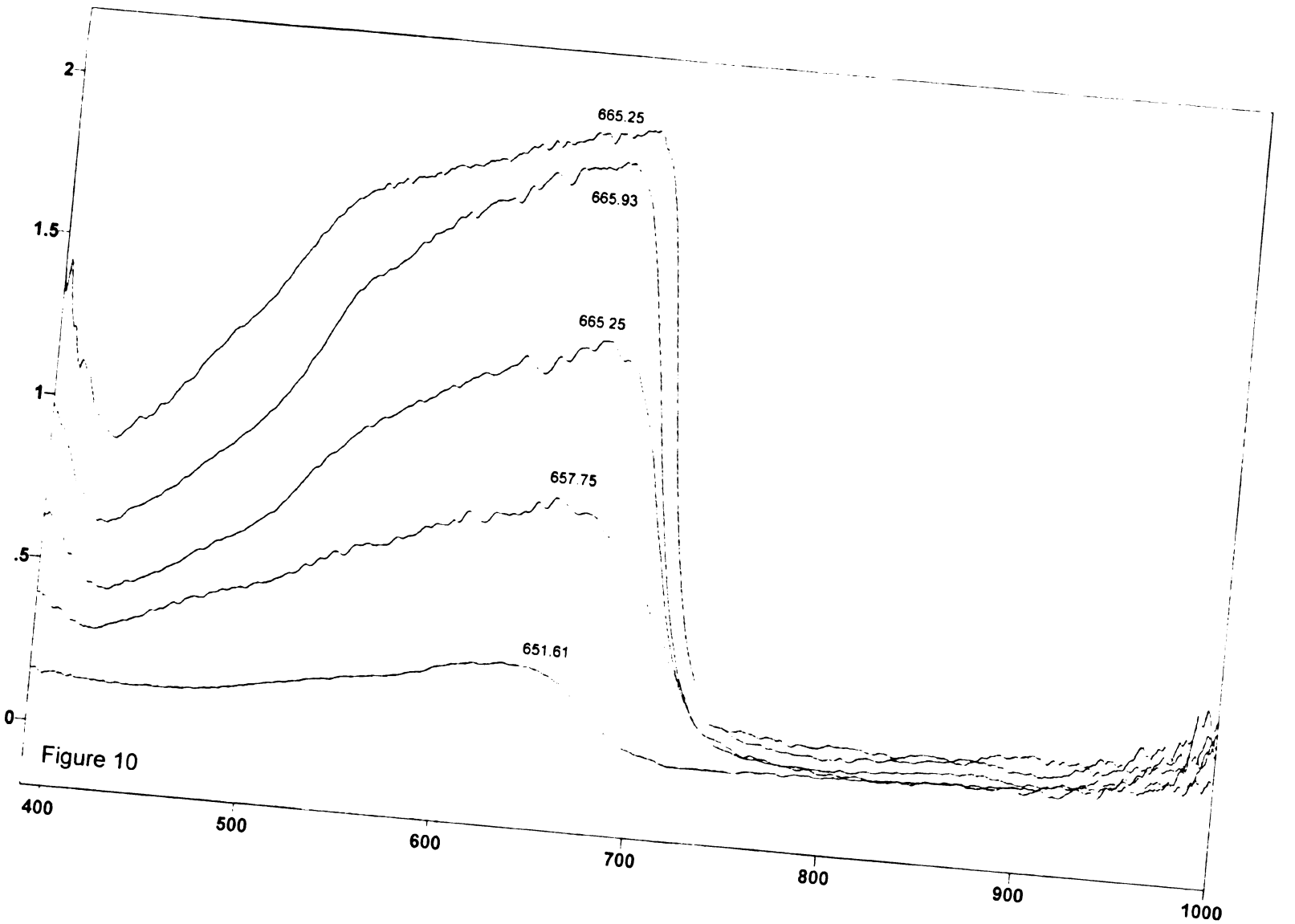
Figure10- Sample 6 Main Study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0
665.25
665.93
665.25
657.75
651.61
400
500
600
700
800
900
1000

