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ORIGINAL ARTICLE

The use of mobile robotic telemedicine technology in the neonatal intensive care unit

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Objective: To describe the use of a wireless, mobile, robotic telecommunications system in the Neonatal Intensive Care Unit (NICU).

Study Design: In this prospective study utilizing 304 patient encounters on 46 preterm and term neonates in a level IIIa NICU, a bedside neonatologist ('on-site neonatologist'; ONSN) and a neonatologist at a distant location ('off-site neonatologist'; OFFSN) evaluated selected demographic information, laboratory data and clinical and radiological findings of the subjects. The OFFSN used a commercial wireless, mobile, robotic telecommunications system controlled from a remote site. The two physicians were blinded to each other's findings and agreement rates of the evaluations between the ONSN and the OFFSN were compared using kappa statistics. Agreement rates between two ONSNs using the same protocol with 39 patient encounters served as the reference standard. The dependability and timeliness of data transmission were also assessed.

Result: Excellent or intermediate-to-good agreements were noted for all but a few physical examination assessments between both the ONSN and OFFSN and the two ONSNs. Poor agreements were found for certain physical examination parameters (breath-, heart- and bowel-sounds and capillary refill time) with or without the use of telemedicine. The median duration of the encounters by the ONSN and OFFSN and the two ONSNs was similar. Five encounters were excluded from the analysis because of technical difficulties. No complications associated with the use of the mobile robot were noted.

Conclusion: Our findings indicate that the use of mobile robotic telemedicine technology is feasible for neonates in the NICU.
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Keywords: telemedicine; NICU; neonate; neonatologist; robot

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Introduction

Telemedicine has been increasingly utilized in both adult and pediatric in-patient and out-patient settings.[1–3] As telemedicine offers bringing the expertise of specialists and subspecialists to locations where their physical presence is not possible or feasible, it has tremendous potential to improve health-care delivery and outcomes. Indeed, the benefits of the use of telemedicine in adult and pediatric intensive care have already been demonstrated.[4–9]

As for neonatal care, there is a growing body of literature on the use of telemedicine primarily at remote areas for the provision of staff and parent education,[10–12] neonatology and other subspecialty consultations[10,13–15] and expert interpretation of echocardiographic[16–21] and radiographic[22] images. The findings of some of these studies suggest that the use of telemedicine improves quality of care and parental satisfaction and may decrease health-care costs and length of hospitalization of neonates requiring intensive care.[12,17–20]

There is a growing pressure to increase the use of telemedicine in neonatal intensive care. During the past decades, there has been a dramatic rise in the demand for more neonatal intensive care units (NICUs) in the United States, because of an increase in preterm deliveries, especially late preterm births and multiple gestations.[23] In addition, advances in neonatal medicine have resulted in improved survival of critically ill preterm and term neonates.[24–26] However, most hospitals with a lower level NICU do not have neonatologists that are in-house around the clock as associated cost and available manpower limit the provision of this type of coverage. Therefore, in emergency situations in these NICUs, the neonates may be initially cared for by a neonatologist who is off-site and assesses the patient based on the information provided on the telephone by nursing staff and/or respiratory therapists. As information received via telephone in emergency situations may be unreliable, the off-site neonatologist (OFFSN) may make recommendations based on limited and potentially inaccurate information. This could result in the initiation of inappropriate interventions and thus may affect outcomes. Telemedicine technology can provide the OFFSN with direct visual and auditory information about the patient and the clinical scenario in real-time, and may facilitate the decision-making process for the neonatologist.

In this study, we assessed the use of a commercial wireless, mobile, robotic telecommunications system in the NICU setting. It comprises an off-site computer control station that remotely controls a robot in the NICU. We chose this telemedicine system because of its realistic physical presence, its ability to be maneuvered to the bedside and provide visual and auditory information on the patient and to directly interact with the NICU staff and parents. To our knowledge, there is no information available on the use of mobile robotic telemedicine technology for the provision of clinical care in neonatal medicine. The use of this technology must be carefully examined before its widespread use for provision of clinical care in the NICU setting can be recommended. We have hypothesized that robotic telemedicine technology can provide the neonatologist with visual and auditory information comparable to that obtained at the bedside in the NICU.

