A preliminary study on a novel method for Depth of Penetration measurement in Ultrasound Quality Assessment

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Abstract – **The maximum Ultrasound (US) Depth of Penetration (DoP) is one of the most important parameters related to medical US systems sensitivity. DoP is also suitable for characterizing those systems since it is usually measured in routine quality controls (QC) of ultrasound scanners. In common practice, DoP assessment is carried on visually and may be affected by various external factors, such as the operator related errors. To minimize these errors, image analysis algorithms have been proposed even if without a complete performance assessment. In the present work, a novel method for the automatic determination of DoP and its measurement uncertainty is proposed: it is based on the Signal to Noise Ratio (SNR) estimation, evaluated from a US phantom and in-air clips, and has been applied on a diagnostic system equipped with three different US probes (vector, convex and linear array) with similar general settings. The results have been compared with the outcomes of both a different automatic approach (already proposed in literature) and a standard procedure based on the scores provided by 5 independent observers. Despite a good agreement has been found among them, the novel method proposed requires both lower acquisition and computational time as well as a lower computational cost, confirming the convenience of an in-depth study on the topic in the next future.**

I. INTRODUCTION

Image quality assessment in medical imaging is a big impact topic [1-3]. In medical ultrasound, one important parameter for quality controls (QC) is the maximum Depth of Penetration (DoP), because it can be related to the sensitivity and more in general to the performance degradation of the scanner. In the technical and scientific literature, DoP is usually associated with the maximum depth at which the echo signals, produced by scattering within a tissue-mimicking phantom (TMP), can be distinguished from electronic noise [4-6]. Typically, as for the uniformity [7], in routine QC, DoP is visually evaluated on the scanner monitor [8-10], as the depth at which the ultrasound speckle from the Tissue Mimicking Material can no longer be distinguished from the background electronic noise [8,11]. The visual method, being patient- (and/or phantom-) and operator-dependent [12,13], is obviously affected by low repeatability even with consistent scanner settings and lighting conditions [4]. To overcome the subjectivity limits of visual tests, off-line methods, based on the image analysis, have been proposed in the scientific literature. Among them, the most used and widespread is the one based on the SNR evaluation at different depths from one or more images produced by means of a US phantom [12,14]: DoP is determined by the maximum depth at which the estimated SNR is above a specific threshold. Even if there are other methods for DoP evaluation [5,6,14,15], the lackage of a shared worldwide standard on ultrasound equipment testing has prevented a systematic approach for characterization and testing.

The present study wants to contribute to the field, by proposing a novel method and comparing the outcomes with the ones provided by the approach in [15], which is the most recent one and those obtained by a subjective procedure (i.e. the (mean) judgement of 5 independent observers on the basis of data acquired from three different US probe models). An estimation of the uncertainty of the above results has been carried out by means of Monte Carlo Simulation.

II. DOP ESTIMATION RATIONALE

In scientific literature, SNR-based methods have already been used to assess the maximum Depth of Penetration [16]. In this work, an alternative SNR-based method (SNR Threshold Method or STM) has been developed using phantom and in-air clips (the latter obtained with the transducer held in air). An in-house software developed in

MATLAB environment has been implemented to process the data acquired by averaging the first 15 frames of each clip, therefore obtaining a single average image ($\bar{I}$ and $\bar{I}_a$) for both phantom and in-air clips. At depth z in $\bar{I}$ the signal $S(z)$ has been estimated as the average pixel value η on a row within a rectangular Region of Interest (ROI):

$$S(z) = \eta(z) \qquad (1)$$

The noise contribution $N(z)$ is obtained by applying the same computation to the in-air average image $\bar{I}_a$:

$$N(z) = \eta_a(z) \qquad (2)$$

The corresponding $SNR(z)$ has been evaluated from the ratio $S(z)/N(z)$. DoP has been found at the depth z_{DoP} where the SNR curve intersects a SNR threshold value SNR_{th}, automatically determined in the algorithm. The threshold SNR_{th} has been calculated as follows:

$$SNR_{th} = \beta \cdot K_{max} \qquad (3)$$

where β is a dimensionless parameter set as the ratio between the minimum gray level difference $\Delta g = 10$ that the human eye can clearly distinguish [17-19] and the full luminance scale $N_{fs} = 256$. K_{max} has been assumed as the maximum US system sensitivity. Such value has been retrieved according to two main steps. Firstly, from $SNR(z)$, the non-linear curve fitting $f(z)$ has been derived by the iterative calculation of the coefficients a, b, c, d according to the sigmoidal function:

$$f(z) = \frac{a}{1 + e^{-bz+c}} - d \qquad (4)$$

The logistic function (4) has been chosen because of the presence of two saturation limits in the $SNR(z)$ curve according to the trend characterized by a predominance of signal for low z values and a predominance of noise for increasing depth values. Secondly, the first order derivative $f'(z)$ has been calculated and its minimum value, i.e. the one at z_{min}, has been used as the maximum sensitivity $K_{max} = f(z_{min})$. As already mentioned in [15], to develop a method for DoP measurement where the threshold is objectively established, the automatic threshold algorithm should select a value on the SNR profile in correspondence of depths where it is decreasing quite rapidly. In order to test the robustness of such method, the algorithm proposed in this work has been compared with:

1. the alternative method presented in [15] according to which DoP value is evaluated thresholding the tangent of the mean depth profile; the latter is obtained by the average of adjacent columns into a ROI in the diagnostic image.

2. the mean judgement of 5 independent observers (no medical staff) through the visual examination of the $\bar{I}$ image. The observers' judgment has been carried on in the same laboratory with identical lightening conditions, on the same monitor with unchanged settings. Each observer has given his judgment without the influence of any other one. The evaluation has been carried on through an in-house MATLAB software. The protocol has been repeated six times to test subjects intra-variability in addition to the inter-variability.

III. EXPERIMENTAL SET-UP

A multi-purpose, multi-tissue US phantom (CIRS, Model 040GSE) has been used to acquire the phantom clips. The phantom [20] is divided into two different zones with attenuation coefficients of 0.50 and 0.70 dB·cm^{-1}·MHz^{-1} respectively. Tests have been conducted on a single diagnostic system equipped with three different US probes (vector, convex and linear array) in the zone with 0.70 dB·cm^{-1}·MHz^{-1} of attenuation only, by positioning the probe through a holder in a specific spot on the scanning surface where no test objects (e.g. nylon monofilaments, anechoic stepped cylinders) can be displayed (speckle background only), as shown in fig.1. Both clips (i.e. the phantom and in air clips) have been acquired under identical scanning settings. The main settings of the experimental set-up are summarized in table 1.

Table 1. Experimental set-up.

Ultrasound System	
Parameter	**Settings**
Nominal Frequency Range (MHz)	3-10
Dynamic Range (dB)	Maximum
Field of View (mm)	70-180
Focus Depth (mm)	$\approx$ 20-110
TGC (dB)	Cursors aligned in medium position
Power Transmission	Maximum
Pre-processing: edge enhancement	Minimum
Pre-processing: persistence	Minimum
Post processing	Linear
Ultrasound Phantom[20]	
US phantom model	CIRS 040GSE
Scanning material	Zerdine® tissue mimicking gel
Speed of Sound (m·s^{-1})	1540
Attenuation (dB·cm^{-1}·MHz^{-1})	0.70

The average images of the phantom $\bar{I}$ and in-air $\bar{I}_a$ used for the DoP assessment have been obtained from the above clip acquisitions. Then $\bar{I}$ and $\bar{I}_a$ have been cropped by automatic masking to extract the proper diagnostic average images.
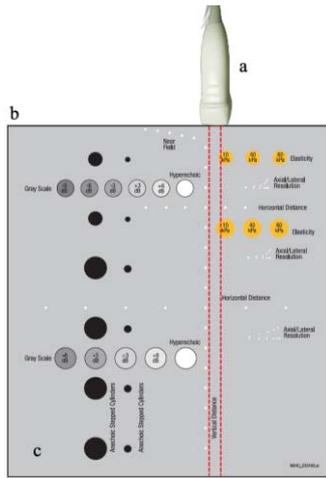
Fig. 1. Probe positioning on the phantom scanning surface to avoid test objects display: (a) US probe, (b) scanning surface, (c) US phantom. The probe holder is not reported.