Figure 10

Figure 11- Sample 7 Main Study

Figure 11

Figure12- Sample 8 Main Study

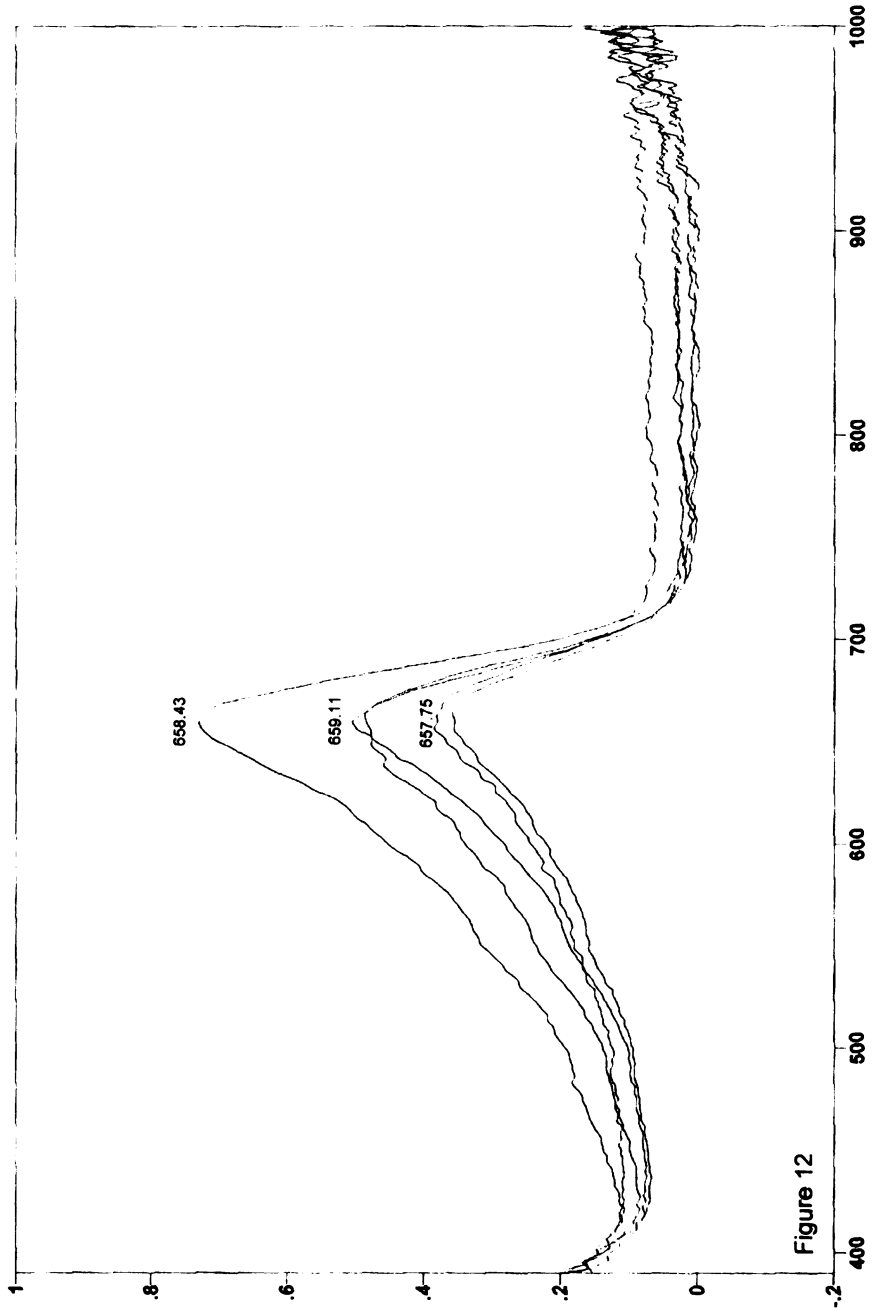

Figure 12

Figure 13- Sample 9 Main Study

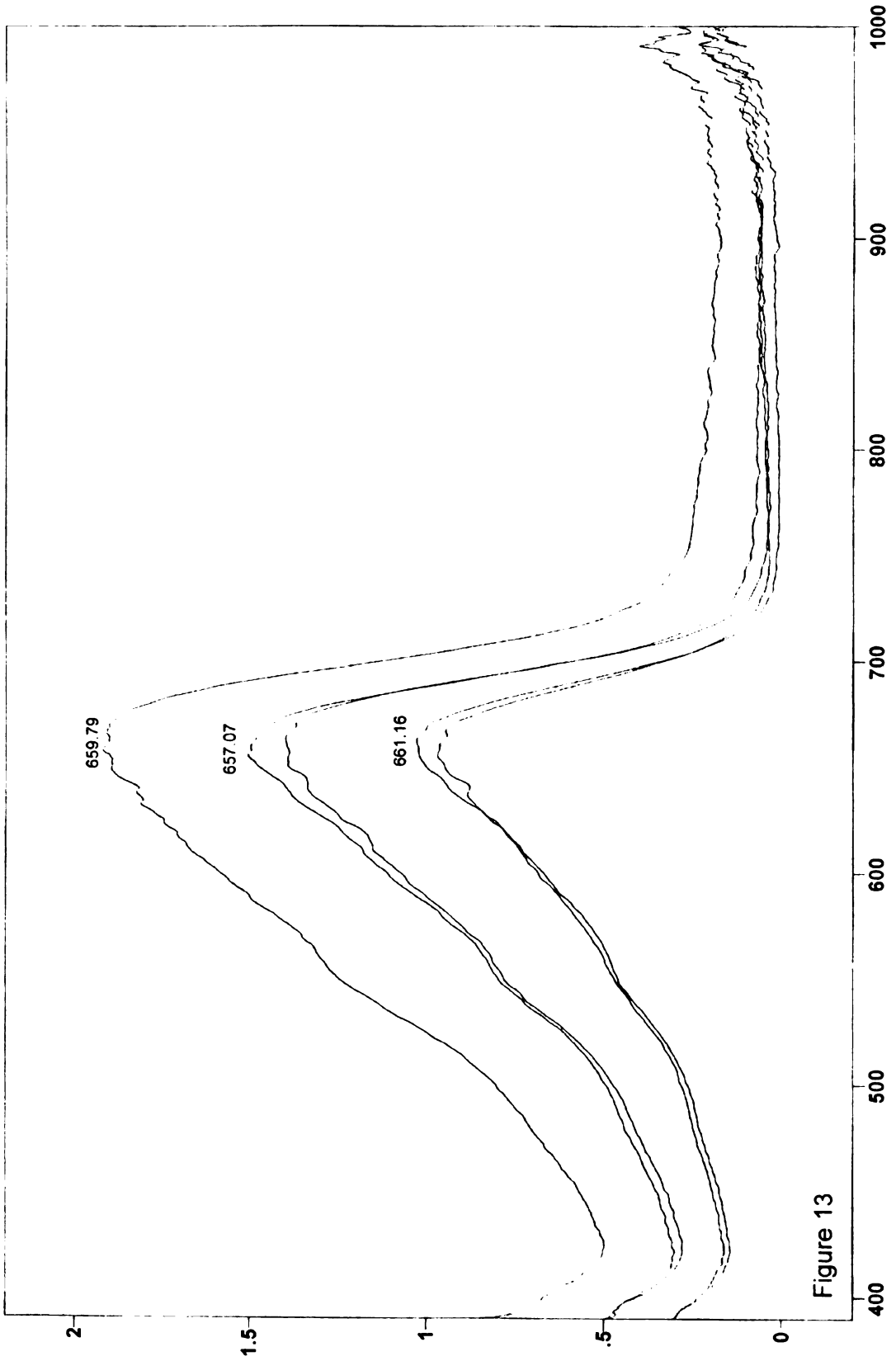

Figure 13

Figure14- Sample 10 Main Study

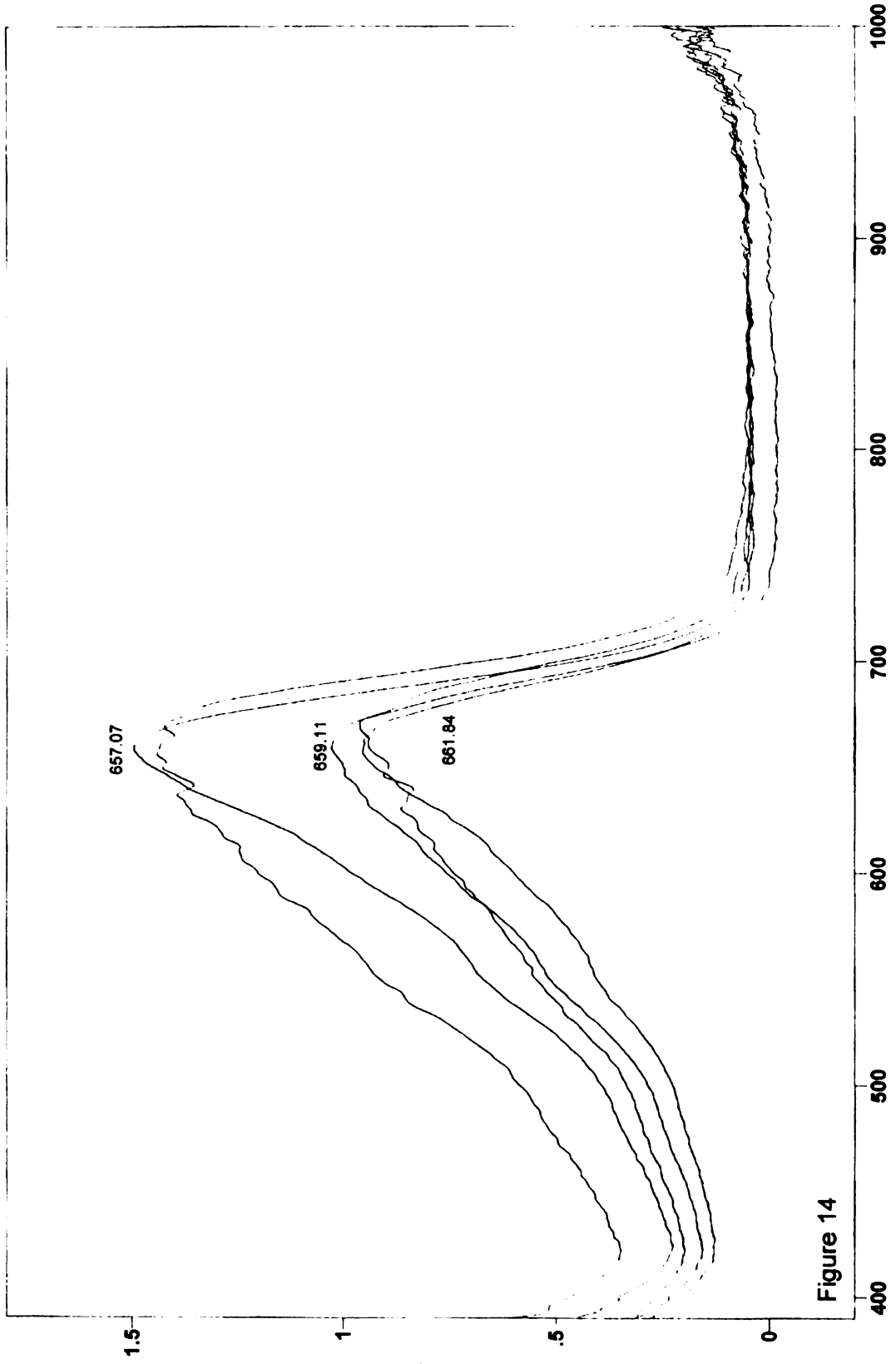

Figure 14

Figure 15- Sample 11 Main Study

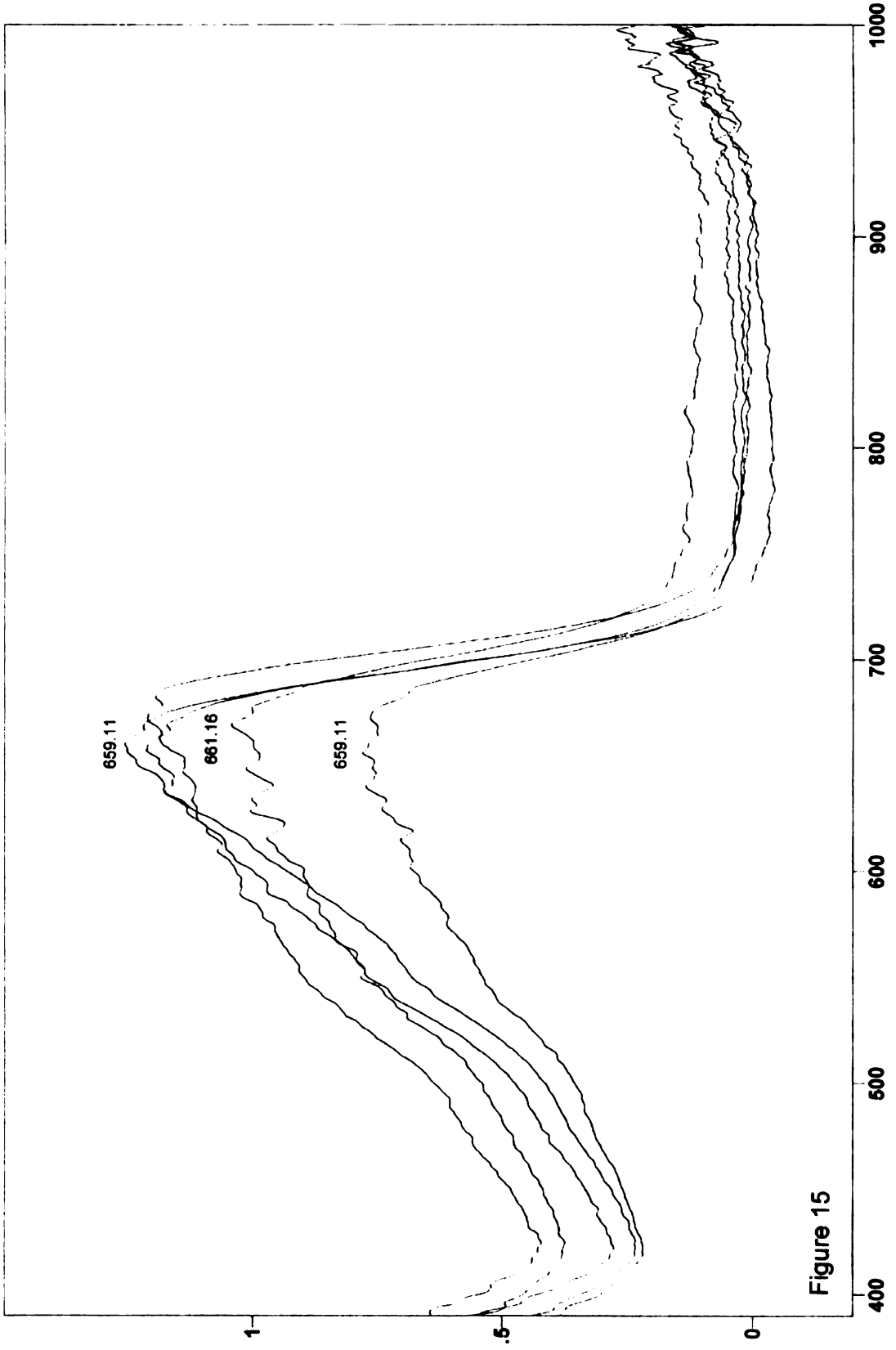

Figure 15

Figure 16- Sample 12 Main Study

656.38
660.46
658.43
660.48
661.16
1.5
1
.5
0
400
500
600
700
800
900
1000

Figure 16

Figure 17- Sample 13 Main Study

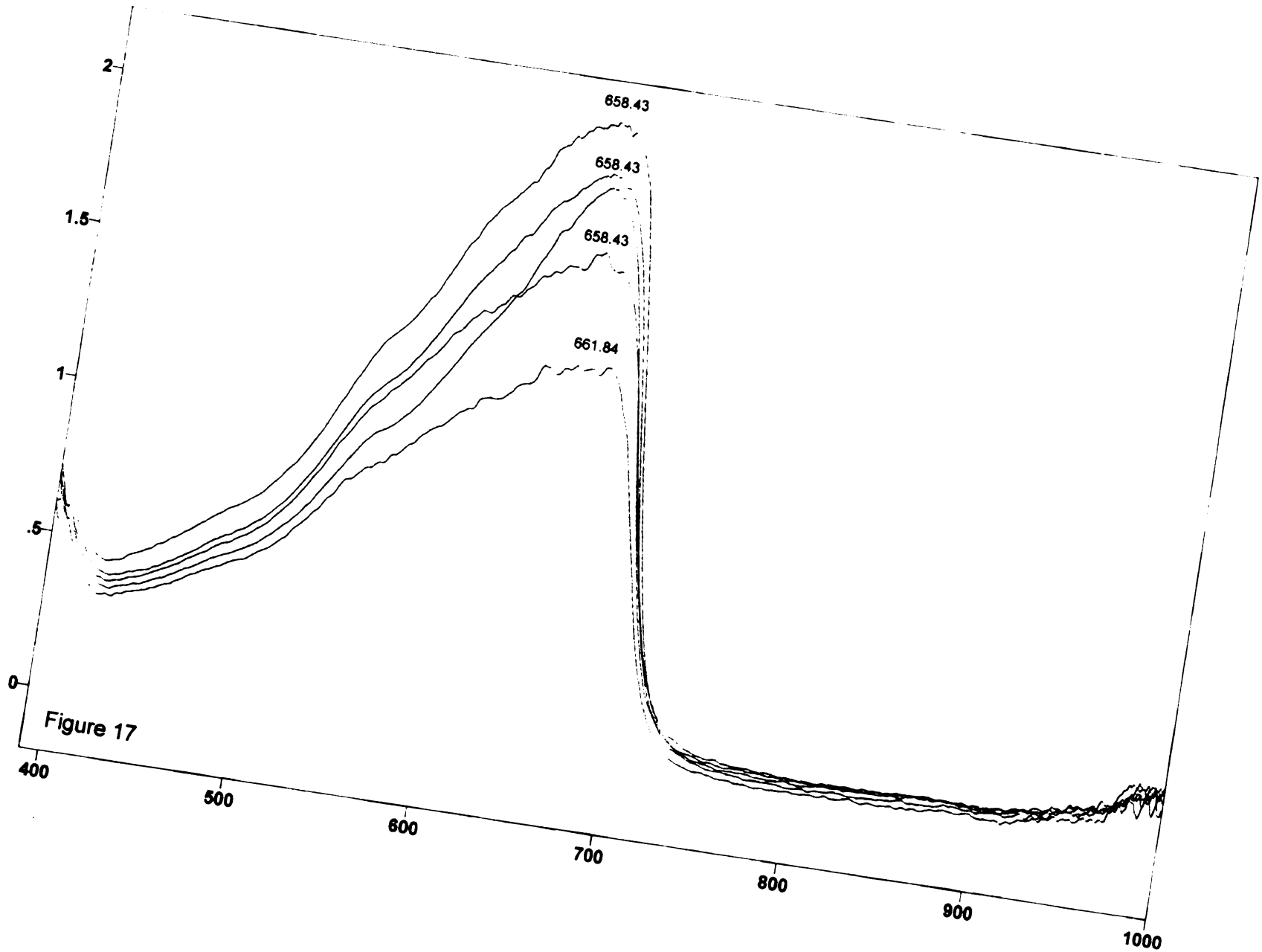

Figure 17

Figure 18- Sample 14 Main Study

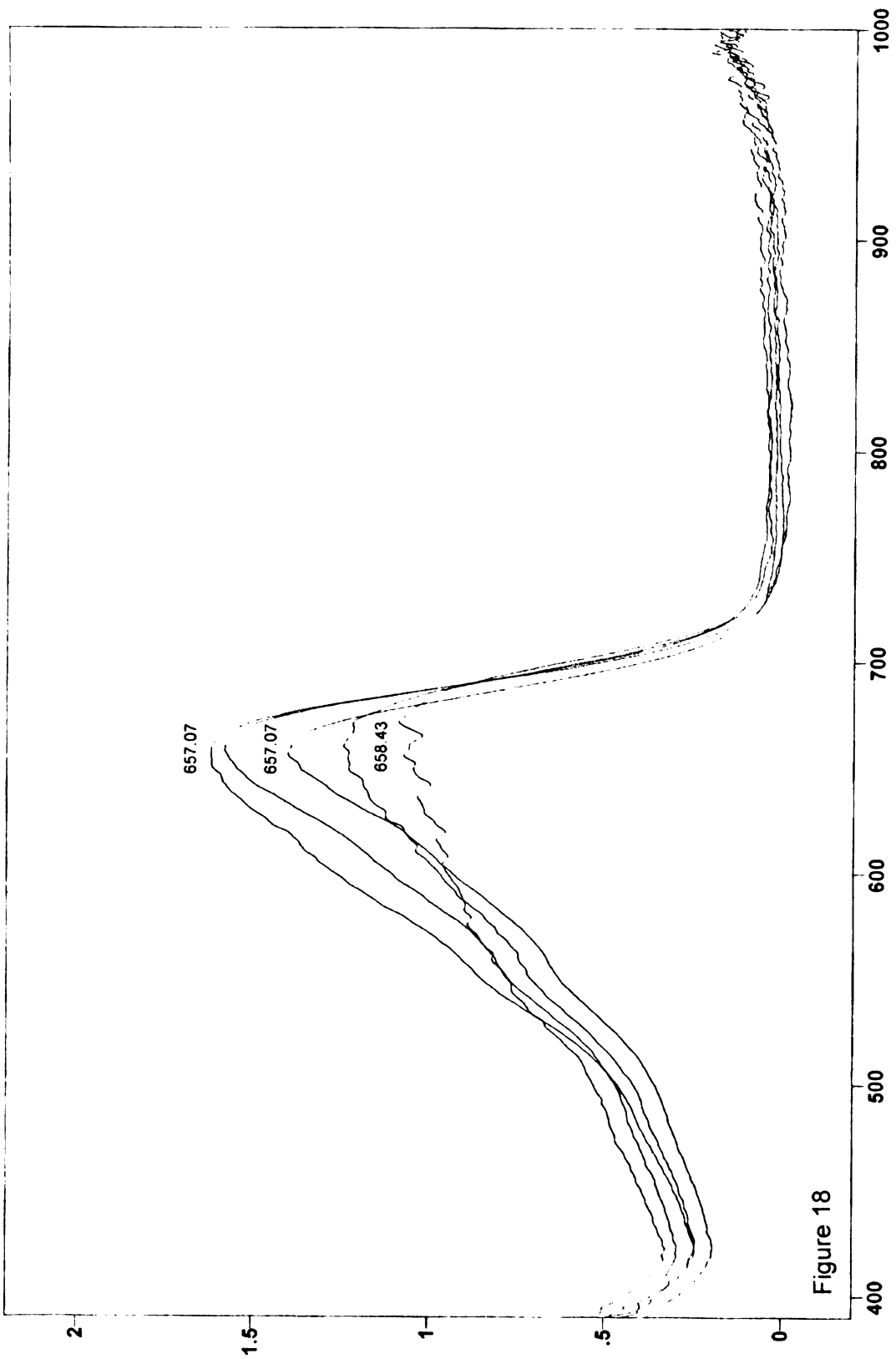

Figure 18