Methods

This prospective study was approved by the Hollywood Presbyterian Medical Center (HPMC) Research Oversight Committee and the Institutional Review Board of Children's Hospital Los Angeles (CHLA). Any neonate admitted to the HPMC NICU was eligible for participation in the study. The only exclusion criterion was if parental consent for participation could not be obtained. Each subject enrolled was eligible for as many study encounters as possible but with only one encounter allowed per day until discharge home or transfer out of the NICU.

According to the study protocol, two neonatologists evaluated the study subjects. One of the neonatologists was at the patient's bedside (on-site neonatologist (ONSN)) while the other one (OFFSN) evaluated the patient using the telemedicine equipment and remote-controlled robot. The OFFSN was physically at a distant location in an office at CHLA equipped with the telemedicine equipment. We used a commercial wireless, mobile, robotic telecommunications system (the 'RP-7 Remote Presence System' (InTouch Health, Santa Barbara, CA, USA)). This system comprises a control station and a remote-controlled robot. The control station and robot are linked via the Internet over a secure broadband connection. The system has bi-directional audio and video communications capability, with real-time video, rapid-response cameras with zoom and auto-focus, panoramic visualization system, a digital camera for image capture, audio microphones, amplification circuitry and custom software. The robot is equipped with a pan-tilt-zoom head (contains the video camera, microphone and liquid crystal display screen) and motorized platform and operates on 802.11 Wi-Fi network under the control of the physician at the control station at the remote site. The OFFSN's face is projected on the liquid crystal display screen of the robot, creating a more realistic physical presence of the OFFSN in the NICU (Figure 1). The robot features different Food and Drug Administration-approved medical devices (digital stethoscope, otoscope and pulse oximeter). We utilized the digital stethoscope for this study, which has the capability to amplify the sound and provides excellent sound quality for auscultation. The RP-7 has multiple safety features, including infrared sensors on the platform that prevent driving the robot into an object or person, as well as features in place that allow medical professionals to remain in compliance with privacy regulations.[27]

Figure 1 Telemedicine equipment (mobile robot) at patient's bedside. The robot is equipped with a pan-tilt-zoom head with a video camera, microphone, and liquid crystal display (LCD) screen and motorized platform and operates under the control of the physician at a remote site. The operator's face is projected on the screen creating a more human-type physical presence at the bedside. The operator's computer screen is also projected in the left lower corner of the screen of the robot, so that the bedside caregiver also sees what the operator of the robot is looking at on the screen of his/her station's computer at the remote site (see text for details).

At each encounter, the ONSN and OFFSN reviewed the patient's demographic information, laboratory data, imaging studies and pre-defined aspects of the patient's clinical condition. The findings were documented on the data collection sheet ('database sheet'; Table 1). The data collection, patient exam and review of the radiologic findings by the two neonatologists took place at the

Table 1 Data collection sheet

vNICU PATIENT ENCOUNTER **RESEARCH # ____________________**
DATE OF ENCOUNTER: _ _/_ _/_ _/
START TIME: _ _: _ _

PATIENT'S LAST NAME: ______________ **BABY BOY [ ] BABY GIRL [ ]**
MEDICAL RECORD #: _ _ _ _ _ _ _ _ _
DATE OF BIRTH: _ _/_ _/ _ _/

Bedside Identification Card matches above information: Yes [ ] No [ ]
Informed Consent Signed by Parent: Yes [ ] No [ ]

CURRENT WEIGHT: _ _ _ _ grams
POSTNATAL AGE: _ _ days
VITAL SIGNS:

NURSING FLOWSHEET	PATIENT MONITOR	
Minimum HR:	HR: [ ] Normal (100-180) [ ] Abnormal (<100 or >180)	
Maximum HR:	RR: [ ] Normal (20-80) [ ] Abnormal (<20 or >80)	
MBP Range:	MBP:	Maximum Temp: ^{o}C
O_2 Saturation range:	O_2 Saturation: [ ] Normal Premie 84-100% ; Term 92-100% [ ] Abnormal Premie < 84%; Term <92%	

Last Chemstrip: ____________
Need Clarification from Bedside Nurse (Writing on Nursing Flowsheet is illegible): [ ] Yes [ ] No

RESPIRATORY SUPPORT:
Nasal CPAP [ ] Oxyhood [ ] Nasal Cannula [ ] None/Room Air [ ]
Ventilator: SIMV [ ] HFOV [ ]
Rate/Hz: _____ PIP/Amplitude: _____ PEEP/MAP: _____ FIO2: _____%

