Contact Angle Measurements Using Cellphone Cameras to Implement the Bikerman Method

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Using the Bikerman equation, the contact angle of a sessile drop can be measured from above. For a known drop volume, the contact angle can be derived from a measurement of the drop diameter. It is shown how this method can be implemented with many currently-available cellphone models. Increased accuracy can be achieved using low-cost close-up lenses and the image can be transmitted to a laptop for subsequent processing. This rapid and straightforward method makes the measurement of contact angles on the shopfloor or in the field, a more attractive proposition.

Beim Verfahren nach Bikerman wird der Kontaktwinkel eines Tropfens durch die Betrachtung von oben. Bei gleichbleibendem Volumen ändert sich mit dem Kontaktwinkel der Durchmesser des Tropfens. Die Methode lässt sich auch mit den heute üblichen Kameras eines Mobiltelefons anwenden. Eine höhere Genauigkeit und Archivierbarkeit des Verfahrens kann durch den Einsatz von kostengünstigen Digitalmikroskopen in Verbindungen mit einem Laptop erzielt werden. Die schnelle und unkomplizierte Methode erhöht den Anreiz zum Einsatz der Kontaktwinkelmessung in der chemischen Technik.

1 Methods

Contact angle measurements, by providing information on the properties of a surface, such as wettability and surface energy, are of growing importance in countless branches of science and technology. Unquestionably, the most accurate means of measuring the contact angle of a sessile drop is by computerized drop shape analysis, known as *DSA* or *ADSA*, which has been described in great detail by *Neumann* [1] and to which the authors have also made a contribution [2]. It should be noted that while most of *Neumann's* work relates to drops viewed in profile, he does also report the use of drop-shape analysis when viewed from above, i.e. the approach discussed here. However, the software used by him is not in the public domain, and it is not clear how to access it.

Over two centuries since the work of *Young* [3], scores of methods have been proposed for contact angle measurement, many of which today are no more than scientific curiosities. However, a small number deserve a reappraisal, because the need remains for easy-to-use, low-cost techniques, not least those which can be used by operatives on the shop floor. Developments in open-source computer software and low-cost digital imaging devices are drivers for such a reappraisal.

In 1941, *Bikerman* [4] proposed a novel method of measuring the contact angle of a sessile drop. This was based on viewing the droplet from above and measuring the diameter of the droplet, on known volume. For small volume spherical drops, he derived the *equation <1>*:

$$d^3/v = (24\sin^3\theta) / (\pi(2 - 3\cos\theta + \cos^3\theta) \qquad <1>$$

Where d is the diameter of the base of the drop, sometimes referred to as the contact diameter, v is the volume of the drop, and θ is the contact angle.

No practical application of this method has been found other than the work of *Miller* [5] who used the method to determine whether aircraft fuselages had been sufficiently cleaned (or excessively so) prior to painting. *Miller*, evidently enthused by his successful use of the method, arranged for *Lockheed Corp.* to market a kit for a wider use of the idea, under the name *Surfascope*. *Miller* also filed a patent [6] which covers much the same ground as his publication. This included a microsyringe, a magnifying glass and a set of nomograms with finite solutions to the equation above. Unfortunately, it appears that *Miller* had not fully understood *Bikerman's* concept and his publication embodies this misunderstanding, which was perpetuated by more recent authors such as *Durkee* et al. [7].

In the *Bikerman* equation, the term d is the diameter of the droplet base – the circular contact area made by the drop on the surface on which it rests. For con-

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tact angles that are less than 90°, where the drop is a hemisphere or less, d is readily measured by viewing the drop from above. However for contact angles greater than 90°, where the drop is greater than hemispherical, the maximum girth of the drop will be greater than its contact diameter, that is to say it will overhang the contact area and obscure it from view. *Bikerman* was well aware of this issue, but neither *Miller* [5, 6] nor *Durkee* et al. [7] mention it. Thus, the *Bikerman* method can only be used for contact angles < 90° unless an alternative means of measuring the contact diameter can be found.