Figure 19- Sample 15 Main Study

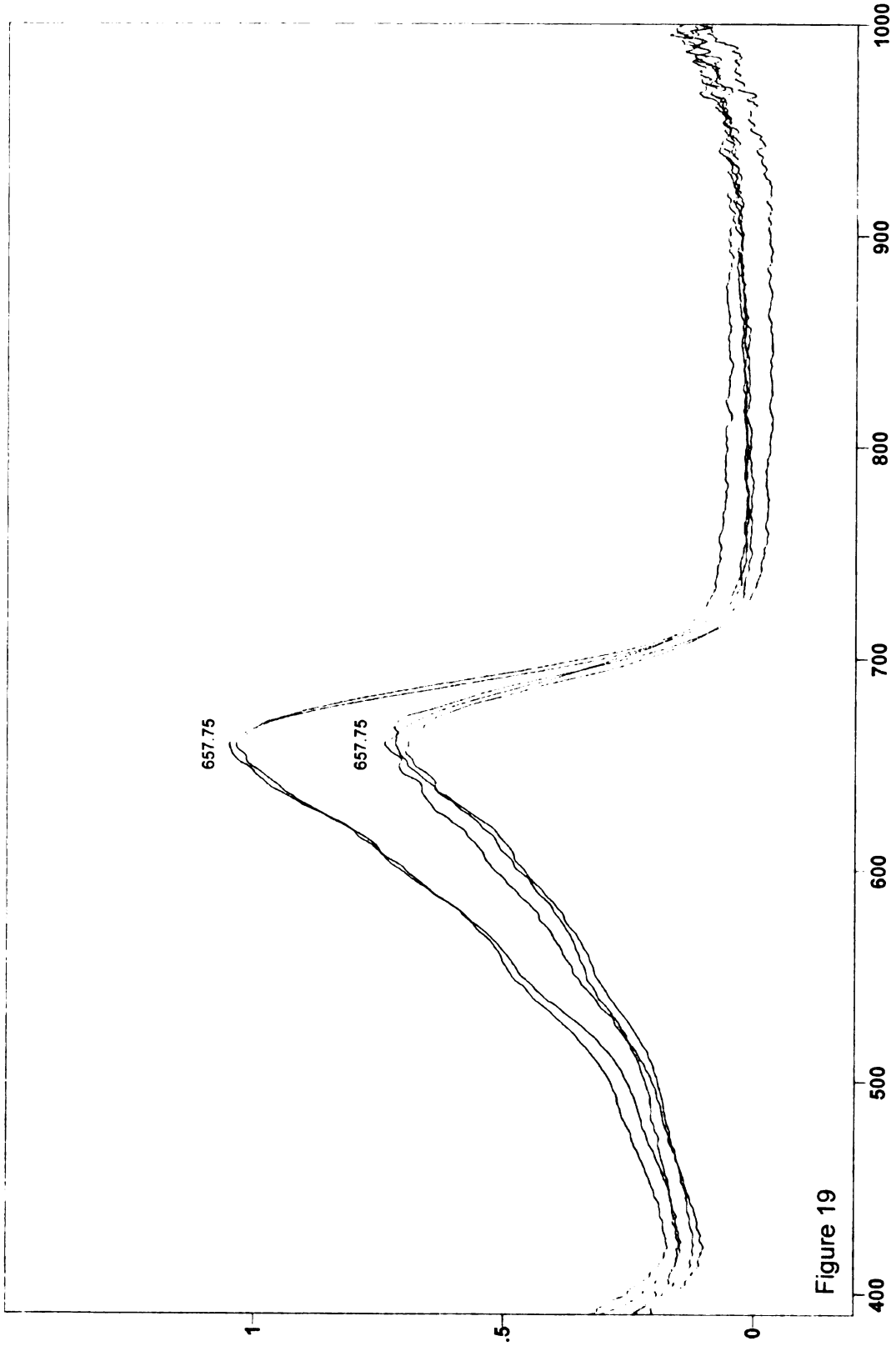

Figure 19

Figure 20- Sample 16 Main Study

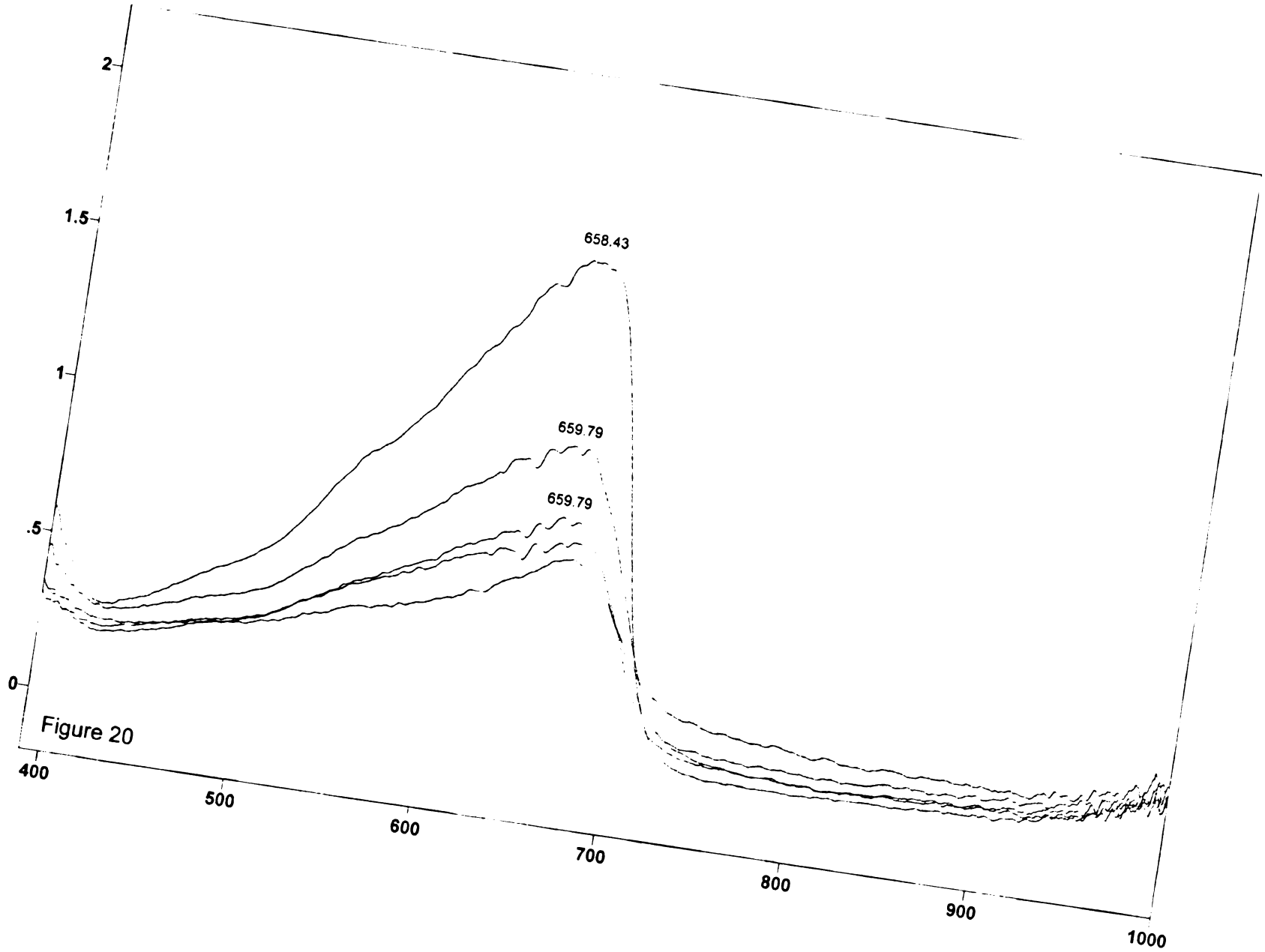

Figure 20

Figure21- Sample 17 Main Study

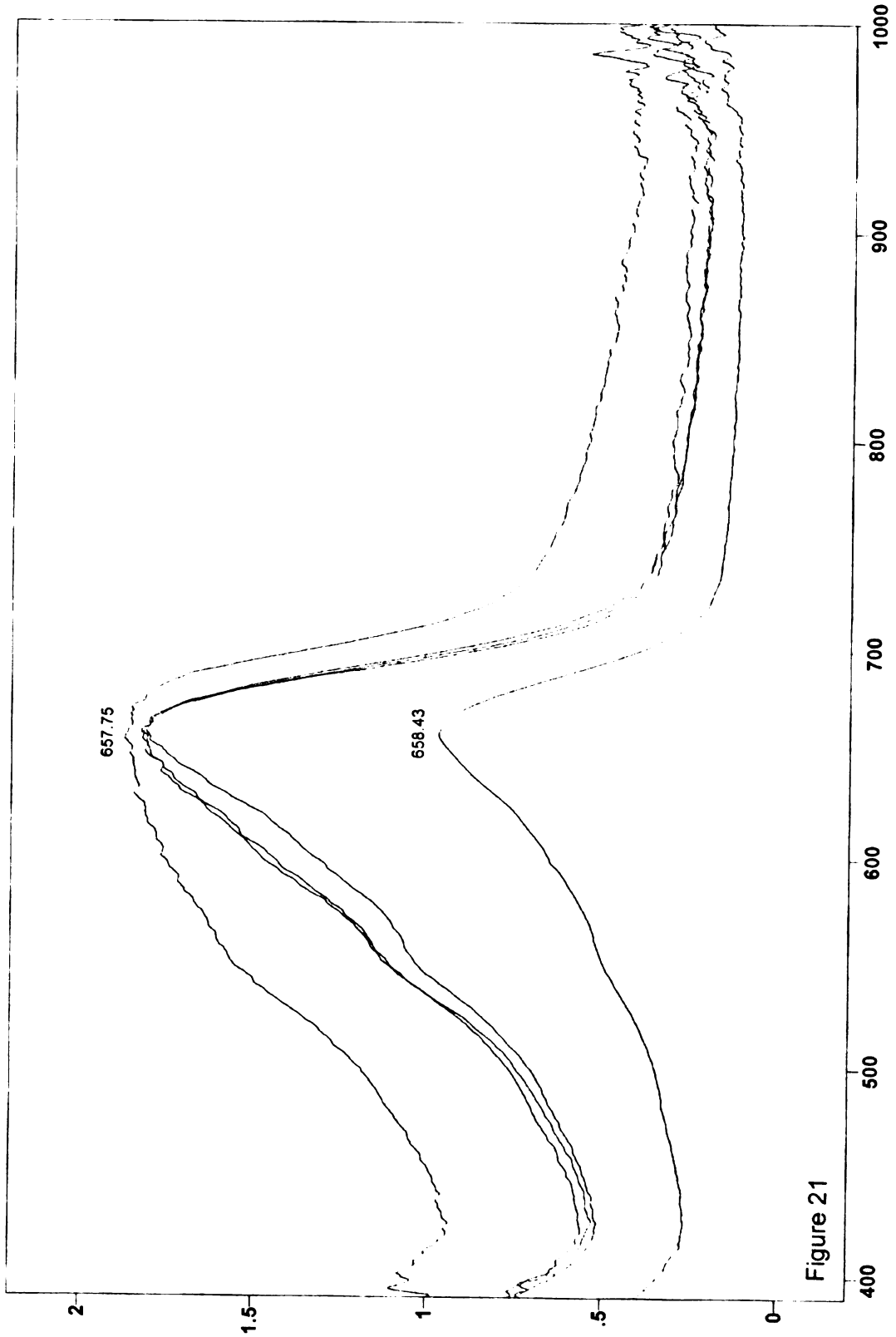

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Figure 22- Sample 18 Main Study

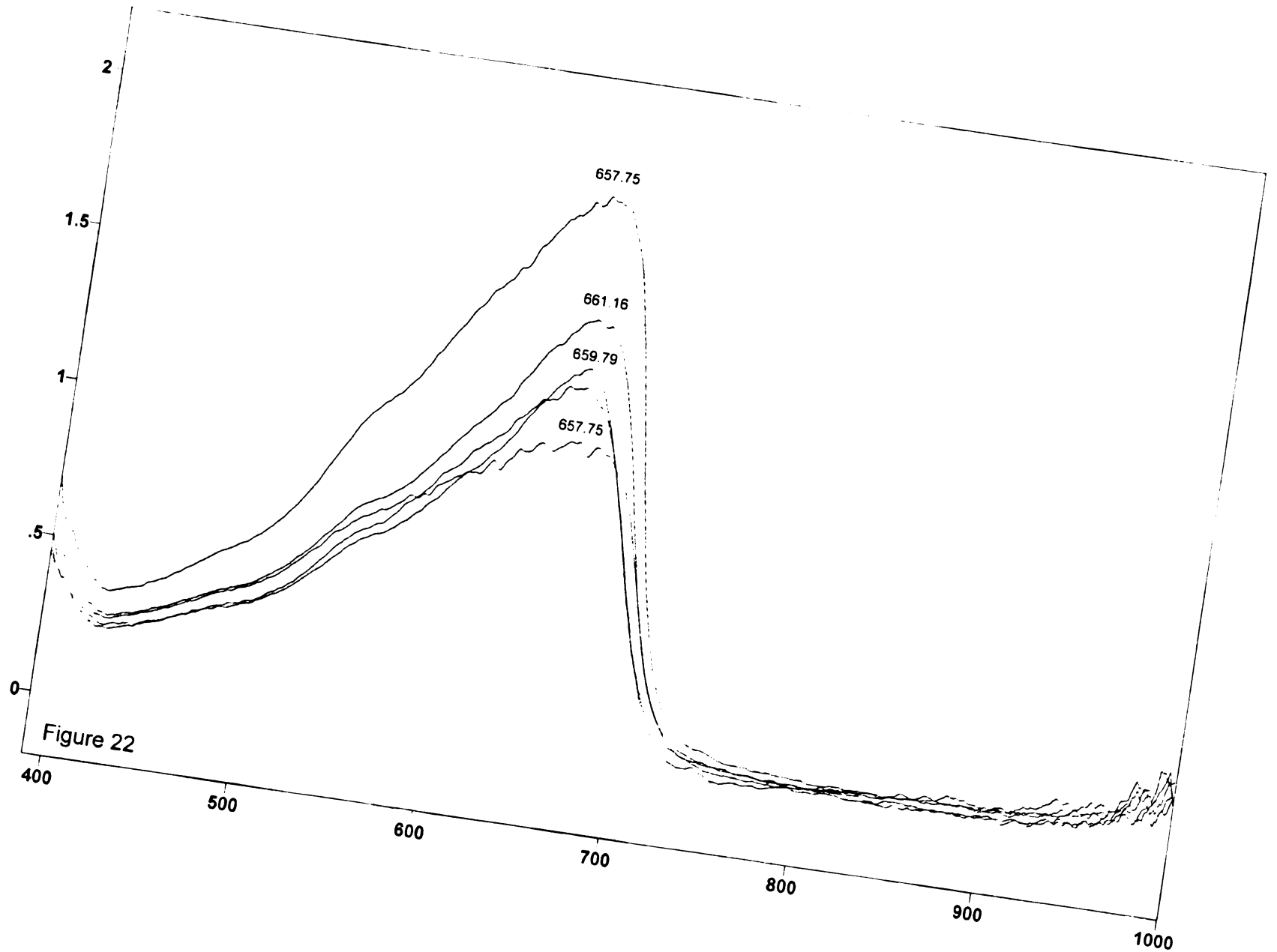

Figure 22

Figure 23- Sample 19 Main Study

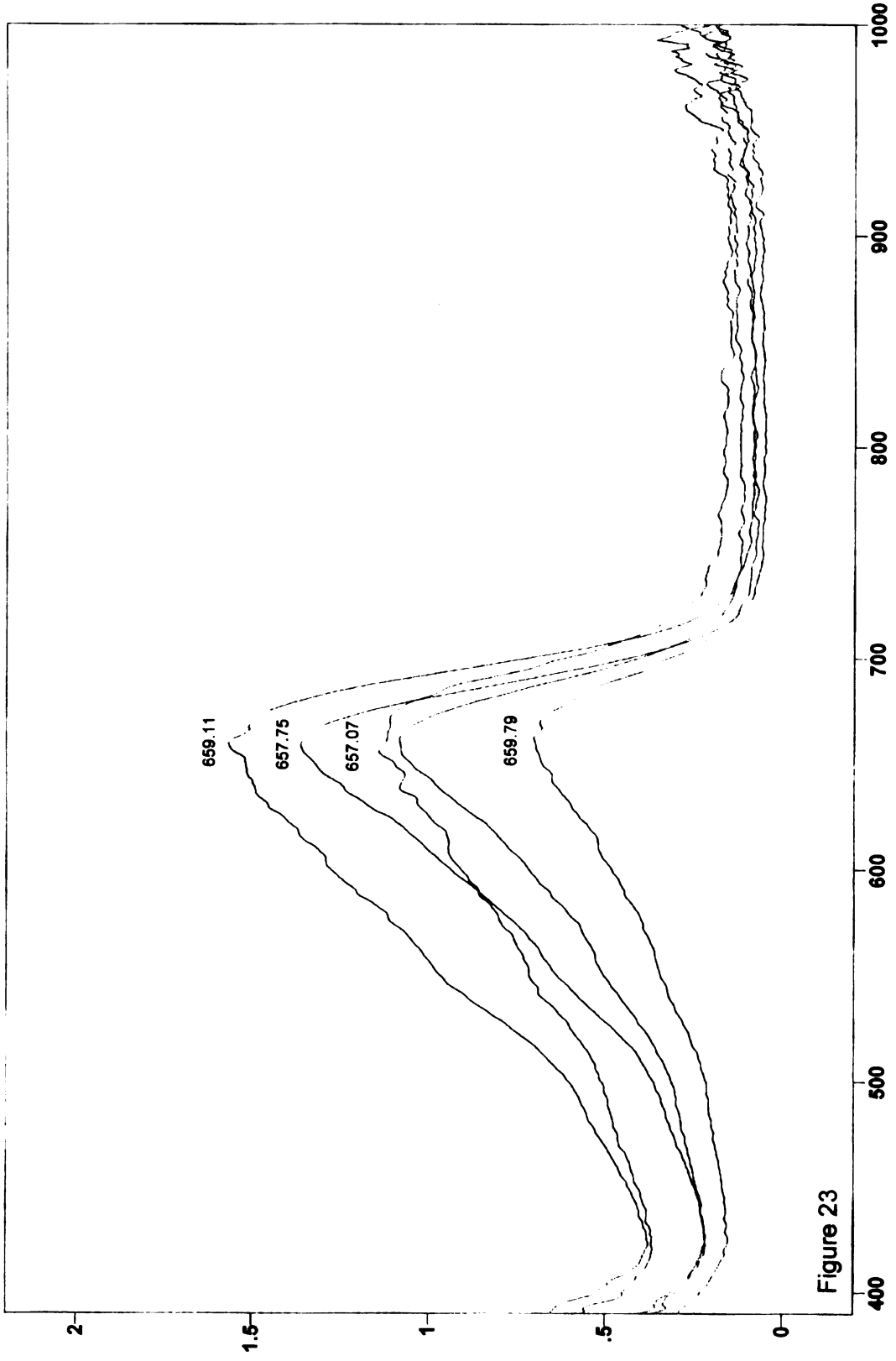

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Figure 24- Sample 21 Main Study

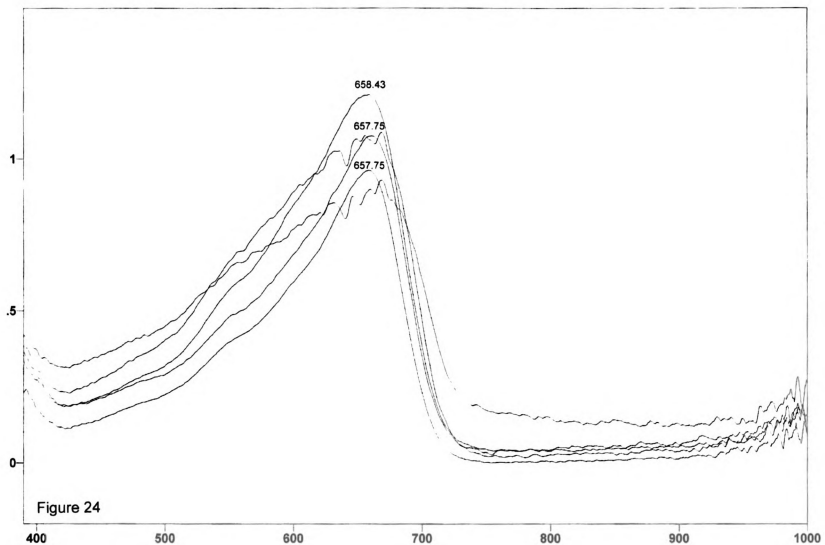

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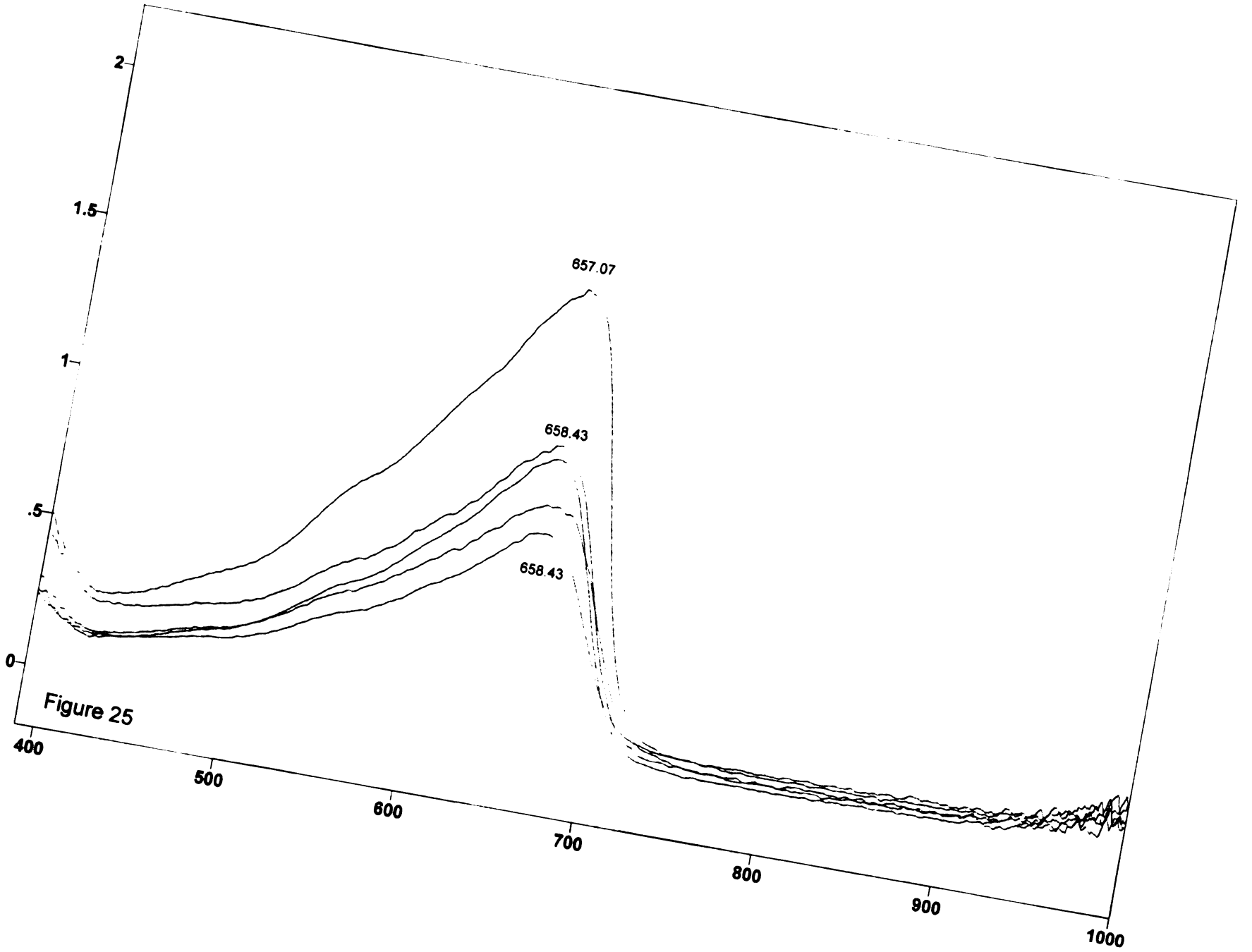
Figure 25- Sample 22 Main Study