NUTRITION: OG in place: Yes [ ] No [ ] TPN/IVF: Yes [ ] No [ ]
Central lines: PICC in upper extremity [ ] Lower extremity [ ] Umbilical lines [ ] None [ ]

PHYSICAL EXAMINATION:
General state: Moving: Yes [ ] No [ ]
Eyes Open: Yes [ ] No [ ]
Lungs: Retractions (Intercostal/Subcostal) Yes [ ] No [ ]
Breath Sounds Equal Yes [ ] No [ ]
Heart: Heart Sounds at Left Sternal Area Yes [ ] No [ ]
Abdomen: Flat Yes [ ] No [ ]
Bowel Sounds at Left mid-quadrant Yes [] No [ ]
GU: Male [ ] Female [ ]
Extremities: Cap Refill Brisk, Less than 3 seconds [ ] Prolonged, More than 3 seconds [ ]

RADIOGRAPHS: YES [ ] NO [ ]
CHEST X-RAY [ ] ABDOMINAL X-RAY [ ] CHEST AND ABDOMEN [ ]
Chest: ETT position at T ___________ Not intubated [ ]
Lung Expansion to __________ribs
Tension Pneumothorax Yes [ ] No [ ]
Umbilical lines: UVC at T________ None [ ]
UAC at T________ None [ ]
PICC line: In SVC [ ] In IVC [ ] None [ ]
Abdomen: OG present/in stomach Yes [ ] No [ ]
Dilated loops Yes [ ] No [ ]

TIME EVALUATION IS COMPLETED: _ _: _ _
Audio/Video Interrupted: Yes [ ] No [ ]
Audio Quality: Poor [ ] Adequate [ ]
Video Quality: Poor [ ] Adequate [ ]

EVALUATION COMPLETED BY: ______________________

same time but the two neonatologists were blinded to each other's findings and no discussions were allowed between the neonatologists during the encounters. Six academic neonatologists were involved in the study. Although efforts were made to match the pair of neonatologists for their level of training and experience in neonatal medicine, this could not be accomplished for all encounters. All neonatologists involved in the study received education and intensive training on the use of the telemedicine equipment and mobile robot by the InTouch Health representatives. Training sessions involved maneuvering the mobile robot in the HPMC NICU, evaluating patients using the robot and the digital stethoscope, and troubleshooting for potential problems with the equipment. Proficiency with the telemedicine equipment was determined by InTouch Health and typically required 4- to 5-hourly sessions. In addition, before initiation of the project, nursing and respiratory staff in the NICU at HPMC received education about the telemedicine equipment, the research protocol and their roles in assisting the OFFSN during patient encounters including the use of the digital stethoscope.

We also compared two neonatologists evaluating a patient at the bedside (two ONSNs) at the same time. For these encounters, efforts were also made to match the pair of neonatologists for their level of training and experience, although this could not be accomplished for all encounters. However, the two ONSNs were any combination of the six neonatologists. The two ONSNs used the same protocol, procedures and database sheet designed for the studies conducted by the ONSN and OFFSN. They were blinded to each other's findings and no discussions were allowed between the neonatologists. By comparing the findings between two neonatologists at the bedside, we determined the inter-rater reliability of our customary method of patient evaluation at the bedside. Thus, the findings obtained by using two neonatologists at the bedside served as the reference standard (that is, the 'baseline' agreement rate) for comparison with the rate of agreement obtained between the ONSN and the OFFSN using telemedicine.

This research project was designed not to interfere with ongoing patient care activities and treatment modalities provided to the patients enrolled in the study or the other patients cared for in the NICU.