Bikerman proposed several solutions to this problem, none of them very satisfactory. His first idea was to allow the drops to evaporate, after which they would leave a *ring-like* mark. This appears problematic, since as the drop evaporates, its volume will contract and so will the wetted contact area. Whatever causes a visible mark to be made might depend on changes in the composition of the liquid. *Bikerman* suggested such residue ring-marks might be caused by corrosion or by a solute being deposited. If there is a change in solute concentration as the drop evaporates, such processes would be extremely complex. It is not believed that these proposals by *Bikerman*, ingenious though they are, are of any practical value. A second idea was to dust the sessile drop with finely-divided powder to characterize its contact area, but this too, does not appear to offer a workable solution.

A simple mathematical test identifies situations where the contact angle is less than 90° and where, in consequence the *Bikerman* equation can be used with direct overhead viewing. If the measured diameter is greater than the 90°-diameter (d90) (*Eq. <2>*), then it is valid to use the *Bikerman* equation.

$$d_{90} = (12v/\pi)^{1/3} \qquad \langle 2\rangle$$

where d_{90} is the diameter of a hemisphere of volume v.

Incorporating this validity test (*Eq. <2>*), the authors have used computer spreadsheets and cell phone cameras to implement the *Bikerman* method with minimal cost and analysis time. The availability of computer spreadsheets is perhaps the most important factor in making the *Bikerman* method more user-friendly. The authors offer a spreadsheet (*Tab. 1*) that accepts user input of individual volume and diameter values, calculating the contact angle using a lookup-table of the *Bikerman* equation with 0.05° increments over the range of θ of 0.10° to 90.00°. The spreadsheet applies the test noted above (*Eq. <2>*), warning the user (*Tab. 1*) if the drop is greater than hemispherical.

The spreadsheet can also be used to generate the nomogram sheets laboriously calculated by *Miller* (*Fig. 1*). The validity test of *Equation <2>* is also used on this worksheet (*Fig. 1*). Lastly, if the user provides uncertainty values, the spreadsheet will compute the uncertainty in contact angle using *Equation*

Tab. 1: Spreadsheet for calculating the contact angle of a drop of known volume when imaged with a calibration object

The Bold-Italic type face indicates a formula cell that I not be edited by the user				*Volume Properties*			*Image Calibration*					*Diameter Measurements*			*Results*			
Image Analyst	*Image Filename*	*Comments*	*Drop Description*	*Drop Volume (v) (cm^3)*	*Drop Volume Uncer-tainity (s_v) (cm^3)*	*Hemi-Diameter ($d_{90°}$) (cm)*	*C_{px} (px)*	*S_{cpx} (px)*	*C_{cm} (cm)*	*S_{ccm} (cm)*	*Cali-bration Result (cm/px)*	*Drop Diameter (d_{px}) (px)*	*Drop Diameter Uncer-tainty (S_{dpx}) (px)*	*Drop Diameter (d_{cm}) (cm)*	*Valid Result? Is d > $d_{90°}$*	*Contact Angle (θ) (deg)*	*+ Conatct Angle Uncertainty (+sθ) (deg)*	*- Contact Angle Uncertainty (-sθ) (deg)*
DLW	Digital Micro-scope.jpg	al foil pressed on 3/16 hole	fake 10 uL drop	0.0100	0.0002	0.337	755	4	0.691	0.005	$9.15\cdot10^{-4}$	525	8	0.480	yes	46.8	1.3	1.4
MMK	Digital Micro-scope.jpg	al foil pressed on 3/16 hole	fake 50 uL drop	0.0500	0.0002	0.576	555	4	0.691	0.005	$1.24\cdot10^{-3}$	403	4	0.502	no	>90°	>90°	>90°

Bikerman Nomogram Worksheet

Procedure

1. Type a relevant volume in the volume cell.
2. Print the nomogram for use in your process.

Volume = 0.010 ***cm***^{3}

d $_{90}$ ***=*** ***0.337 cm***

Drop Diameter cm	*Contact Angle deg*
0.1	#N/A
0.105	#N/A
0.11	#N/A
0.115	#N/A
0.12	#N/A
0.125	#N/A
0.13	#N/A
0.135	#N/A
0.14	#N/A
0.145	#N/A
0.15	#N/A
0.155	#N/A
0.16	#N/A
0.165	#N/A
0.17	#N/A
0.175	#N/A
0.18	#N/A
0.185	#N/A
0.19	#N/A
0.195	#N/A
0.2	#N/A
0.205	#N/A
0.21	#N/A
0.215	#N/A
0.22	#N/A
0.225	#N/A
0.23	#N/A
0.235	#N/A
0.24	#N/A
0.245	#N/A
0.25	#N/A
0.255	#N/A
0.26	#N/A