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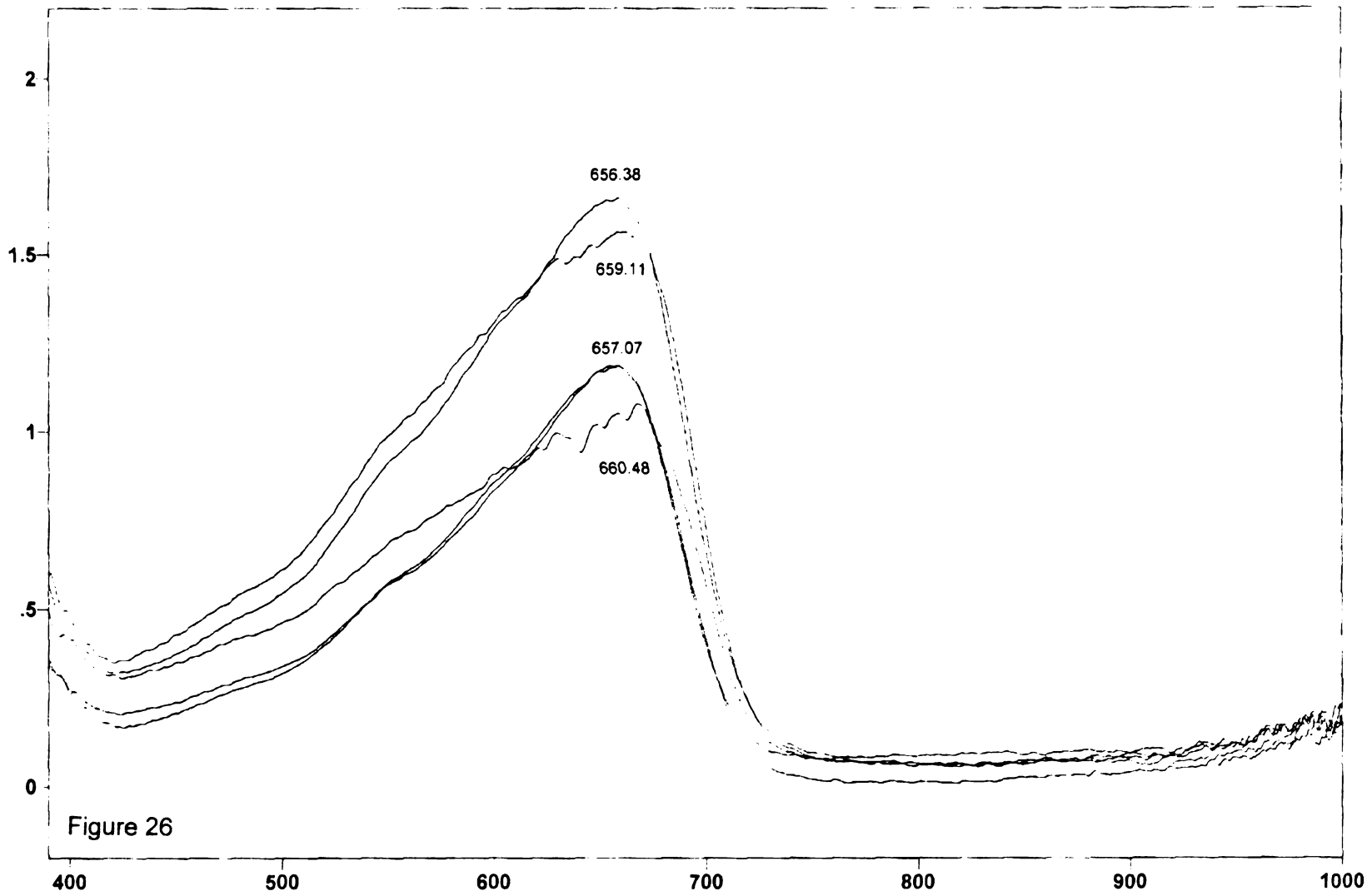


Figure 26

Figure 27- Sample 39 Main Study

Figure 27

Figure 28- Sample 48 Main Study

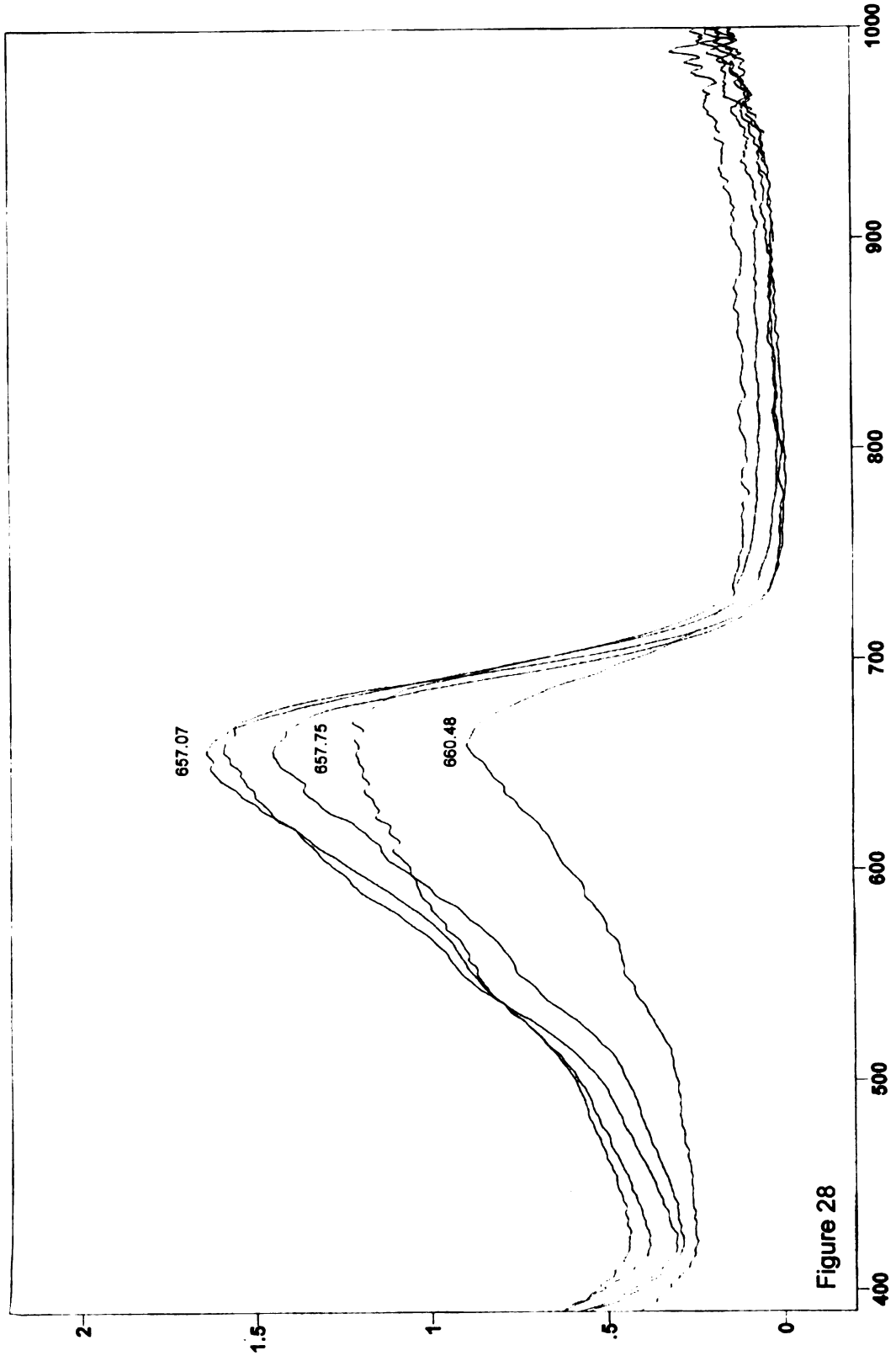
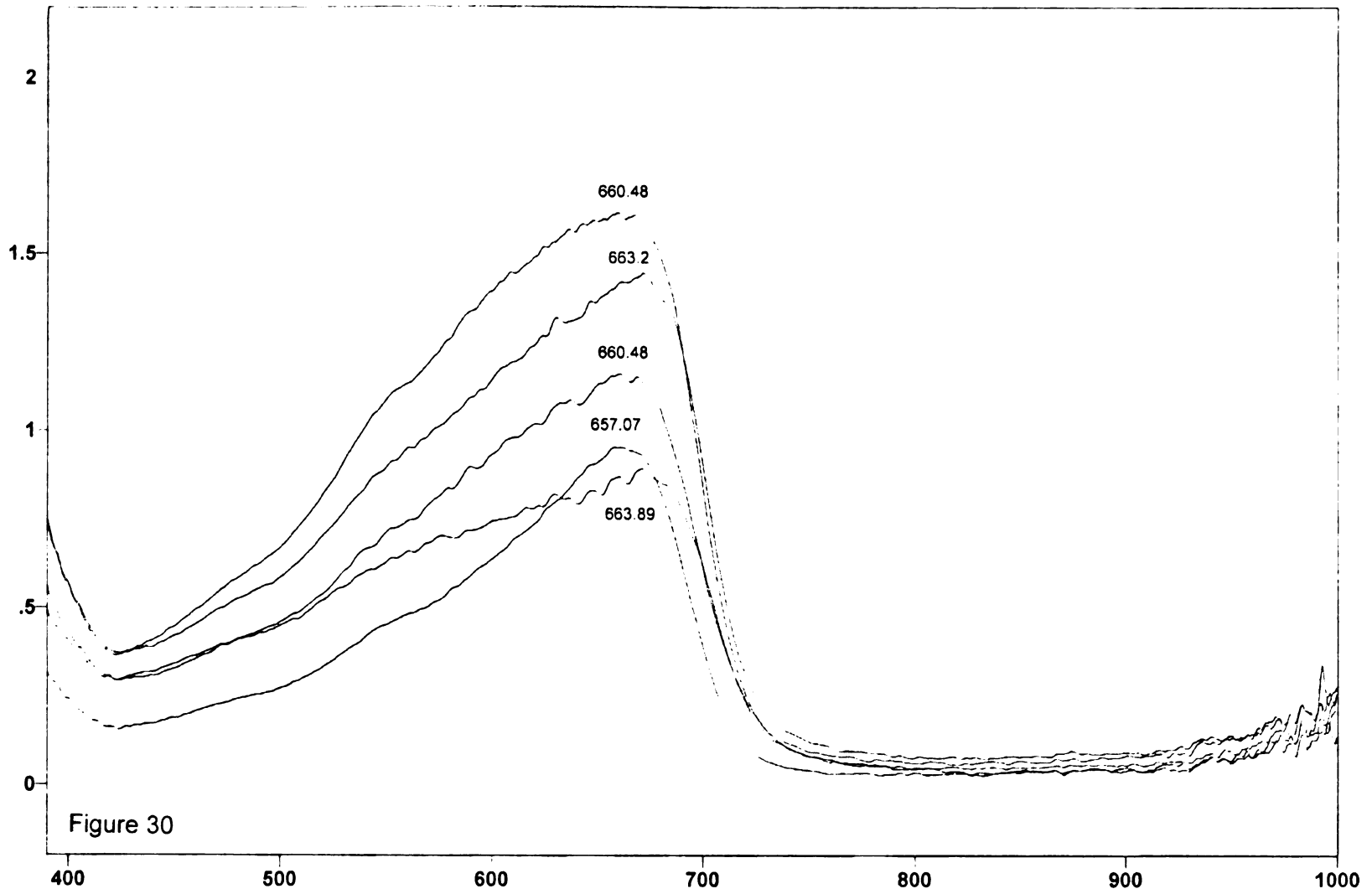


Figure 28

Figure 29- Sample 1 Worn Study

Figure 29

Figure 30- Sample 2 Worn Study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663.2
660.48
657.07
663.89
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1.5
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0
400
500
600
700
800
900
1000