Study protocol and data collection pairing an ONSN with an OFFSN

At the start of each encounter, the OFFSN maneuvered the remote-controlled robot to the patient's bedside to perform the study with the ONSN being at the bedside. The investigators followed a strict protocol as to how each assessment and examination would proceed. The ONSN and OFFSN first reviewed patient demographic information from the patient's identification card on the isolette and the medical chart. Then the neonatologists read the pertinent clinical data from the chart, the neonatologists then noted selected vital signs displayed on the monitors. Information on heart rate, respiratory rate, arterial oxygen saturation and blood pressure were directly collected from the monitors by both neonatologists at the same time, since these vital signs vary in time. During the study period, the use of the Electronic Medical Records System was not available to the neonatologists, therefore, vital signs and clinical information were collected directly from the paper medical chart and patient monitors. Assessments of the patient's activity level and respiratory exam characteristics along with the characteristics of the abdominal exam, skin perfusion and capillary refill time were also assessed by both neonatologists simultaneously. The OFFSN then proceeded with the remainder of their physical assessment using the robot and the electronic stethoscope with assistance from the bedside nurse or respiratory therapist. Once the OFFSN completed his/her physical assessment, the ONSN examined the patient for the same clinical findings. The ONSN was not allowed to observe the OFFSN's evaluation of the patient studied and vice versa. Finally, both neonatologists proceeded to separately evaluate the patient's digitally transferred radiographs on a special computer screen in the NICU if imaging studies were performed the morning of the encounter. The OFFSN did not have remote access to the hospital's Picture Archiving and Communication System during the time the study commenced. Therefore, the OFFSN viewed the radiographs through the robot's camera using a special computer screen in the NICU. As only 13% of the ONSN vs OFFSN encounters (40 of 304) had radiographs on the day the baby was evaluated, the number of encounters was too small to be analyzed. Therefore, we added 109 radiograph-only encounters to our study and included these encounters in our statistical analysis. Of the 109 'radiograph-only' encounters, 53 were performed with the use of the telemedicine equipment (ONSN vs OFFSN).

Study protocol and data collection pairing two ONSNs

By also comparing the findings between two neonatologists who both evaluated the patient at the bedside using the same protocol, we established the reference standard for comparison with the agreement rate obtained between the ONSN and the OFFSN. As for the 'radiograph-only' evaluations, out of the 109 encounters, 56 were performed between two ONSNs. The patients assessed by the two ONSNs were a subset of patients from the ONSN vs OFFSN comparisons.

Data collection to assess the dependability of the robotic telemedicine equipment in the NICU

Dependability was assessed by collecting information on the sustainability of the Internet connection measured as a categorical variable ('uninterrupted' or 'interrupted') and the quality of the real-time video and audio transmission (assessed as poor to adequate). As per the protocol, in case of an interruption, reconnection had to be established within 5 min or the encounter would be excluded from the final analysis. We chose 5 min as the cut-off time because loss of connection for longer duration would likely affect the remote neonatologist's ability to appropriately assess the patient's condition in real-life scenarios. Finally, we evaluated the timeliness of data transmission by timing the duration of each encounter.

Data collection to assess the safety of the robotic telemedicine equipment

To assess the safety of the robotic telemedicine equipment, we noted the ability of the OFFSN to evaluate patient identifiers such as name, medical record number and date of birth, as the use of the remote robotic telecommunications system had the potential to increase episodes of patient misidentification. In addition, we collected information on any event where the robot might have caused direct harm to patients, parents, staff or hospital equipment.

Information technology
As the initial set-up using the hospital's bandwidth and the access points established in the NICU area had resulted in inconsistent performance of the robot during the early part of the study, we switched to an external digital subscriber line connection consistently providing the required rate of 400 kbps. In addition, we replaced the original routers and power modules as well as their location. These changes resulted in stable Internet connectivity and system performance during the remainder of the study.

Sample size calculations
Sample size calculations were based on an alpha level of 0.05 with a power of 0.90. To test the hypothesis that the inter-rater reliability of tested measurements has a 98% agreement, a sample size of 1200 patient encounters was required. However, as the planned interim analysis after completing over one-fourth (304) of the originally calculated number of ONSN vs OFFSN encounters found highly significant agreements and since the pattern of agreements between the two ONSNs (ONSN vs ONSN encounters) supported the consistency of the findings of the ONSN vs OFFSN encounters, data collection was stopped and the study terminated.

Inter-rater agreements were measured using kappa statistics. Kappa calculation is based on the difference between how much agreement is actually present ('observed' agreement) compared with how much agreement would be expected to be present by chance alone ('expected' agreement) when two or more independent observers are evaluating the same variable. Kappa is a measure of the inter-rater agreement standardized to lie on a -1 to 1 scale, where 1 is perfect agreement, 0 is exactly what would be expected by chance and negative values indicate agreements that are worse than if they occurred by chance alone. Interpretation of inter-rater agreement using kappa statistics is described in Table 2. In addition, the Wilcoxon rank-sum test and χ^2 analysis were used where appropriate.

Inter-rater variability, the degree of agreement between the neonatologists paired with each other was also calculated.