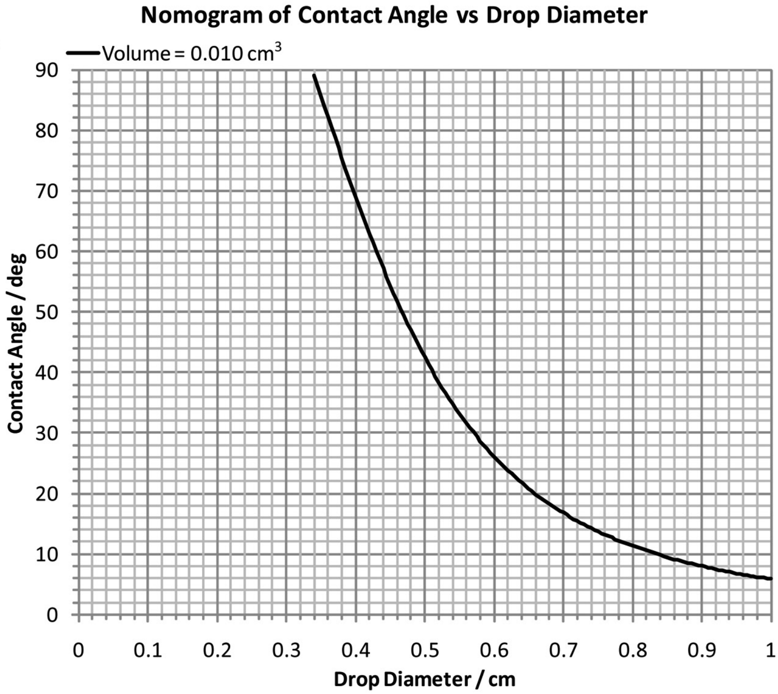

Fig. 1: Image of the authors‘ nomogram creation worksheet. The “#N/A” values in the contact angle column indicate that the contact angle is > 90° for the given drop diameters

<3>, which was derived using standard propagation of uncertainty techniques [8].

$$s_{d^3/v} = \frac{d^3}{v}\left(3\left(\frac{s_{C_{px}}}{C_{px}}\right)^2 + 3\left(\frac{s_{C_{cm}}}{C_{cm}}\right)^2 + 3\left(\frac{s_{d_{px}}}{d_{px}}\right)^2 + \left(\frac{s_v}{v}\right)^2\right)^{1/2} \quad <3>$$

Where $s_{d3/v}$ is the uncertainty in the d^3/v term, s_d is the uncertainty in the diameter measurement (d), and s_v is the uncertainty in the drop volume (v). The calibration object (C) is measured in pixels and in cm. The px subscripts in *Equation <3>* indicate an image analysis measurement in pixels. The image analysis will be further explained by a description of the various measurement methods.

There are slight differences in the positive and negative uncertainties of contact angle because of the non-linear nature of the *Bikerman* equation. To account for this, the uncertainty in contact angle is calculated by looking up the positive and negative deviations separately using the *Bikerman* lookup-table (*Tab. 1*).

2 *Experimental*

To implement this method one merely needs an accurate drop delivery system such as a *Hamilton microsyringe* (v and s_v in *Eq. <3>*) and a digital camera with a macro focus capability. In the present study, a piece of aluminum foil (*Reynolds*, *Heavy Duty*, 25 µm thick) was pressed with a finger into a 0.475 cm (3/16 in.) hole of a gage card to produce a non-evaporating standard drop shape. After three attempts, a wrinkle-free simulated drop was produced (*Fig. 2*).

Using the spreadsheet and *Equation <1>,* a 10-µL drop with this diameter would express a 48.1° contact angle. This standard drop shape was viewed from above and analyzed using various measurement methods, a digital microscope, four cell phone cameras and two types of cell phone macro lenses.

2.1 Calibrated Reticle

Contact angle measurement using a magnifying eyepiece with a calibrated reticle is a tempting option because of its portability. However, most magnifying eyepieces are constructed to view flat objects, and are unable to image a sessile drop without unacceptable distortion. A telescope-style eyepiece was constructed that accepts collimated light from the sample that passes through the calibrated reticle before magnification. Even then, parallax effects made it impossible to obtain an acceptable reading. Additionally, the cost of these eyepiece components approaches that of a small digital microscope, which is much more useful even though it is tethered to a computer.