Figure 30

Figure 31- Sample 3 Worn Study

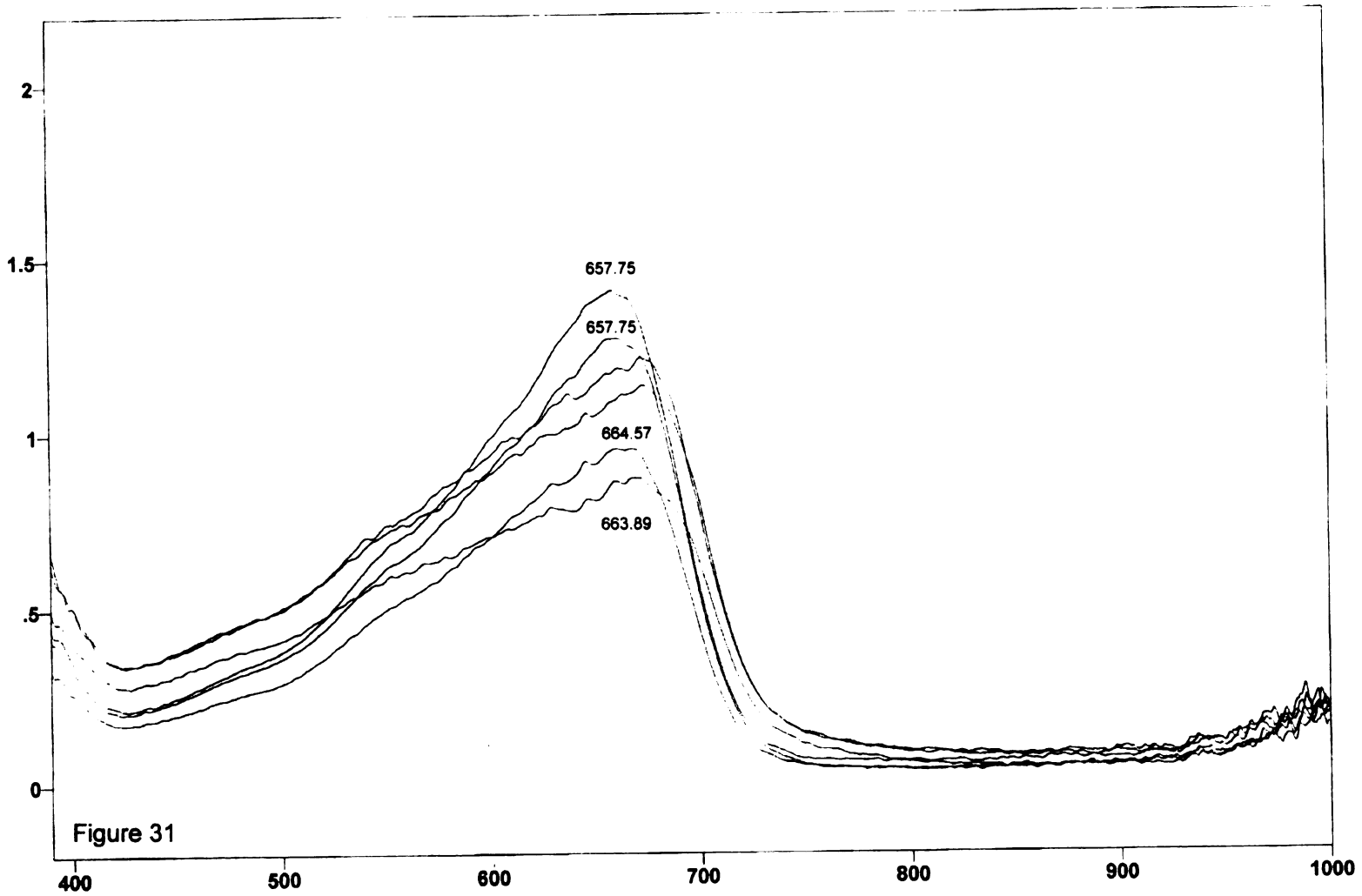

Figure 31

Figure 32- Sample 4 Worn Study

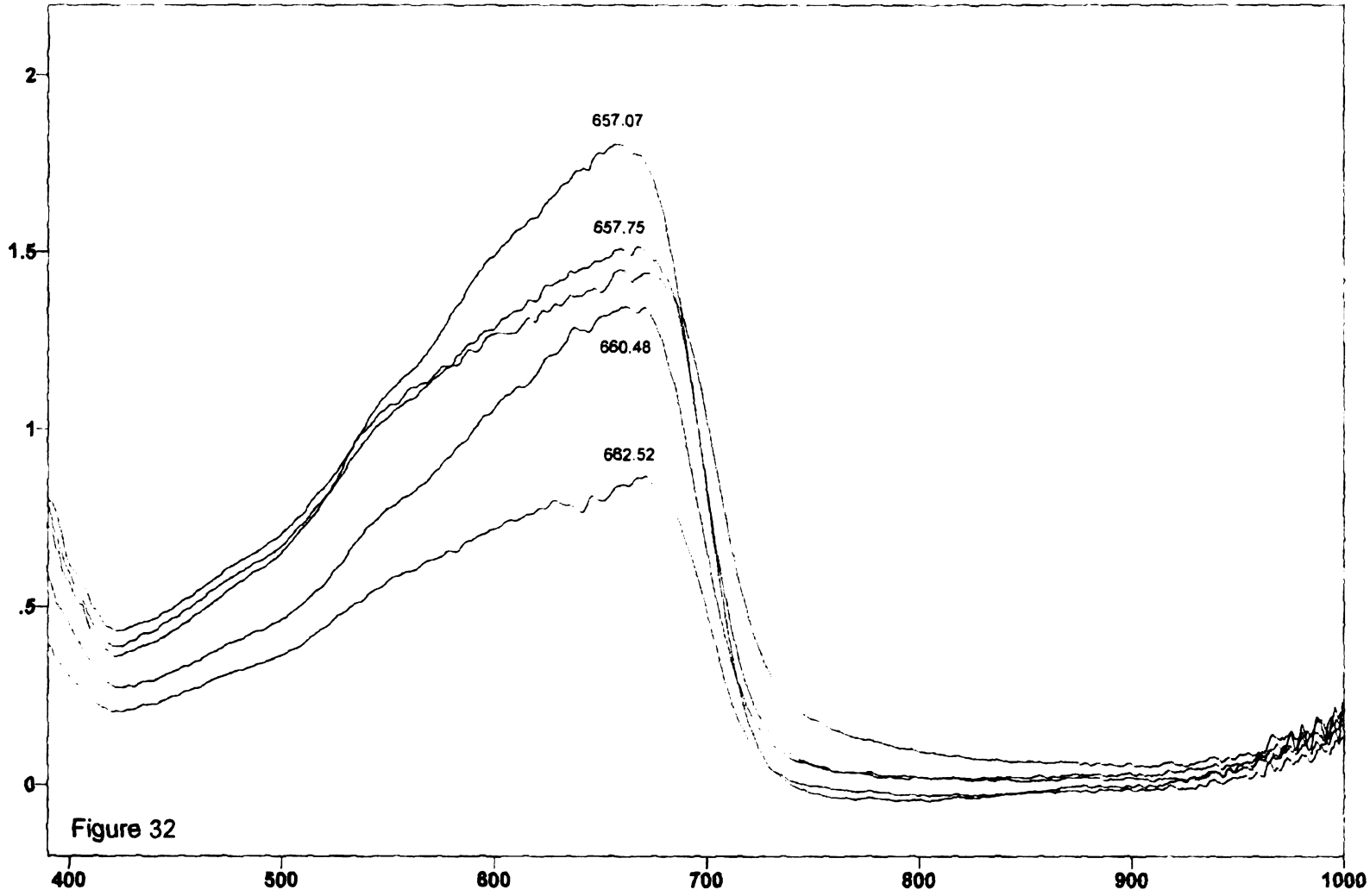

Figure 32

Figure 33- Sample 5 Worn Study

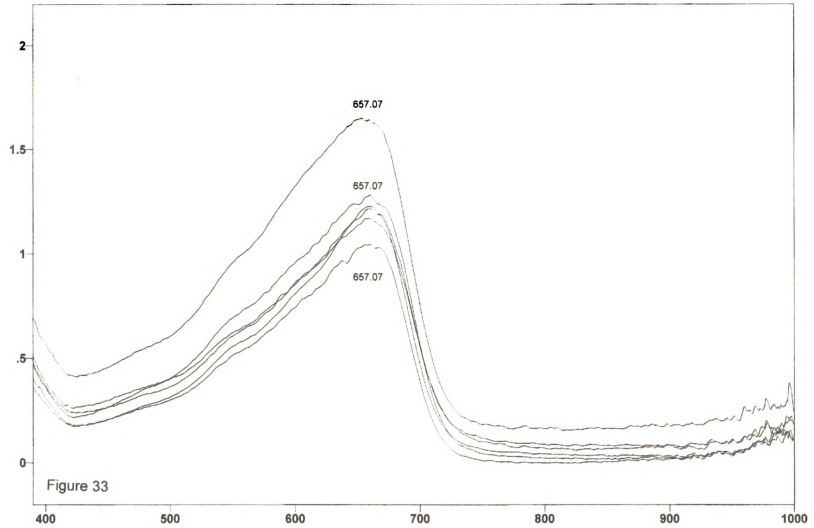

Figure 33

Figure 34- Sample 6 Worn Study

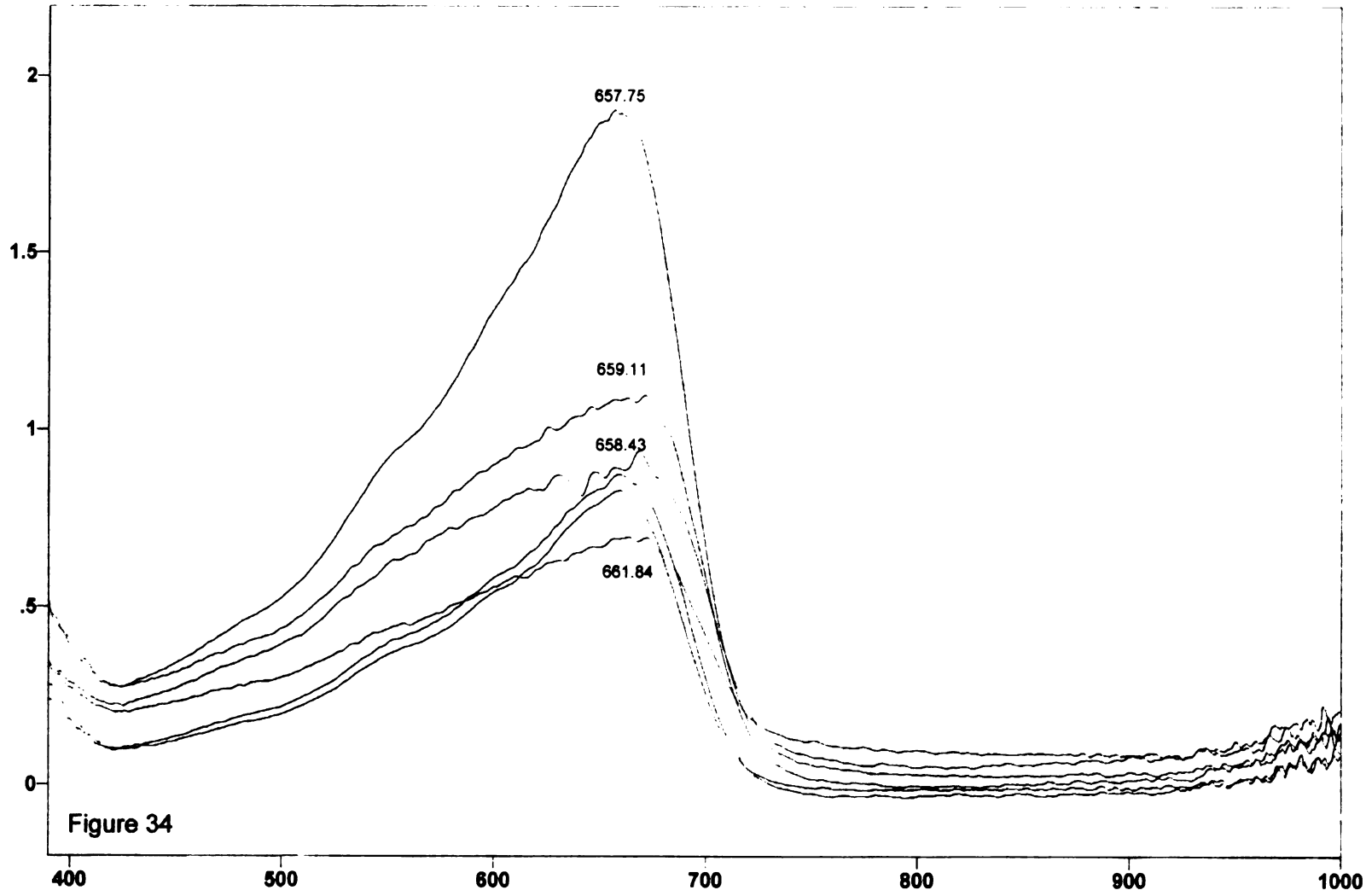

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Figure 35- Sample 7 Worn Study

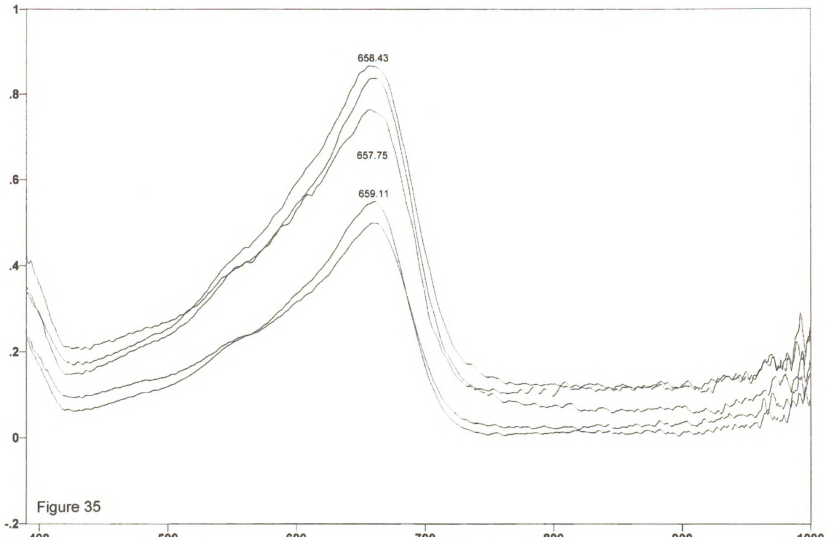
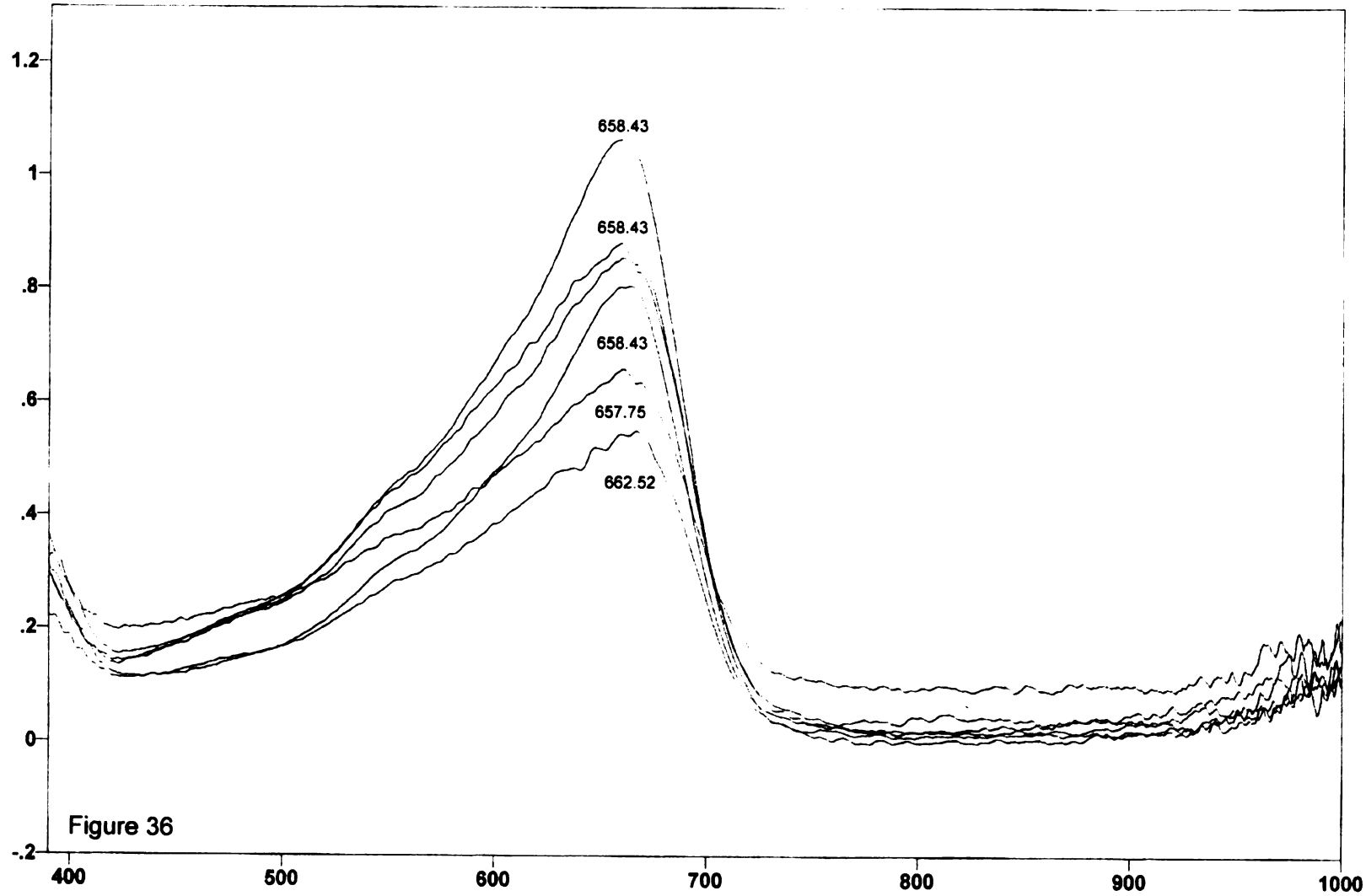