Table 2 Interpretation of kappa statistics (percent agreement beyond chance)

Kappa value	*Interpretation*
$\geqslant$0.75	Excellent agreement
0.40–0.75	Intermediate-to-good agreement
$<$0.40	Poor agreement
$=$0	Agreement as expected by chance alone
$<$0	Agreement is worse than expected by chance alone

Inter-rater variability is expressed as the percentage of encounters where complete agreement occurred for the parameter examined.

Results

A total of 46 patients were enrolled and a total of 452 patient encounters were obtained during the 16 months of the study from October 2007 to January 2009. Out of the 452 patient encounters, 304 encounters were obtained using the telemedicine equipment (ONSN vs OFFSN) and 39 encounters were completed by two neonatologists at the bedside (ONSN vs ONSN). The remaining 109 encounters represent radiography-only evaluations in a subset of patients. In the radiography-only evaluations, 53 and 56 encounters were performed with (ONSN vs OFFSN) and without (ONSN vs ONSN) the use of telemedicine, respectively. The median number of encounters per individual patient was 5 ± 1.6 (range: 1 to 56 encounters). Four families declined to participate and no patients were withdrawn or requested to be withdrawn from the study once enrolled.

Mean birth weight and median gestational age were 1697 ± 114g (range: 420 to 4421g) and 3 ± 0.5 weeks (range: 22 to 39 weeks), respectively. Mean weight and median postnatal age at time of enrollment were 2034 ± 108g (range: 940 to 4235g) and 13 ± 3 days (3 to 112 days of age), respectively. In all, 24 of the 46 patients were male (52%) and 5 sets of twins and one set of triplets were included in the study.

Data from the 304 ONSN vs OFFSN encounters using the telemedicine equipment are reported on Table 3. Median duration of the ONSN vs OFFSN encounters was 13 ± 5 min (range: 5 to 36 min). Excellent to perfect agreements were noted for patient identifying information (kappa range $=$ 0.78 to 0.99), recorded vital signs from nursing notes (kappa range $=$ 0.90 to 0.93), real-time physiologic parameters obtained from patient monitors and ventilator settings (kappa range $=$ 0.84 to 1.00), some of the physical findings (presence of respiratory support, central lines and feeding tubes, and level of activity and the genitourinary examination (kappa range $=$ 0.77 to 0.99)). For physical examination findings, intermediate-to-good agreement was noted for subcostal retractions (kappa $=$ 0.49) while poor agreements were noted for abdominal distension and capillary refill time (kappa $=$ 0.36 and -0.01, respectively) and for the assessments utilizing the electronic stethoscope (heart sounds, breath sounds and bowel sounds (kappa range $=$ 0.17 to 0.30)). Three reports of stethoscope malfunctioning are included in the data analysis.

In the studies determining the inter-rater reliability of the customary method of patient evaluation at the bedside, 39 encounters were completed with the two neonatologists evaluating the patient at the bedside at the same time (Table 3). Median duration of the ONSN vs ONSN encounters was 11 ± 4 min (range $=$ 5 to 20 min) and not statistically significant when compared with the ONSN vs OFFSN encounters.

Table 3 Agreements between ONSNs vs OFFSNs and ONSNs vs ONSNs in the assessment of patient data, vital signs and physical examination

	ONSN vs *OFFSN* (N = 304)		*ONSN* vs *ONSN* (N = 39)	
	Kappa	*s.e.*	*Kappa*	*s.e.*
Patient data verified				
Gender	0.99	0.06	1	0.16
Medical record #	0.96	0.01	0.97	0.05
DOB	0.99	0.01	1	0.07
ID match	0.78	0.05	100%[a]	
Consent signed	100%[a]		100%[a]	
Weight	0.96	0	0.97	0.03
Postnatal age	0.98	0	1	0.05
Vital signs from flow sheet				
Lowest heart rate	0.90	0.01	0.92	0.04
Highest heart rate	0.91	0.01	0.85	0.04
Mean blood pressure	0.93	0.01	0.94	0.04
Maximum temperature	0.91	0.02	0.86	0.07
Lowest O_2 saturation	0.92	0.02	0.97	0.05
Highest O_2 saturation	0.92	0.03	0.92	0.10
Vital signs from monitors				
Heart rate	0.93	0.06	0.92	0.04
Respiratory rate	0.87	0.06	0.78	0.15
Mean blood pressure	0.98	0.01	1	0.04
O_2 saturation	1	0.06	0.97	0
Supportive measures				
Respiratory support	0.99	0.04	0.96	0.05
Ventilator rate	0.84	0.03	1	0.16
PIP	0.97	0.03	1	0.10
PEEP	0.94	0.04	0.90	0.11
FiO_2	0.86	0.04	0.72	0.10
Oro-gastric tube in place	0.92	0.06	0.85	0.14
Intravenous infusion given	0.86	0.05	0.95	0.16
Central line in place	0.95	0.04	0.96	0.10
Physical exam				
General state	0.51	0.11	0.55	0.16
Patient moving	0.77	0.06	0.54	0.16
Eyes open	0.93	0.06	1	0.16
Retractions	0.49	0.06	0.74	0.16
Breath sounds equal	0.17	0.05	−0.36	0.15
Heart sounds at left sternal area	0.30	0.05	−0.04	0.15
Abdominal distension	0.36	0.05	0.56	0.15
Bowel sounds	0.18	0.04	−0.41	0.13
Genitourinary exam	0.95	0.6	0.90	0.15
Capillary refill time	−0.01	0.05	−0.36	0.15