2.2 Pass-Fail Images

In the case of *Miller's* use of the *Bikerman* method [5, 7], a wettable surface with a water contact angle less than 72.8° was required for 90 % paint adhesion to occur. The authors' spreadsheet may be used to determine that a 3.884-mm diameter 10-µL drop would exhibit a contact angle of 72.8°. A washer with a 4-mm inner diameter may be used directly as a secondary standard. Drops of 10-µL with diameters larger than 4 mm indicate a surface that passes the wettability test, and vice versa. A visual comparison to the 4-mm washer is all that is needed, but a cell phone camera could be used for documentation purposes.

2.3 Bracket Images

Further efficiency can be achieved by employing a drill gage card, which can be purchased from most tool suppliers. Instead of using a calibration washer, this method quickly determines the approximate contact angle by placing a known volume (1, 2, 5, 10, or 15 µL) of liquid onto a surface and then selecting the best matching gage hole on the card (*Fig. 2*). The size selected on the card and the drop volume is then referenced in *Table 2* (Imperial) or *Table 3* (metric) to determine an approximate contact angle. While this method is only an estimate, it is useful for bracketing

Tab. 2: Contact angles of an Imperial drill gage card for various drop volumes

Hole Diameter (in.)		*Drop Volume (µL)*				
		1	*2*	*5*	*10*	*15*
1/16	0.062	89.2	> 90°	> 90°	> 90°	> 90°
5/64	0.078	60.9	89.4	> 90°	> 90°	> 90°
3/32	0.093	40.6	67.8	> 90°	> 90°	> 90°
7/64	0.109	26.6	48.5	86.0	> 90°	> 90°
1/8	0.125	18.0	34.3	69.1	> 90°	> 90°
9/64	0.140	12.9	25.2	55.0	83.7	> 90°
5/32	0.156	9.4	18.5	42.6	70.3	86.9
11/64	0.171	7.2	14.2	33.6	58.7	75.7
3/16	0.187	5.5	10.9	26.3	48.1	64.4
13/64	0.203	4.3	8.5	20.9	39.3	54.3
7/32	0.218	3.5	6.9	17.0	32.6	46.1
15/64	0.234	2.8	5.6	13.8	26.8	38.6
1/4	0.250	2.3	4.6	11.4	22.3	32.4
17/64	0.265	2.0	3.9	9.6	18.8	27.6
9/32	0.281	1.7	3.3	8.0	15.9	23.5
19/64	0.296	1.4	2.8	6.9	13.7	20.2
5/16	0.312	1.2	2.4	5.9	11.7	17.4

Tab. 3: Contact angles of a metric drill gage card for various drop volumes

Hole Diam. (mm)	*Drop Volume (µL)*				
	1	*2*	*5*	*10*	*15*
2.00	59.7	> 90°	> 90°	> 90°	> 90°
2.50	35.05	60.7	> 90°	> 90°	> 90°
3.00	21.15	39.8	76.15	> 90°	> 90°
3.50	13.5	26.3	56.85	85.55	> 90°
4.00	9.1	17.95	41.6	69.05	85.7
4.50	6.4	12.75	30.55	54.4	71.25
5.00	4.7	9.3	22.75	42.45	58.05
5.50	3.55	7	17.3	33.15	46.8
6.00	2.75	5.4	13.4	26.1	37.65
6.50	2.15	4.25	10.6	20.8	30.4
7.00	1.75	3.45	8.5	16.8	24.75
7.50	1.4	2.8	6.95	13.75	20.35
8.00	1.15	2.3	5.7	11.35	16.9