Figure 35

Figure 36- Sample 8 Worn Study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.4
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-.2
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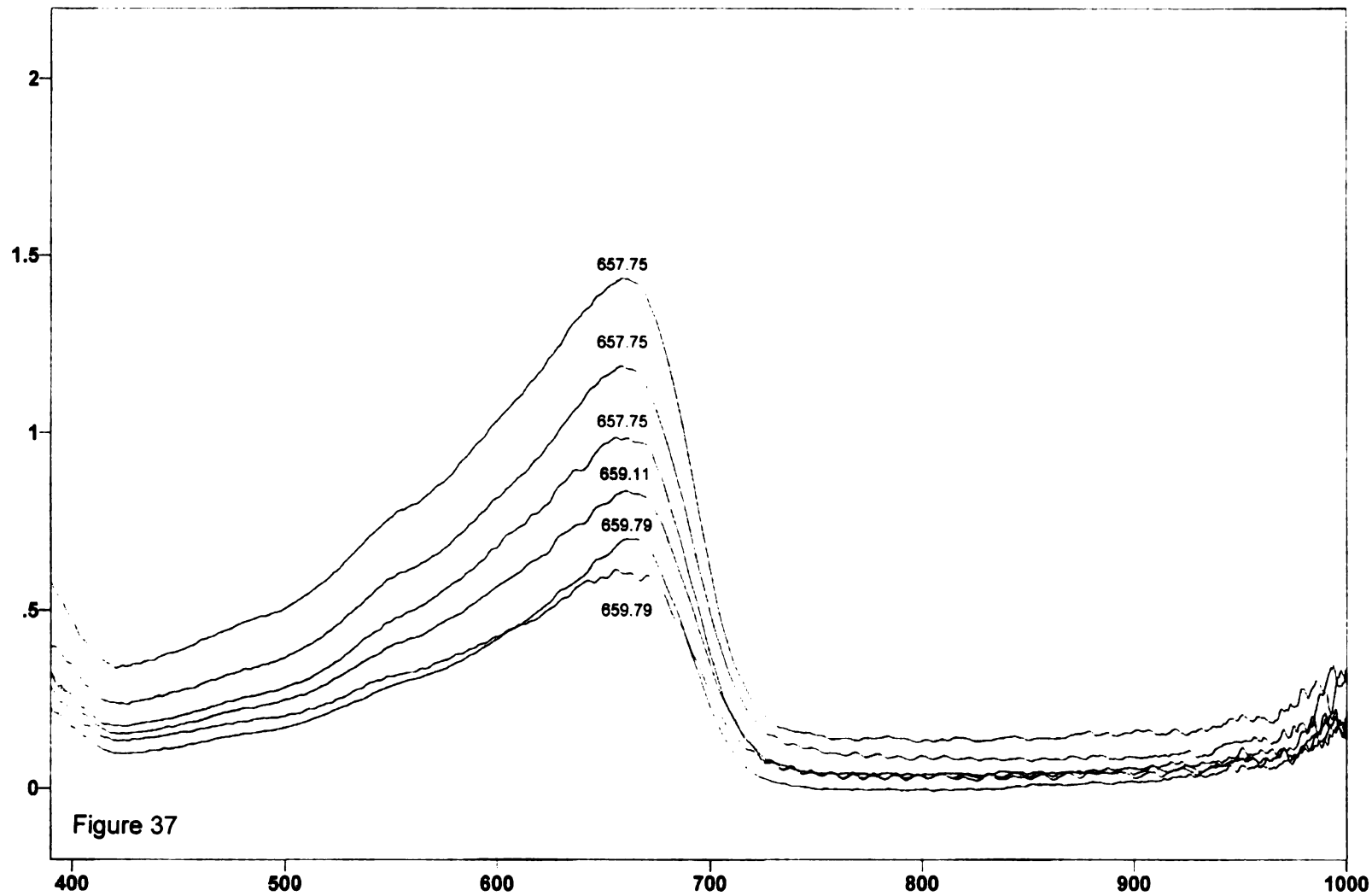
658.43
657.75
662.52
400
500
600
700
800
900
1000

Figure 36

Figure 37- Sample 9 Worn Study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1
.5
0
657.75
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400
500
600
700
800
900
1000

Figure 37

Figure 38- Sample 10 Worn Study

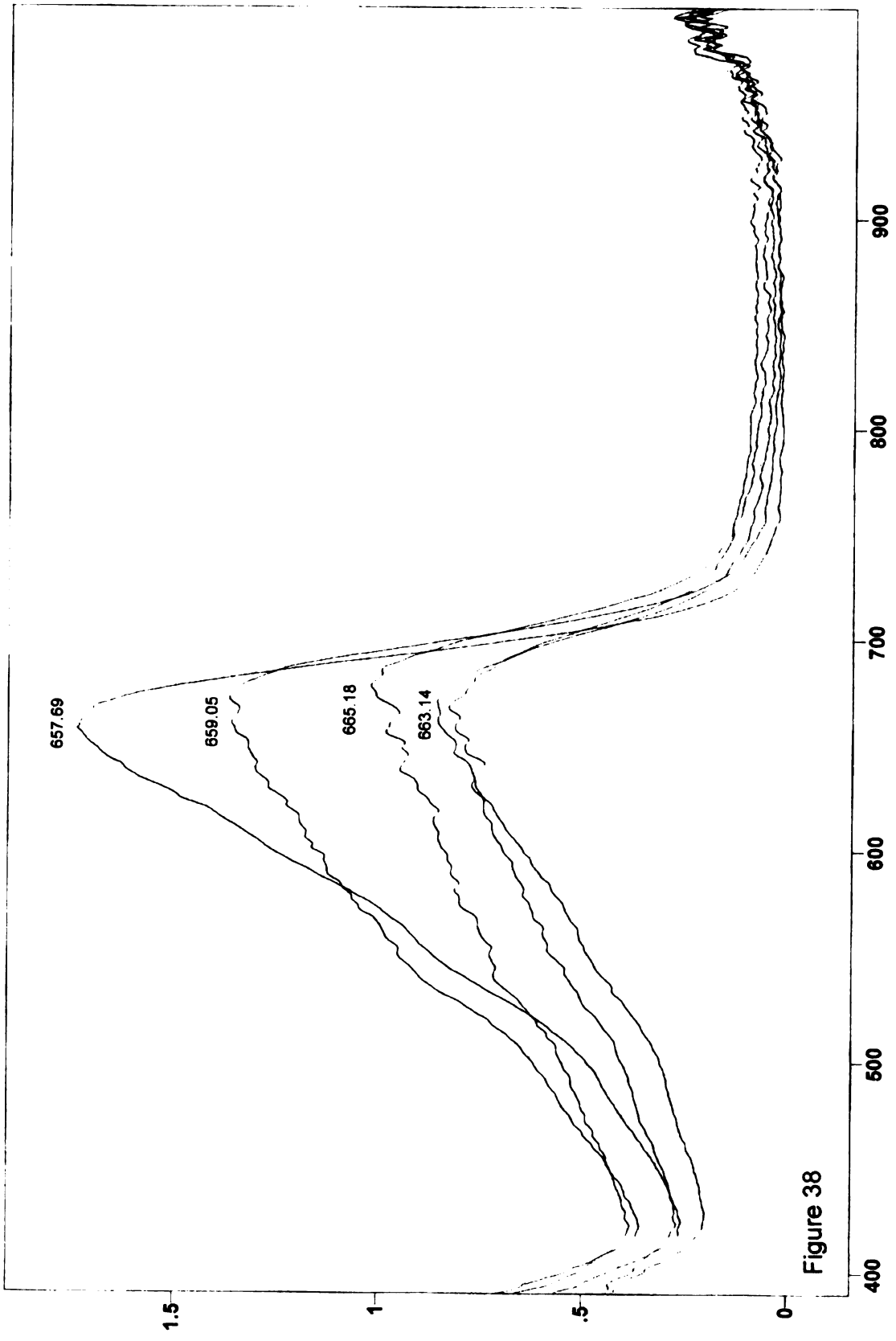


Figure 38

Figure 39- Sample 11 Worn Study

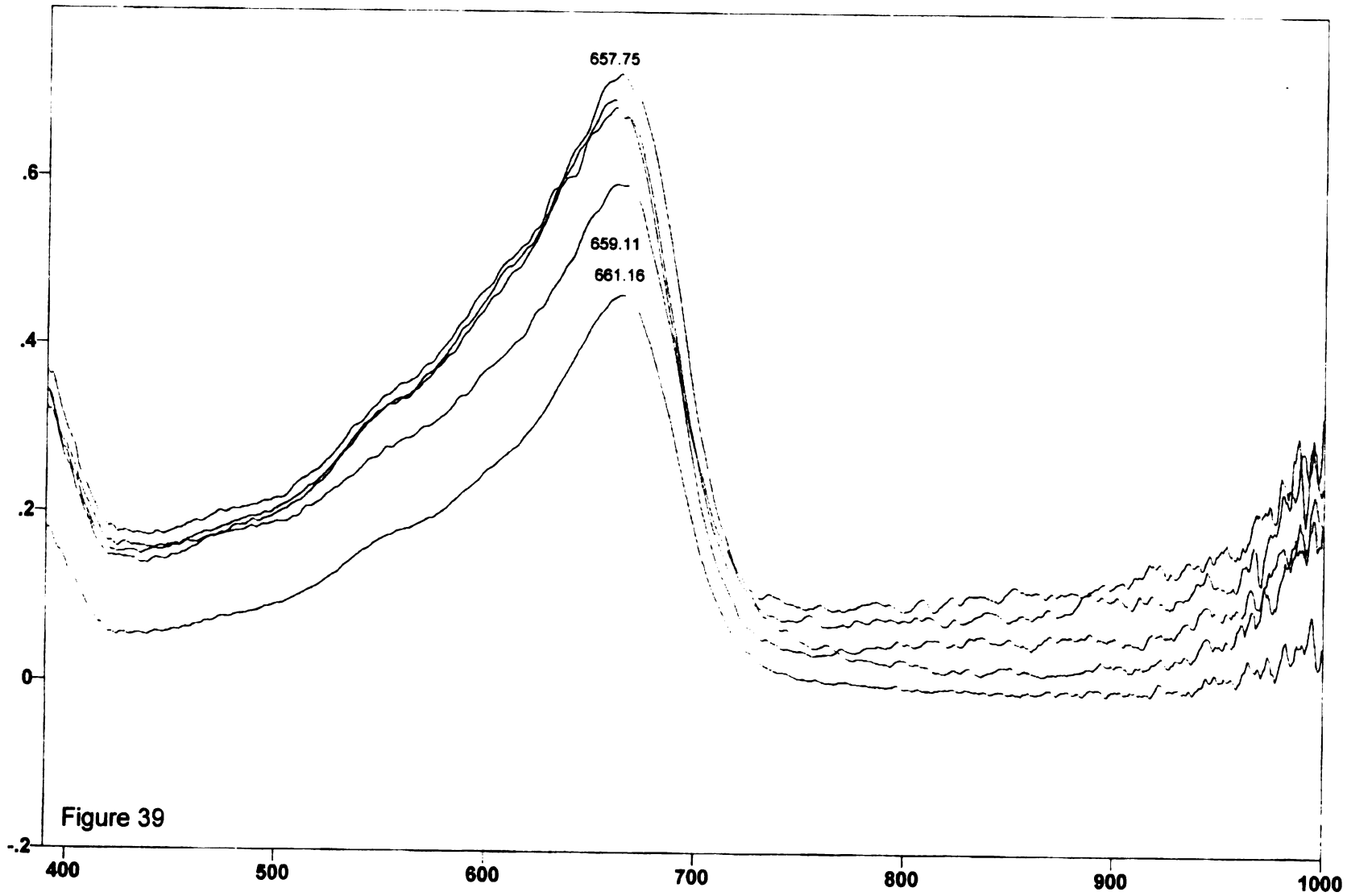


Figure 39

Figure 40- Sample 12 Worn Study

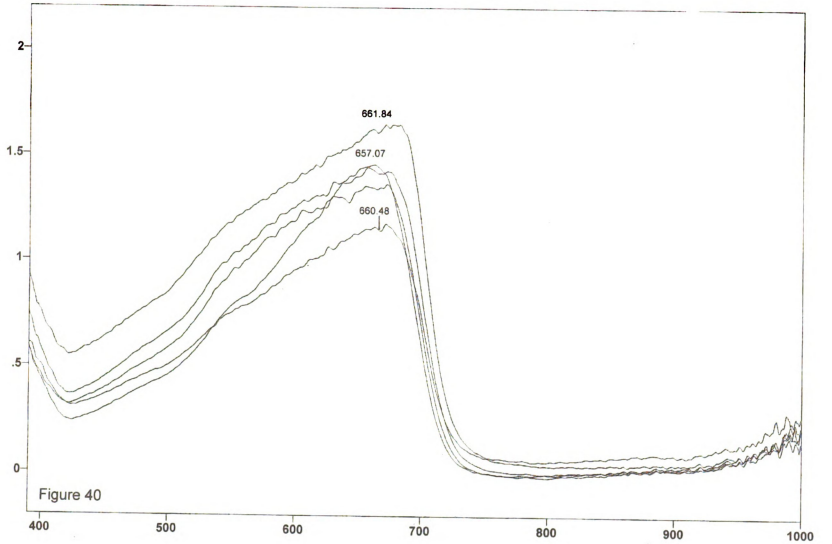
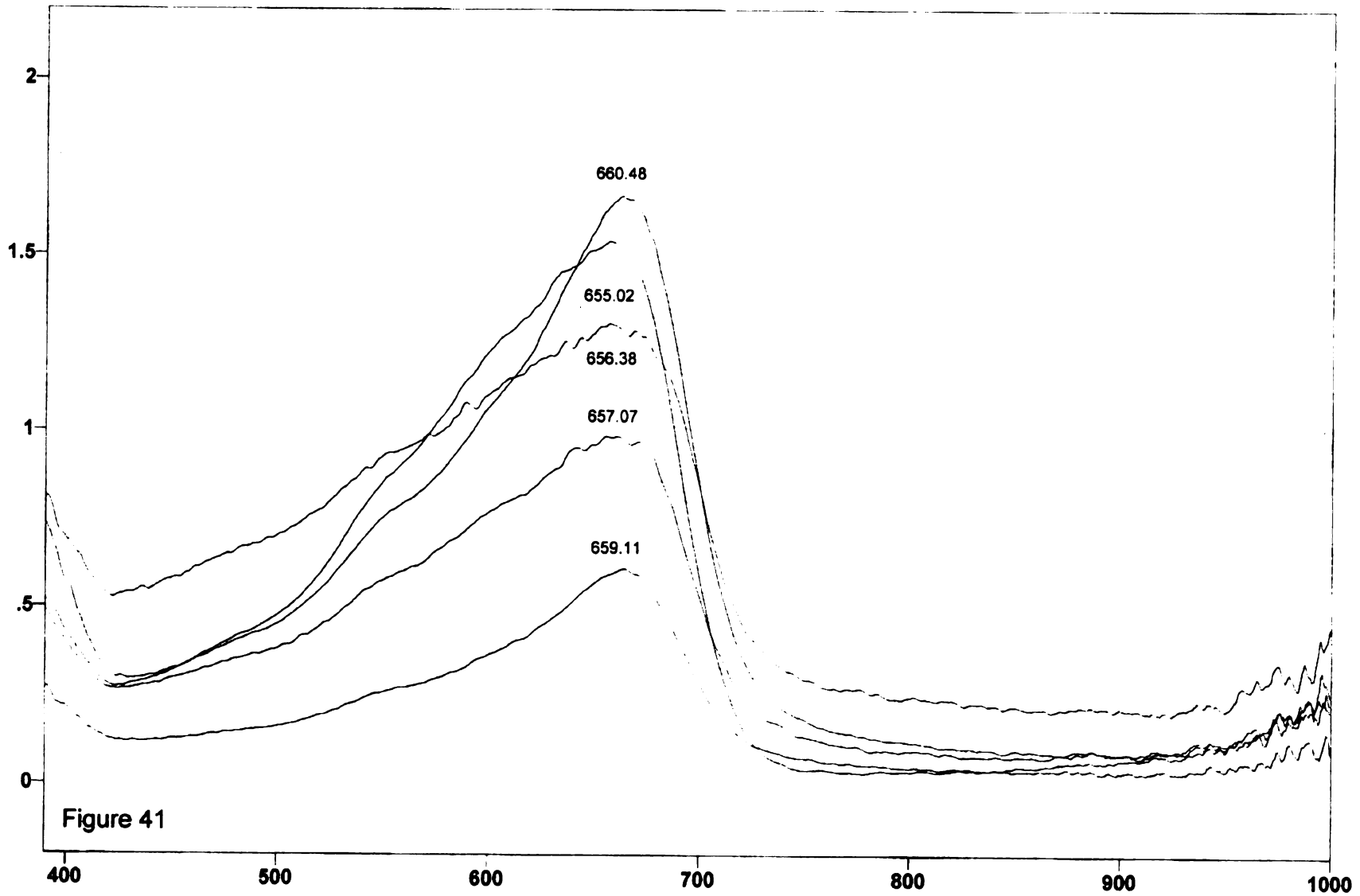