Abbreviations: DOB, date of birth; OFFSN, off-site neonatologist; ONSN, on-site neonatologist; PEEP, positive end expiratory pressure; PIP, peak inspiratory pressure; s.e., standard errors.
[a]In case of a perfect agreement, kappa value cannot be computed and the rate of agreement is expressed as 100%.
Kappa values and the respective s.e. for comparison of assessments with (ONSN vs OFFSN) and without (ONSN vs ONSN) the use of telemedicine of the parameters studied for patient demographics, vital signs verified from flowsheet and monitors, respiratory and nutritional supportive measures as well as different aspects of physical examination. In general, intermediate-to-good or excellent agreements have been found for the same parameters when the assessments between an ONSN and an OFFSN and two ONSNs were compared. See text for details.

Intermediate-to-good or excellent agreements were noted for most of the assessments (kappa range = 0.54 to 1). However, physical examination findings obtained by using the stethoscope (heart sounds, breath sounds and bowel sounds) and for capillary refill time showed poor agreements (kappa range = −0.04 to −0.041).

Table 3 depicts the agreement rates for all encounters with and without the use of the telemedicine equipment. There were excellent agreements (kappa values $\geqslant 0.75$) between the OFFSN and ONSN and the two ONSNs in the assessment of patient data, vital signs from the flow sheet and monitors, and supportive measures. The agreements were intermediate-to-good (kappa values = 0.40 to 0.75) or excellent (kappa values $\geqslant 0.75$) in the assessment of physical examinations requiring primarily visual inspection with or without the use of the telemedicine equipment. As for these categories, there was no difference in the level of agreements between the reference group (two ONSNs) and when the telemedicine equipment was utilized (OFFSN vs ONSN). The only exception in the agreement rates was the finding that the agreement in the assessment of abdominal distension was intermediate-to-good (kappa value = 0.56) between the two ONSNs and poor (kappa value = 0.36) between the OFFSN vs ONSN. Finally, agreements rates for capillary refill time or for those relying on the use of a standard or digital stethoscope (presence or absence of breath, heart and bowel sounds), in general were poor (kappa values <0.4). Of note, the data with poor agreements in the ONSN vs OFFSN encounters using the telemedicine equipment such as the heart, bowel and breath sounds, were actually worse than expected by chance alone between the two ONSNs (kappa values <0).

A total of 109 'radiograph-only' evaluations were performed with 53 and 56 performed with (ONSN vs OFFSN) and without (ONSN vs ONSN) the telemedicine equipment, respectively (Table 4). Both the on-site assessments (ONSN vs ONSN) and the assessments made by the use of the telemedicine equipment (ONSN vs OFFSN) yielded intermediate-to-good or excellent agreements for most parameters in the assessment of radiographic findings. The only difference in the assessments was the presence or absence of dilated intestinal loops, where the agreement rate was excellent between the two ONSNs and poor between the ONSN vs OFFSN.