To compute an accurate estimation of DoP, an adequate number of pixels at each depth should be included in a ROI: in this work, a number of 30 pixels has been chosen as ROI width (fig. 2).
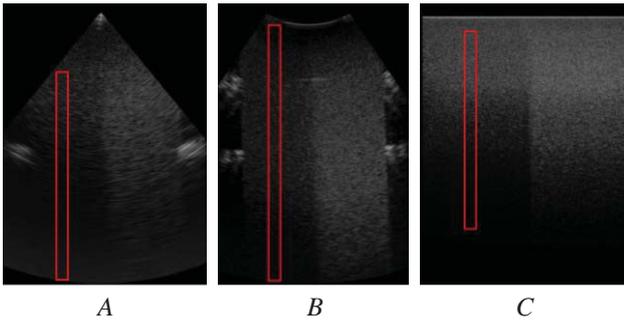

| A | B | C |

Fig. 2. ROI applied to the phantom average images for A) vector, B) convex, C) linear array probes.

IV.   MONTE CARLO SIMULATION

As observed in other similar studies [21-25], MCS is a suitable way to evaluate both the uncertainty and robustness of the algorithm used in the measurement system set-up.

Table 2. Variables settings in MCS to estimate the uncertainty of STM outcomes.

Symbol	Parameter	Distribution		Mean value	St. dev.
w	ROI width	Uniform		30	1
δ	ROI shift	Uniform		0	2
			A	1.12	0.01
SNR_{th}	SNR threshold	Normal	B	1.94	0.01
			C	3.62	0.02

A = vector array probe; B = convex array probe, C = linear array probe. The SNR_{th} is probe-dependent and therefore mean and standard deviation

values are different for each probe. The parameters w and δ are expressed in terms of number of pixels, while SNR_{th} is a dimensionless parameter.

In particular, the following uniform distributions have been assigned to the variables influencing the present study: ROI width w, expressed as number of pixels; ROI shift δ, expressed as number of pixels to simulate the operator drawing uncertainty; SNR threshold SNR_{th}, a dimensionless parameter whose standard deviation has been evaluated through a previous MCS (executed for 10^4 cycles because of the high computational cost of the interpolation process) in which w and δ distributions have been set as in table 2. The algorithm has been performed for 10^5 cycles and DoP distribution histograms have been determined.

V.   RESULTS AND DISCUSSION

DoP results for the three different US probes obtained by the STM and tangent method as well as the mean observers' judgment are reported in table 3. The uncertainties of the results, in terms of repeatability, have been retrieved from 2.5 and 97.5 percentiles and combined with the uncertainties due to the probe position on the phantom scanning surface, whose values have been estimated on the basis of previous studies [26]. For the vector probe (fig. 3A), DoP values estimated with STM and tangent method are compatible therefore suggesting that the outcomes are very close to the actual vector probe maximum depth of penetration. The observers' judgment has been probably affected by the high amount of noise in the image. On the other hand, convex probe average image (fig. 3B) shows a lower noise level that probably led the observers to assess a DoP value which is compatible with the ones obtained from the two methods. Finally, the linear probe results (fig. 3C) show that the STM provides compatible DoP values with observers' judgement while there is a disagreement with the ones retrieved by the tangent method. Such discrepancy is probably due to an incorrect assessment of the mean depth profile tangent on the average image.

Table 3. Maximum depth of penetration: measurements comparison for three US probes.

	STM (mm)		Tangent method[15] (mm)		Observers (mm)	
A	76 ± 2	(1.1%)	74 ± 1	(0.6%)	90 ± 10	(5.6%)
B	123 ± 3	(1.7%)	128 ± 6	(3.3%)	119 ± 14	(7.8%)
C	32 ± 1	(1.4%)	49 ± 1	(1.4%)	40 ± 2	(2.9%)

A = vector array probe; B = convex array probe, C = linear array probe. In brackets the percentage error with respect to the FOV (180 mm for A and B, 70 mm for C) has been reported.