Figure 40

Figure 41- Sample 13 Worn Study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400
500
600
700
800
900
1000

Figure 41

Figure 42- Sample 14 Worn Study

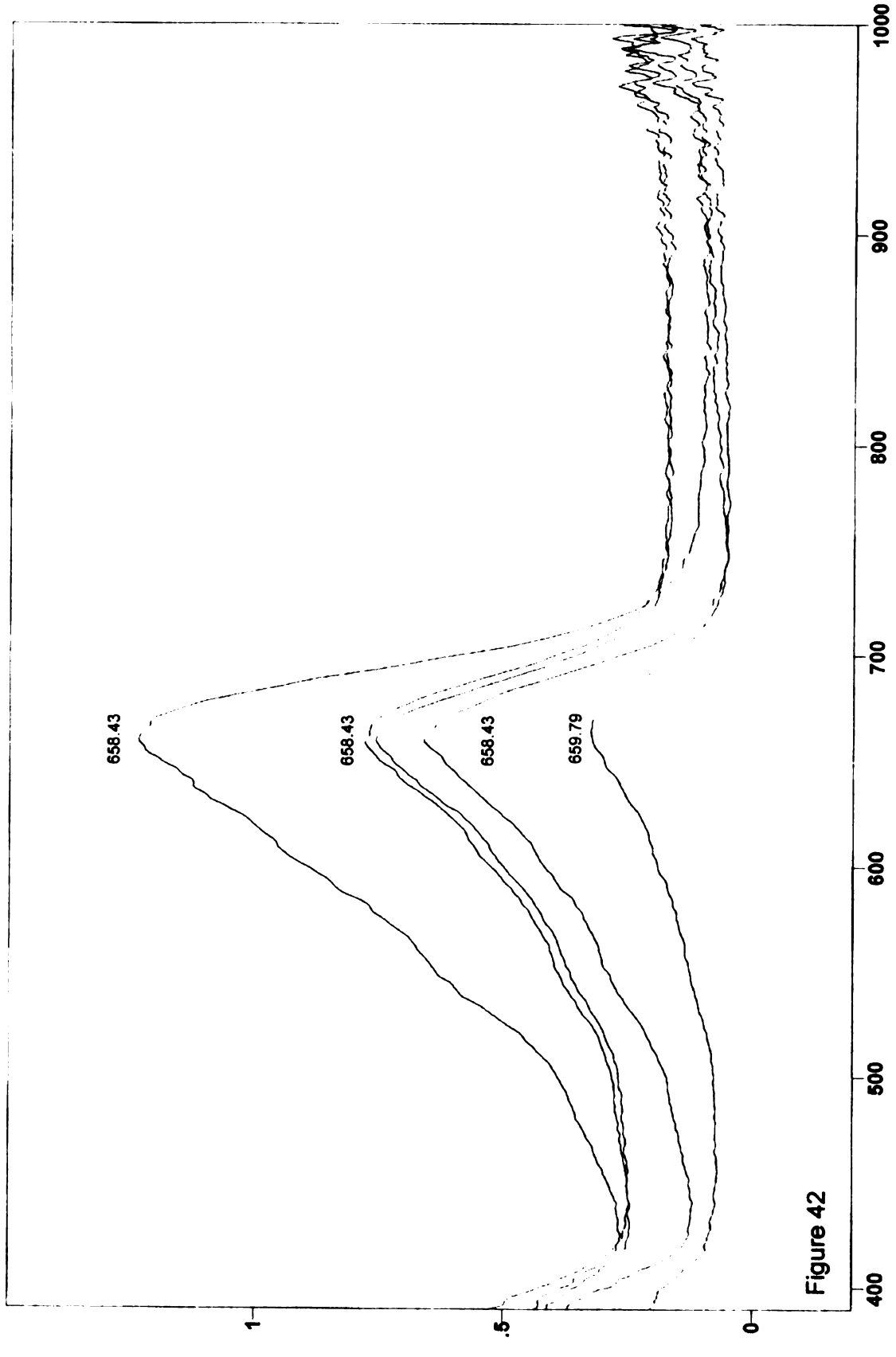

Figure 42

Figure 43- Sample 15 Worn Study

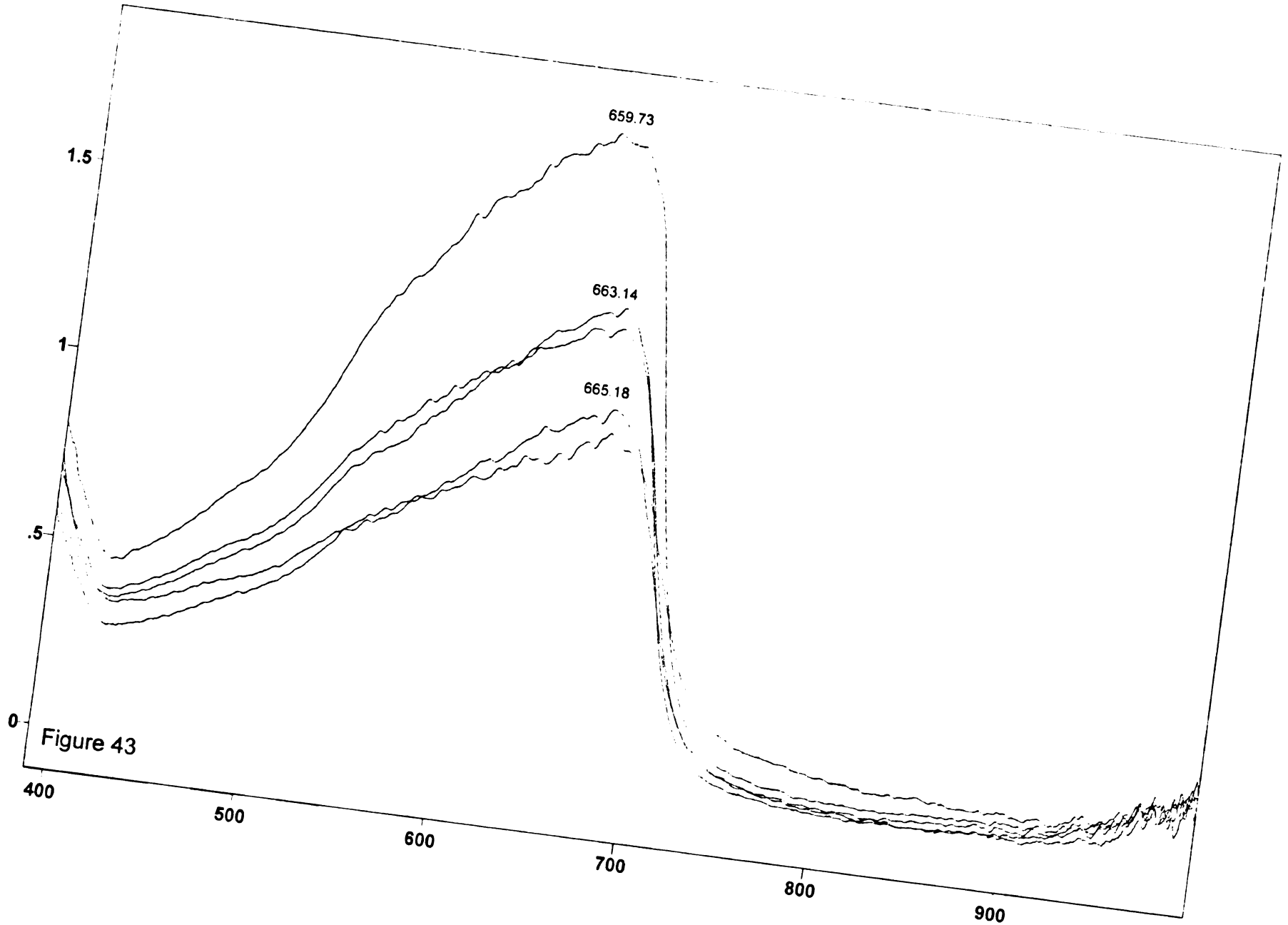

Figure 43

Figure 44- Sample 16 Worn Study

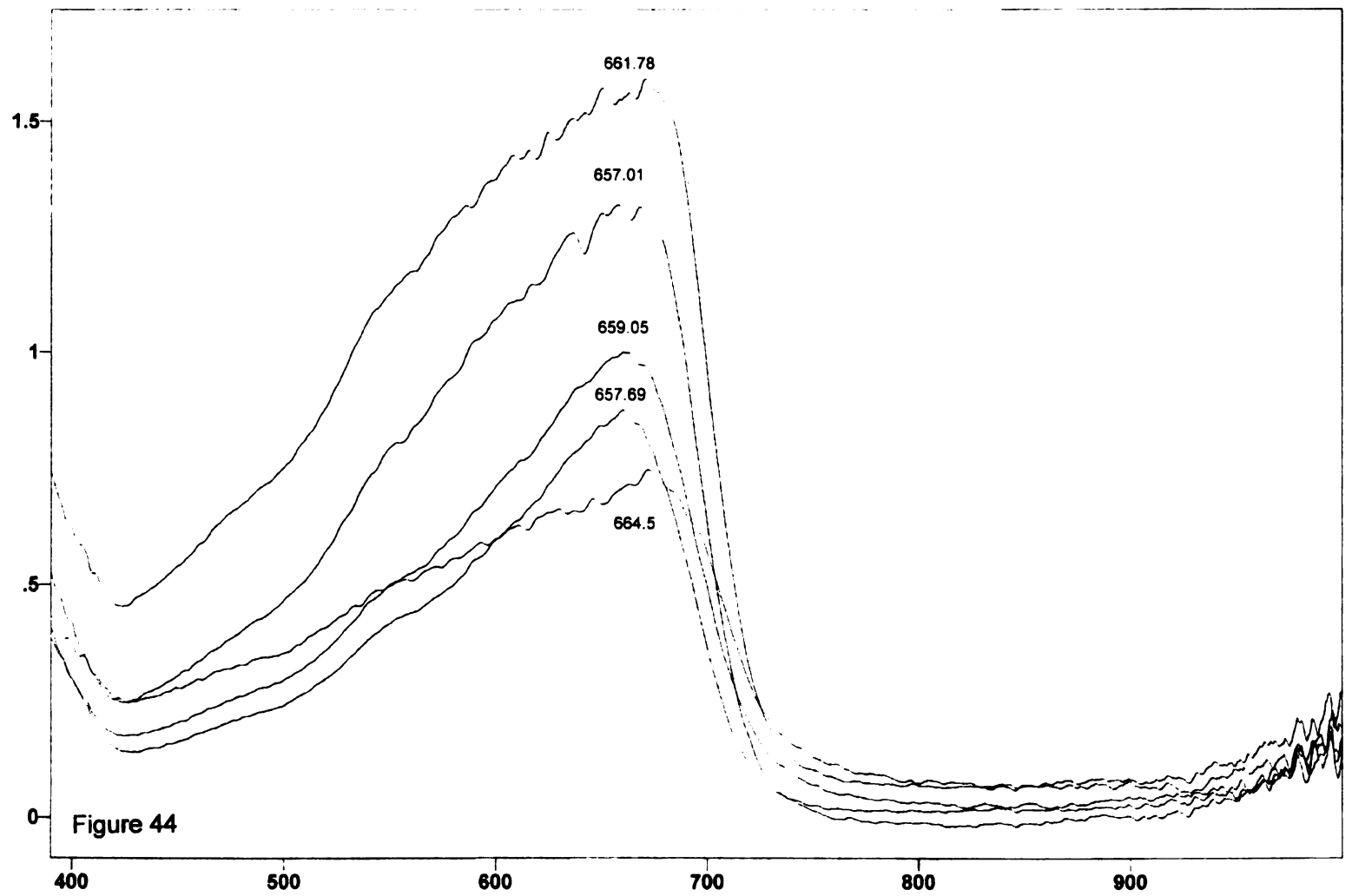

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Figure 45- Sample 17 Worn Study

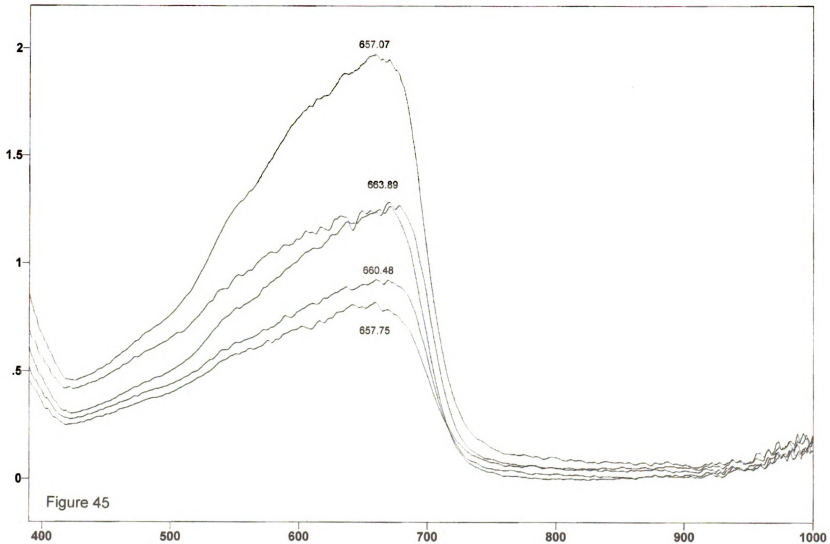

Figure 45

Figure 46- Sample 18 Worn Study

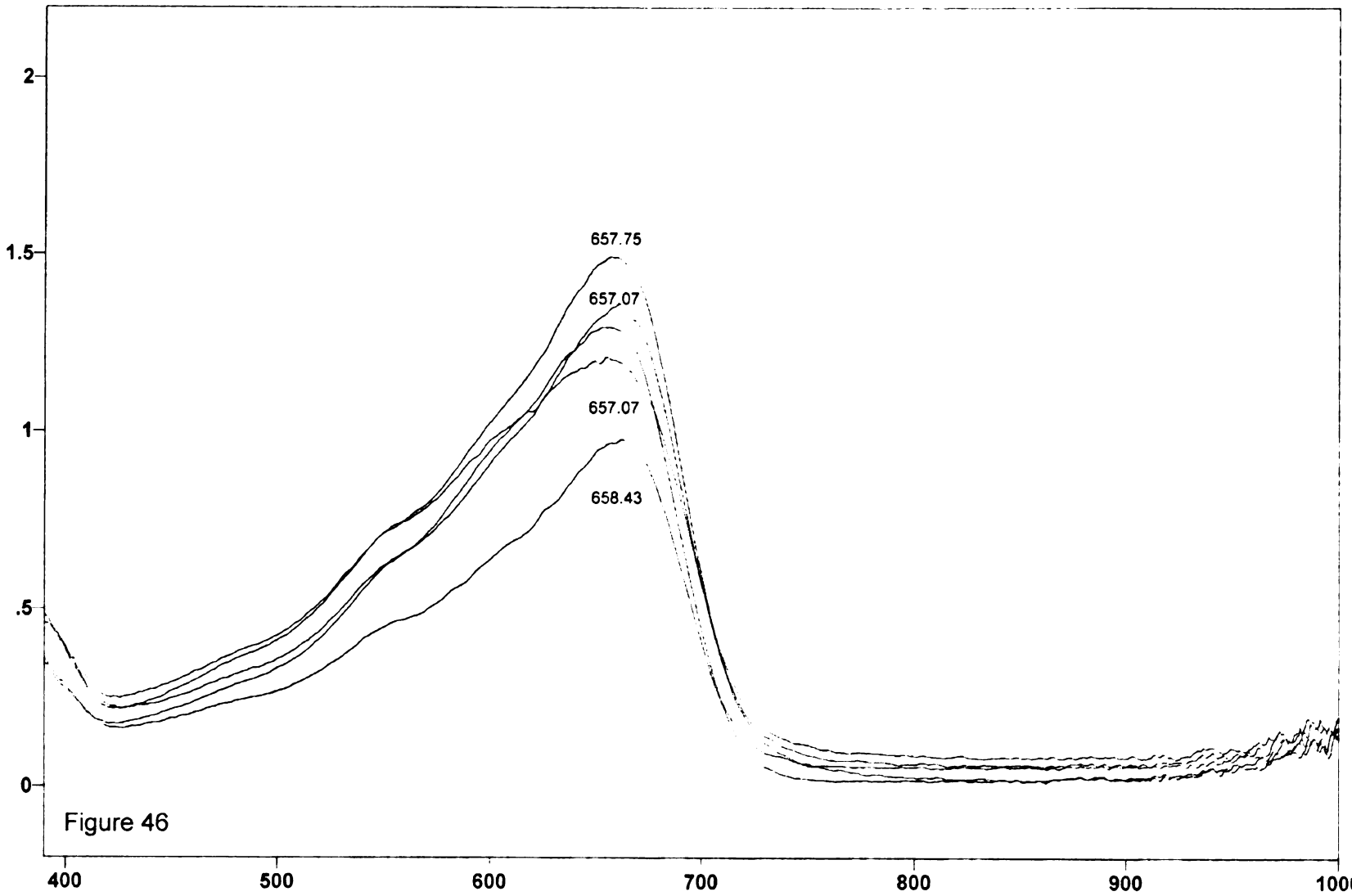

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Figure 47- Sample 19 Worn Study