Inter-observer variability was also calculated (data not shown). For the majority of clinical parameters, we noted a good concordance between the two neonatologists with agreement rates of 90 to 100% between the ONSN and OFFSN or ONSN and ONSN. Moderate variability was seen for the assessment of the general state of the patient and the position of umbilical venous catheter in the ONSN vs OFFSN encounters (74 and 78%, respectively) and the ONSN vs ONSN encounters (78 and 78%, respectively). Moderate variability was also seen for the assessment of the position of the endotracheal tube (78%) in the ONSN vs ONSN encounters. Finally, poor agreement (that is, high variability) was seen in the

Table 4 Agreements between ONSNs vs OFFSNs and ONSNs vs ONSNs in the assessment of radiological findings

	ONSN vs *OFFSN* (N = *53)*		*ONSN* vs *ONSN* N = *56)*	
	Kappa	*s.e.*	*Kappa*	*s.e.*
Type of X-ray	0.91	0.11	1	0.10
Endotracheal tube present	1	0.10	1	0.06
Endotracheal tube position	0.89	0.14	0.74	0.10
Lung expansion	0.79	0.07	0.47	0.05
UVC present	1	0.11	1	0.05
UVC position	0.65	0.13	0.69	0.12
UAC present	0.96	0.12	1	0.06
UAC position	0.73	0.14	0.54	0.12
PICC line position (in SVC or IVC)	1	0.14	1	0.13
orogastric/nasogastric tube present	100%[a]		100%[a]	
Dilated bowel loops	0.29	0.14	0.80	0.11

Abbreviations: IVC, inferior vena cava; OFFSN, off-site neonatologist; ONSN, on-site neonatologist; PICC, peripherally inserted central catheter; s.e., standard errors; SVC, superior vena cava; UAC, umbilical arterial catheter; UVC, umbilical venous catheter.
[a]In case of a perfect agreement, kappa value cannot be computed and the rate of agreement is expressed as 100%.
Except for the assessment of dilated bowel loops using the telemedicine equipment, or other parameters of radiological findings showed intermediate-to-good or excellent agreements. See text for details.

assessment of the position of the umbilical arterial catheter (62%) and lung expansion (55%) but only in the ONSN vs ONSN encounters.

Technical difficulties were experienced in 77 (25%) of the ONSN vs OFFSN encounters using the telemedicine equipment. In 10 encounters, the OFFSN neonatologist noted 'poor' audio (muffled sounds) or 'poor' video quality ('grainy' or blurry video), but still was able to complete the encounter. Therefore, these encounters were included in the data analysis. Difficulties in maintaining internet connection occurred in 72 out of the 304 encounters using the telemedicine equipment. As 67 of the 72 interruptions were brief and the OFFSN was able to reconnect within 5 min, patient assessment was continued and these encounters were included in the final analysis as well. However, in the remaining five interrupted encounters, reconnection and data collection could not be established within 5 min and, as per protocol, these encounters were excluded from the data analysis. The five reconnection-failures had occurred before we updated the Internet connection, the access points and power modules as described in the Methods section.

In addition, during the ONSN vs OFFSN encounters, the OFFSN and ONSN requested assistance or clarification from the bedside nurse for one or more components of the assessment or evaluation in 56 and 40% of the encounters, respectively ($P<0.01$). The most common requested occurrence was the neonatologist asking the bedside nurse to verify the handwriting in the nursing flowsheet.

There were no complications with the use of telemedicine equipment in the NICU including injuries to the subjects or the staff inflicted by the telemedicine equipment or the remote-controlled mobile robot.

Discussion

Telemedicine technology can be divided into three major forms according to the primary goal of the service provided to the patient. The first and simplest form uses tele- or videoconferencing to enable direct interaction between the patient and/or the patient's primary care provider and a specialist who is at a different physical location. This form of telemedicine has been utilized primarily by large health-care systems to provide services at medically underserved or remote areas involving disciplines such as obstetrics and neonatal–perinatal medicine,[11,13,14] medicine, surgery, pharmacy, nursing and home health care.[1] The second and most common form of telemedicine provides the local physician with interpretation of imaging by a remote expert in different areas such as cardiac electrophysiology and echocardiography,[16–21,29,30] radiology[22,28] and ophthalmology.[15,31] The third and most complex form of telemedicine requires the provision of direct care or invasive interventions by a physician not physically located at the same place with the patient.[2,32–34] This form of telemedicine has been used in adult and pediatric patients, requires the availability of sophisticated medical- and information-technology and entails the provision of care by a remote intensivist[2,32] or performance of an invasive procedure by a cardiologist or a surgical or other specialist.[30,33,34] To our knowledge, there is little information available on the use of this most complex form of telemedicine technology in the neonatal patient population.