Alongside the uncertainty values, the percentage error with respect to the FOV has been reported (table 3). The mean error percentage for the STM is around 1.4%, while for the tangent method it is around 1.8%. Therefore, the data confirm that the methods are almost equivalent in the
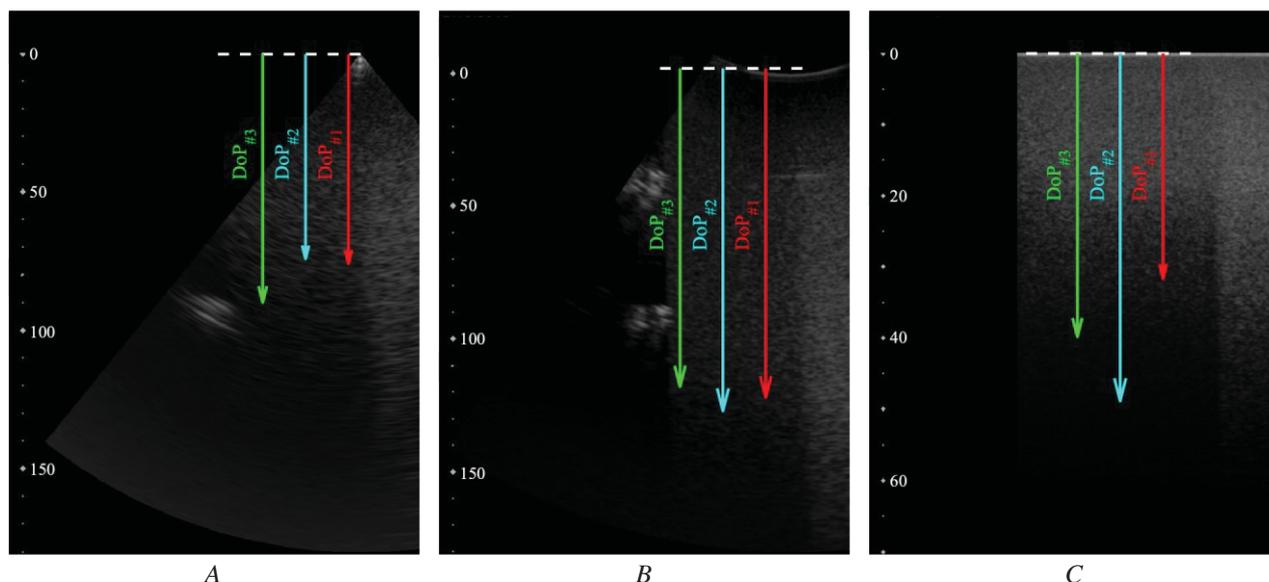
A   *B*   *C*

Fig. 3. Maximum depth of US signal penetration for three different US probes: A) vector, B) convex and C) linear array probes. DoP$_{\#1}$ is evaluated through STM, DoP$_{\#2}$ is determined with the tangent method [15] *and DoP$_{\#3}$ is assessed by the observers' judgement.*

uncertainty of DoP evaluation. Instead, the mean error percentage for the observers' estimation is around 5.4% therefore indicating that the visual DoP estimation, usually used in clinical practice, is far more inaccurate than the objective DoP assessment algorithms tested in this work.

VI.   CONCLUSIONS

In the present work, a novel SNR-based method for DoP measurements using a novel automatic threshold algorithm in US quality assessment has been implemented. The data have been collected on the same ultrasound system equipped with three different US probes. Firstly, the uncertainty related to the SNR threshold has been estimated by means of a MCS by varying both width and position of the average image ROI. Afterwards, the SNR_{th} uncertainty retrieved has been used in a further MCS to estimate DoP uncertainty for the implemented method in terms of repeatability. The results obtained in this preliminary study are compatible with the outcomes retrieved from another method already published in literature and with the mean DoP value visually assessed by 5 independent observers. Moreover, SNR Threshold Method requires both lower acquisition and computational time as well as a lower computational cost: considering also the time needed for the probe positioning and data transfer, STM has taken about 10 minutes, while the tangent method at least 20 minutes. Nevertheless, further investigations and tests should be performed on several US systems and phantoms to assure more robustness and reliability of the novel method.

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