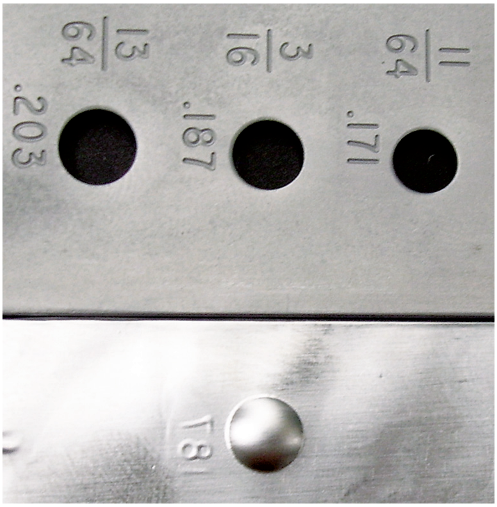

Fig. 2: Comparison of the aluminum foil contact angle standard with the gage card that was used to produce it

the contact angle. *Figure 2* shows that the diameter of the aluminum contact angle standard is a best match to the 0.187-inch (4.75 mm) hole, which for a 10-µL drop would be a contact angle near 48°. Without image analysis it is difficult to specify the exact contact angle, but this image shows that the drop diameter is certainly between the next larger (0.203 inch) and smaller (0.171 inch) holes – a contact angle range of 39° to 59° (*Tab. 2*).

2.4 Digital Microscope

A digital microscope (*DinoLite, AM411T*) was used to capture an image of the foil contact angle standard (*Figs. 2* and *3*), and the spreadsheet was used to calculate the actual contact angle as if it were a 10-µL drop. Adjacent to the drop, and included in the same image, was an object of a similar size, in this case a metal washer (*Fig. 3*) with dimensions of 0.691 ± 0.005 cm (C_{cm} and s_{ccm} in *Eq.* <*3*>) measured by five separate persons using a vernier micrometer. The uncertainty term s_{ccm} is the standard deviation of the five measurements. The resulting image was then analyzed using a freely available image analysis package (*Meazure*) [9]. To obtain data from *Meazure*, a circle was fitted to the inner diameter of the washer to calibrate the scale (C_{px} and s_{cpx} in *Eq.* <*3*>). A circle was also fitted to the outline of the drop from which the diameter (W in *Fig. 3*, d_{px} and s_{dpx} in *Eq.* <*3*>) was read. The advantage of this approach is that it allows the user to test the circularity of the drop and, should it not be truly circular, to derive mean, minimum, and maximum values for d and by extension for θ. The uncertainties in pixels (s_{cpx} and s_{dpx}) were conservatively estimated using the range of repeated measurements in pixels.

The pixel count measured by the *Meazure* program [9] is dependent upon the software magnification, so care was taken to measure the washer and the drop at the

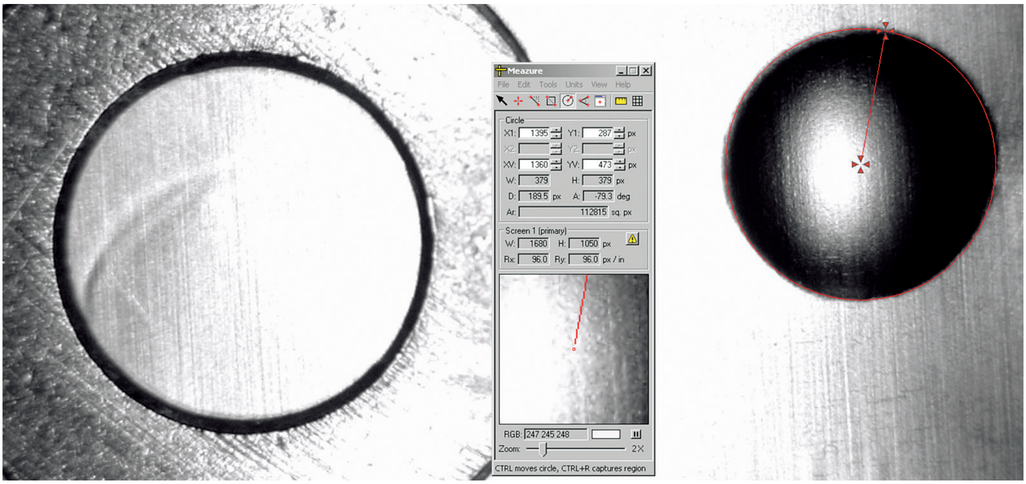

Fig. 3: The use of the image analysis software (Meazure) [9] to calibrate the digital microscope image using a metal washer (left) and to measure the diameter (W = 379 px) of the aluminum foil contact angle standard (right)

same magnification. For this reason, it was preferable to measure the inner diameter of the washer, since bringing the outer diameter of the washer into view would reduce the pixel count across the drop (*Fig. 3*).