Accordingly, this study is the first research project describing the use of remote, robotic telemedicine technology in neonates. We have found that the robotic telemedicine system used in this study is feasible as the remote neonatologist was able to accurately identify and assess the patients and maneuver the mobile robot in the NICU without incident. Our finding that most agreement rates between the ONSN and the OFFSN were excellent or good support the utilization of robotic telemedicine technology in the NICU. Although the agreement rates for certain elements of the physical examination parameters were poor when the use of the robotic telemedicine technology was compared with on-site assessment, similar poor agreement rates were obtained when the assessments of two ONSNs were compared for the same parameters. Thus, these findings strongly suggest that the observed disagreement in the physical examination parameters between the ONSN vs OFFSN was not due to the use of the remote, robotic telemedicine system. Rather the assessment of these parameters is inherently subjective with disagreement occurring even when two neonatologists assess the same patient at the bedside.

Data on the inter-rater variability demonstrated that for most parameters agreements between the two neonatologists were good with or without the use of telemedicine. Importantly, the few poor agreements noted only occurred between the two ONSNs. These findings demonstrate an acceptable inter-rater variability between two neonatologists irrespective of the use of the remote, robotic telemedicine system and suggest that the use of this technology does not affect the consistency of assessments between two neonatologists.

Furthermore, the robotic telemedicine system we have used is reliable and audio and video quality is acceptable. The median duration for the encounters comparing the use of the robotic telemedicine system to the on-site assessment was not statistically different from that when the encounters between the two ONSNs were compared. Thus, it appears that the use of the remote, robotic telemedicine equipment does not prolong the time necessary to evaluate a neonate. Of note is that we encountered problems with internet connectivity and signal stability during the early part of the study. However, interruptions rarely occurred after the local access points, power modules and internet connection had been updated and all further patient encounters with telemedicine were completed once these upgrades were performed. These findings also imply that a dedicated information technology team with appropriate infrastructure and physicians and staff trained in and familiar with the use of the robotic telemedicine system are required for running a successful robotic telemedicine program in the NICU.

Although our findings are reassuring, the study has a number of limitations. First, this study was performed in a 15-bed, academic-affiliated, level IIIa NICU of a community hospital with a large delivery service with 5000 deliveries per year and in close proximity to a free-standing academic children's hospital. In the NICU, board-certified neonatologists along with neonatal–perinatal fellows and pediatric residents provide around the clock in-house coverage. The academic affiliation, the level IIIa assignment of the NICU and the in-house coverage make it unlikely that telemedicine will be routinely used in a similar unit. Rather, lower level NICUs, where continuous in-house neonatology coverage is not routinely provided would likely benefit from and thus, be the target of the use of robotic telemedicine technology. Therefore, a similar study targeting a lower level NICU may be required to specifically address this issue. Second, as we utilized only six academic neonatologists in this research study, the relatively small number of physicians involved may have introduced bias. For instance, as our practice is guideline-driven, neonatologists may tend to approach clinical practice similarly. We also might have paired neonatologists who tend to either agree or disagree with each other. Third potential limitation is that, although we had calculated the number of encounters to be studied based on statistical power analysis, we stopped patient enrollment earlier because the agreement rates of objectively definable parameters were excellent and thus there was an extremely small likelihood that performing more encounters would affect these findings. Finally, HPMC did not have an Electronic Medical Records System or Picture Archiving and Communication System in place during the initiation of our research project. Having access to these systems would have eliminated many of the robot's functions assessed in this study (that is, the interrogation of the paper medical chart). However, the 'traditional' environment enabled us to assess whether the use of the robotic telemedicine system could be helpful in a lower level NICU without access to Electronic Medical Records System and/or Picture Archiving and Communication System. This aspect of the study, supports our notion that utilization of this robotic telemedicine technology would be the most useful in lower level NICUs where 24/7 coverage by an ONSN is usually not available.

Our next objective in studying the use of the robotic telemedicine system for the provision of clinical care in the NICU is to assess whether the use of this technology impacts clinical outcomes and health care costs. Therefore, in an ongoing study, we are assessing whether the use of robotic telemedicine technology results in comparable clinical outcomes and resource utilization to the care provided by ONSNs. We must emphasize although that, as a robotic telemedicine exam cannot replace a bedside exam, robotic telemedicine technology should not be conceived as a replacement for the provision of on-site intensive care but rather a way to ensure that prompt attention and early intervention based on direct and accurate information can be provided to sick neonates when on-site medical care is not immediately available.

Conflict of interest

The authors declare no conflict of interest.

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