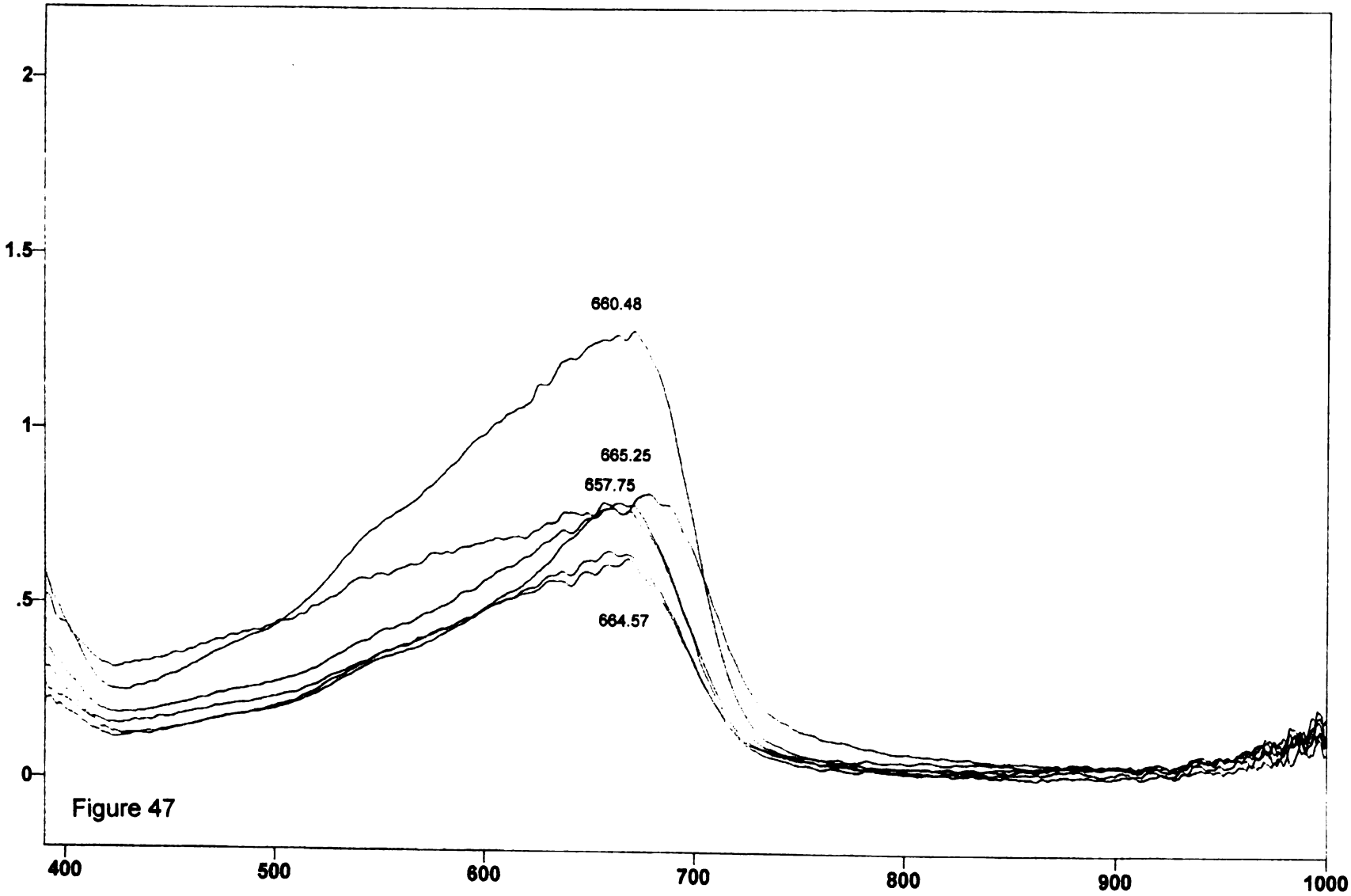

Figure 47

Figure 48- Sample 20 Worn Study

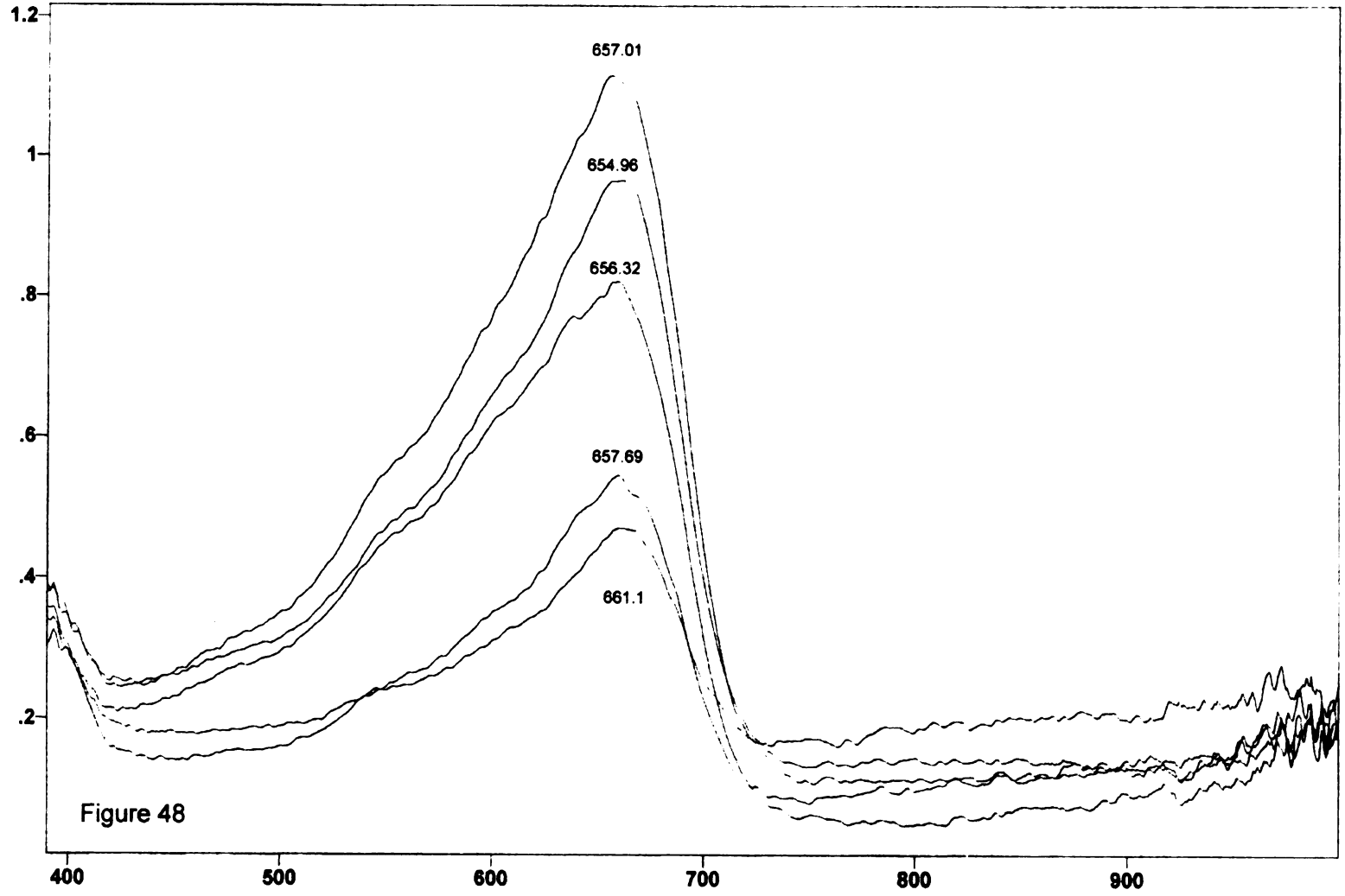

Figure 48

Figure 49- Sample 1 Wash Study

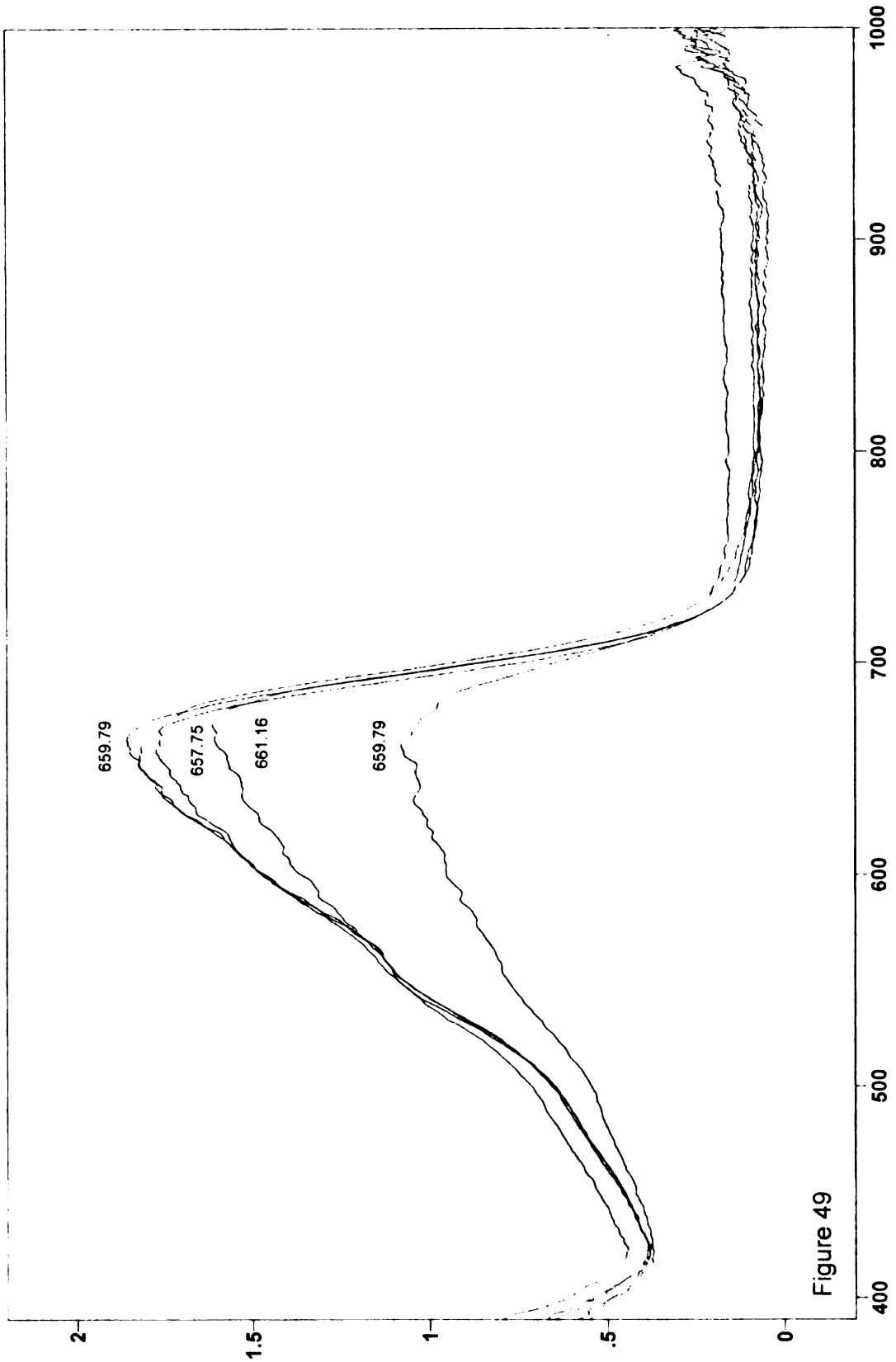

Figure 49

Figure 50- Sample 2 Wash Study

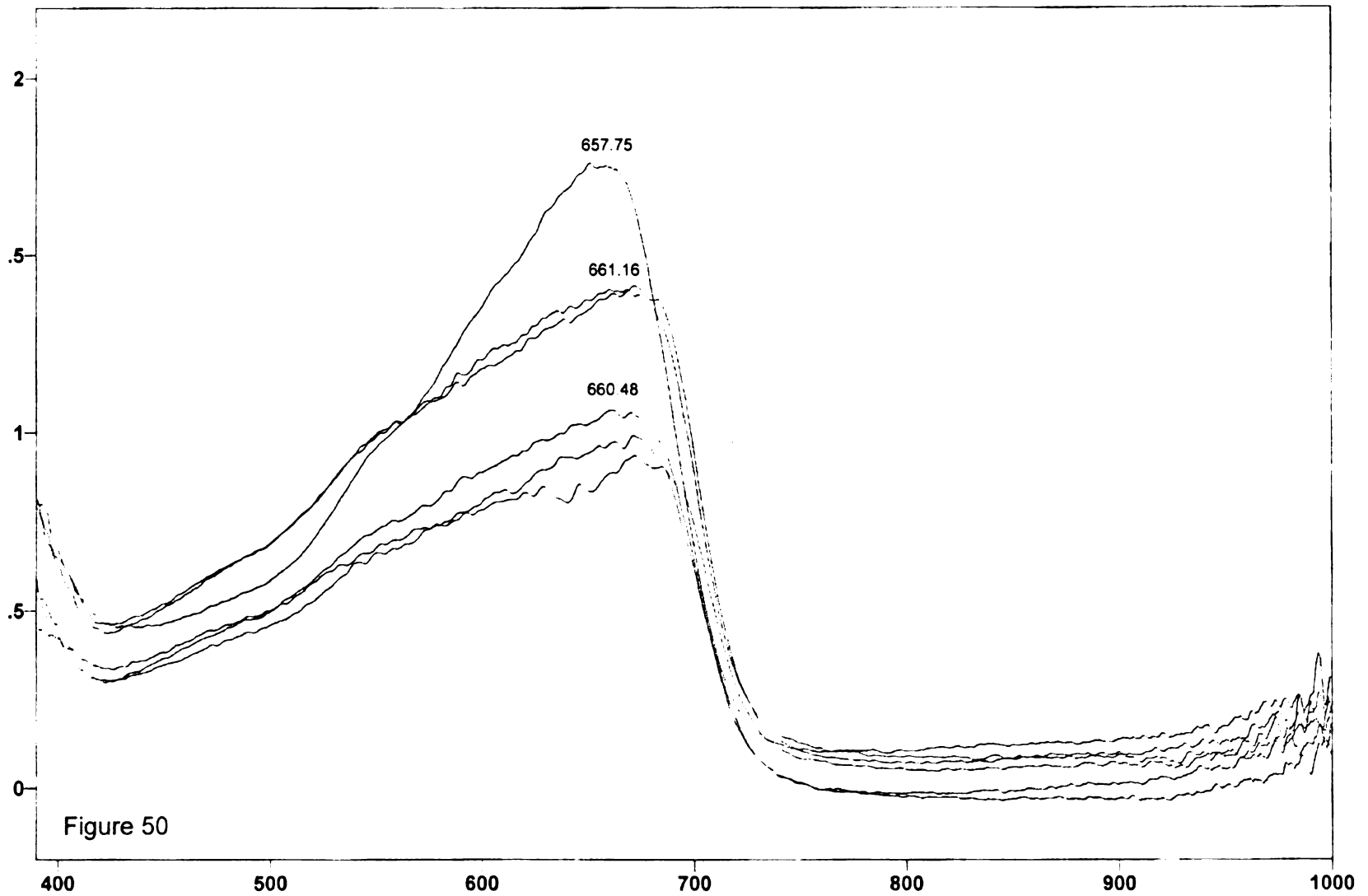

Figure 50

REFERENCES

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