2.5 Cell Phone Macro Photography Using Auxiliary Lenses

The digital microscope is preferred if the samples can be analyzed in the laboratory, but for shop-floor or field data collection the use of cell phones holds promise. Cell phones are not made to take close-up photos, but one may purchase snap-on macro lenses for most camera models [10, 11]. Camera alignment is not critical since the calibration object placed next to the drop serves as an internal optical standard. The only requirements are a close-up image with a substantial number of pixels across the drop and the calibration washer, and a crisply-focused image which aides the measurement of the drop and washer diameters.

A variety of cell phone models [12–15] were employed with and without the snap-on lenses [10, 11] to take pictures of the aluminum foil standard and the calibration washer. The photos were then analyzed by multiple persons using the authors' spreadsheet.

The two smart phones (*HTC* [14] and *iPhone* [15]) yielded images which were sufficiently crisp and clean without requiring any auxiliary lenses. These smart phone models are equipped with auto zoom and auto focus features that allow the capture of images with adequate pixel resolution for analyzing 10-µL drops. More basic cell phones (*Samsung* [12] and *Blackberry* [13]) were not equipped with these features, and thus, the close-up photos appeared out of focus.

The magnetically mounted macro lens [10] is shipped with an adhesive-backed mounting washer and a magnetic ring on the back of the lens so that it can be added and removed at will. However, when using this lens, the user must remove any protective covering or case around the phone. The lens is designed to be attached to the phone, and any form of covering will push the lens too far from the photo sensor. The magnetic adhesion to the phone allows the user to use both hands to steady the camera phone thus reducing image blurring.

The *Jelly Lens* [11] is so named because it uses a tacky gel polymer ring to adhere the lens to the phone body. There are some drawbacks to using the *Jelly Lens*. The tacky adhesive did not stick well to the

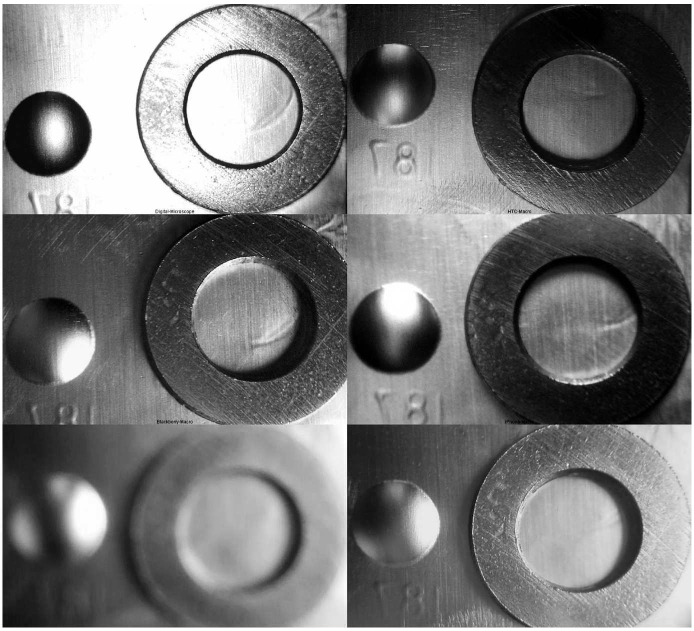

Fig. 4: A montage sample of images showing the crisp detail (or not) of the Digital Microscope, the HTC-Macro Lens, the Blackberry-Macro Lens, the iPhone-Macro Lens, the Samsung-No Lens, and the Samsung-Jelly Lens configurations listed left-to-right and top-to-bottom

phones in this study, and the user was required to hold the lens in place to keep it from falling while a second person positioned the phone to capture the image. Furthermore, the lens itself is contained in a bulky plastic casing that often obscured parts of the image. This lens functions best when the camera face has a flat and texture-free surface. The *Jelly Lens* has a very short focal length requiring the user to hold the camera very close to the drop, thus, making difficult to obtain an image that contained both the drop and the calibration washer.

3 Results

The digital microscope was very easy to use because the on-board LED illumination was always sufficient, the microscope mounting was stable, and the fine adjustment provided crisp photos with good resolution. This image is seen in the top-left panel in *Figure 4*.

Modern smart phones can acquire very crisp photos when used with a makeshift hand rest. Some difficulty was encountered when trying to get the camera auto focus to lock onto the objects. Using the magnetic *Macro Lens*, the pictures were very close in quality to those obtained with the digital microscope (*Fig. 4*). The *Macro Lens* improved the quality of the images taken with the basic model phone also, but the quality did not match those taken with the smart phone models.

Tab. 4: Contact angle results, standard deviations, and error from the nominal value (θ – 48.1°) for various camera and lens configurations

Lens	*Phone*	θ (°)	*s*θ (°)	*Error* (°)	*Error* (%)
Jelly	Samsung	47.8	1.1	-0.3	-0.7
Macro	HTC	46.9	1.8	-1.2	-2.5
None	Blackberry	46.4	2.5	-1.7	-3.5
Macro	iPhone	46.0	2.0	-2.1	-4.3
Macro	Blackberry	44.6	1.6	-3.5	-7.4
None	HTC	44.2	2.2	-3.9	-8.2
None	iPhone	43.9	0.4	-4.2	-8.7
None	Microscope	43.5	2.3	-4.6	-9.6
Macro	Samsung	41.1	4.2	-7.0	-15
Jelly	iPhone	33.1	10.8	-15	-31
None	Samsung	32.7	3.3	-15	-32
Jelly	Blackberry	29.2	4.1	-19	-39
Jelly	HTC	24.5	1.2	-24	-49

The *Jelly Lens* did not perform well with the smart phones. Its magnification appeared to be too strong for the auto zoom and auto focus features which then worked against their proper function. Most of the images were poorly defined, lacking the crispness of those obtained using the more advanced cell phones with or without auxiliary lenses. However, the *Jelly Lens* proved to be an ideal tool for use with the basic model phone (*Samsung*) to obtain almost the same quality of image as with the smart phones (*Fig. 4*).

The accuracy, or bias, of this method was tested by calculating the mean of the contact angle results obtained by four analysts measuring the same images. Also calculated, was the absolute error in contact angle (θ – 43.1°) where 48.1° is the contact angle of a nominal 10-µL drop with the diameter of the aluminum contact angle standard. As seen in *Table 4*, the most accurate phone-lens configurations were the *Samsung-Jelly Lens, HTC-Macro Lens, Blackberry-No Lens* – all with absolute errors that fall within the experimental uncertainty values. The *iPhone, Blackberry*, and *HTC* cameras performed slightly better than the microscope without any additional lenses.

The precision of this method (sθ) was tested by calculating the standard deviation of the contact angle results obtained by the four analysts (*Tab. 4*). This captures the variability of the user-dependent image analyses. The uncertainties are quite good considering that each analyst determined on their own the best fit of the circles to the objects in each of the images.

3.1 Wider Status of the Bikerman Method

Bikerman's approach appears to be almost unknown and unused. *Neumann*, arguably the leading authority in the field, while clearly aware of the method, notes it but without comment. Interestingly, however, one recent patent [16], though without naming or acknowledging *Bikerman*, has, one might say, *re-invented* the method, setting out an equation essentially identical to *Eqation <1>*. While using the *Bikerman* approach, the patent addresses a rather special case, where the sessile drop rests on a transparent surface (in the context of fingerprint recording sensor). This 2D sensor array allows a direct imaging of the underside of the drop, thereby removing the restriction noted above, as regards droplets of greater than hemispherical size.

4 Conclusion

In conclusion, apart from the restriction noted above, the *Bikerman* method is admirably simple and low-cost. Direct application of *Bikerman* for all contact angles would require a view from below via transparent samples or the very special case noted above. In all other cases overhead viewing of less-than-hemispherical drops is facile. Overhead viewing allows measurements to be made on large surface areas, where it is more difficult to view sessile droplets in profile. The digital microscope is the tool of choice for many, however, the microscope is tethered to a computer or laptop – a relatively bulky device when compared to a cell phone. The cell phone has the additional advantage that, if required, the measurement result can be instantly transmitted to remote locations. The cell phone camera enables the lab to go to the sample when used in conjunction with high-quality microsyringes. This is therefore a method that can be used both for simple pass-fail analyses to provision of accurate and precise contact angle values.

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[14] HTC Incredible II, 8.0 megapixel camera with autofocus

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